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# Study on <sup>99</sup>Mo Production by Mo-Solution Irradiation Method (3)

- Activation Analysis of Irradiation Target -

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# Study on <sup>99</sup>Mo Production by Mo-Solution Irradiation Method (3) —Activation Analysis of Irradiation Target—

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The impurity concentrations in both  $(NH_4)_6Mo_7O_{24}$  and  $K_2MoO_4$  solutions, which were selected as the advanced targets of the Mo-solution irradiation method for <sup>99</sup>Mo production, were determined by the instrumental Neutron Activation Analysis (NAA) using the k<sub>0</sub>-standardization method. As a result, Na, Mn and W were identified as impurities in the received molybdates. After the compatibility test with structural material (SUS304) under gamma-ray irradiation, activation analysis of the molybdate solutions by the NAA method was also carried out. It was found that the identified impurity concentrations stayed stably in the solutions and that no elements came from the structural material. However, a small corrosion of the structural material was observed from the ICP measurement.

Keywords: <sup>99</sup>Mo, Radioisotope, Medical Diagnosis, Production Technology, Mo-solution Irradiation Method, Activation Analysis

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溶液照射法による<sup>99</sup>Mo 製造に関する研究(3)--照射ターゲットの放射化分析-

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(2009年5月20日 受理)

<sup>99</sup>Moを製造するための溶液照射法の照射ターゲットとして、モリブデン酸アンモニウムとモリ ブデン酸カリウムの2つの水溶液を選定し、水溶液中の不純物濃度を評価するためにk<sub>0</sub>標準法を 用いた放射化分析を実施した。この結果、始発粉末中に Na、Mn 及び W の不純物が同定された。 また、これらの水溶液を用いた y 線照射下でのキャプセル等の構造材(SUS304)との両立性試験 において、試験後の水溶液の放射化分析を実施した結果、同定された不純物濃度の変化がないこ と、構造材から溶出した元素が検出されないことが明らかとなった。しかし、同水溶液を ICP で 分析した結果、構造材のわずかな腐食が認められた。

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#### 1. Introduction

 $^{99m}$ Tc is the most widely used radioisotope for the medical diagnosis such as the checks of cancer, bowel disease and brain faculty in the world and the demand is continuously growing up year by year. In case of Japan,  $^{99}$ Mo radioisotope, parent nuclide of  $^{99m}$ Tc, is imported. However, the importance of the domestic production is pointed out from a viewpoint of the stable supply of  $^{99}$ Mo because of some troubles on transportation or the research reactor, and so on. Therefore, the (*n*, *y*) method using solid molybdenum target had been planned in JMTR. However, it will be difficult to satisfy domestic demand because of the limited irradiation volumes of the hydraulic rabbit irradiation facility.

To increase the amount of <sup>99</sup>Mo production, the molybdenum solution irradiation method (M-SUIMIT) was proposed as a new production method [1-3]. This method is based on the neutron irradiation by circulating molybdenum solution, and several advantages can be pointed out such as a large irradiation volume, high efficient and low cost comparing with conventional methods using enriched <sup>235</sup>U(n, f)<sup>99</sup>Mo or using a solid molybdenum target of MoO<sub>3</sub> as the minor (n,  $\gamma$ ) method. In order to develop the molybdenum solution irradiation method, un-irradiated and gamma ray irradiated tests of the molybdenum solution were carried out [4-6]. The comparison among these three methods is shown in Table 1 assuming the production in the Japan Materials Testing Reactor (JMTR) [3].

In order to realize the M-SUIMIT, study on the impurities of irradiation targets which became important as a medicine was carried out.

Criteria of  $^{99m}$ Tc generator as medicine are shown in Table 2 [7, 8]. According to these criteria, the identification of impurities was necessary to select a molybdate solution for neutron irradiation. The k<sub>0</sub>-standardization method [9-11], one of Neutron Activation Analysis (NAA) methods, was selected to determine elemental concentration in the molybdate solutions. This method has the advantage of being quick and effective, especially the preparation of standards was not necessary. Hence, the activation analysis of these irradiation targets was carried out by the k<sub>0</sub>-standardization method to estimate impurities, and to develop the impurity removal system.

#### 2. $k_0$ -Standardization Method

The  $k_0$ -standardization method was intended to be an absolute technique where the uncertain nuclear data are replaced by nuclear constants which are experimentally determined with high accuracy. Basically, this determination is done as for the k-factors (single-comparator method), which are then transformed into  $k_0$ -constant by the experimental parameters.  $k_0$ -factors are thus generally applicable to the condition where the activation analyst recombines them with parameters of the local irradiation and counting conditions.

From this point of view, the  $k_0$ -method is a flexible single-comparator technique.

The concept of the NAA k<sub>0</sub>-standardization method [9-11] can be expressed as follow: the concentration  $\rho_a$  of an analyte "*a*" is obtained from measured isotope/gamma ray as

$$\rho_a(\mu g / g) = \frac{\left(N_p / Wt_m SDC\right)_a}{\left(N_p / wt_m SDC\right)_{Au}} \times \frac{1}{k_{0,Au}(a)} \times \frac{G_{th,Au}f + G_{e,Au}Q_{0,Au}(\alpha)}{G_{th,a}f + G_{e,a}Q_{0,a}(\alpha)} \times \frac{\varepsilon_{p,Au}}{\varepsilon_{p,a}} \times 10^6 \tag{1}$$

where

 $S = 1 - \exp(-\lambda t_{d}), D = \exp(-\lambda t_{d}), C = [1 - \exp(-\lambda t_{m})] / \lambda t_{m},$ 

"Au" refers to the co-irradiated gold monitor [ $^{197}$ Au(*n*, *y*) $^{198}$ Au]

 $N_p$  : the net number of counts in the full-energy peak

- W: the weight of the sample
- W: the weight of the gold monitor
- $t_m$  : the measuring time
- $t_i$  : the irradiation time
- $t_d$  : the decay time
- $\lambda$  : the decay constant
- f : the thermal to epithermal neutron flux ratio
- $Q_0 = I_0/\sigma_0$  (resonance integral to 2200 ms<sup>-1</sup> cross-section ratio)
- $\alpha$ : the measure for the epithermal neutron flux distribution, approximated by a  $1/E^{1+\alpha}$  dependence (with  $\alpha$  considered to be independent of neutron energy)
- $G_{th}$ : the thermal neutron self-shielding factor
- $G_e$ : the epithermal neutron self-shielding factor
- $\varepsilon_p$  : the full-energy peak detection efficiency.

Furthermore, in the equation (1), the  $k_{0,Au}(a)$  factor is defined as:

$$k_{0,Au}(a) = \frac{M_{Au}\theta_a \sigma_{0,a} \gamma_a}{M_a \theta_{Au} \sigma_{0,Au} \gamma_{Au}}$$
(2)

where

- M: the atomic weight
- $\theta$  : the isotopic abundance
- $\sigma_0$  : the 2200 ms<sup>-1</sup> (*n*, *y*) cross-section
- Y : the absolute gamma-ray intensity (emission probability).

The ko-constants were therefore measured directly in some specialized institutes [12] as Institute for Nuclear Sciences in Gent, KFKI institute in Budapest and Riso in Denmark.

When the  $k_0$ -constants were determined by once characterized the irradiation facility and the detector, each sample needs to be co-irradiated with a gold comparator only. Errors in standard preparation are thus excluded. In exchange, systematic errors in the  $k_0$ -constants will affect all obtained results. These errors have been shown to be small, however. The general agreement is that the errors in the constants are smaller than 3.5%.

#### 3. Experiment

#### (1) Preparation of samples

In the present work, three kinds of sample were prepared as following:

- Powder samples: Samples were collected from different companies. These samples would be estimated in original impurity contents before making into a solution, and contained in polyethylene bags with a thin wire Al-0.1%Au as a comparator. The prepared sample and makers are shown in Table 3.
- 2) Liquid samples (circulating state): ammonium molybdate powder and potassium molybdate powder were selected to make the molybdate solution [4, 5]. Molybdate solutions in the circulating state were obtained by mixing with pure water and gamma ray irradiated in many hours with aluminum alloy or stainless steel enclosed [5]. After gamma ray irradiation, molybdate solution was dropped on the filter paper, and was dried. After that, the samples were contained in polyethylene bags with a thin wire Al-0.1%Au enclosed, which was as a comparator. The prepared samples and sample name are shown in Tables 4 and 6.
- 3) Liquid samples (stilled state): the sample is similar to the above sample, but molybdate solution was obtained in stilled state [5]. The prepared sample and sample name are shown in Tables 5 and 7.

In this work, two Standard References Materials, namely NIST SRM-1577b (~ 100 mg) and SRM-1633b (~50 mg), which are used as reference standards to check the measurement precision, are prepared.

#### (2) Irradiation facility

JRR-3 was used for neutron irradiation in this work. JRR-3 achieved the first criticality in 1962 as the first research reactor constructed with the homegrown technology and had been utilized in a lot of researches from the drawn of nuclear research and industry. In 1990, JRR-3 was modified for upgrade and resumed its operation as a high performance and multi purpose research reactor with thermal power of 20 MW. The arrangement of the irradiation holes in the JRR-3 reactor is shown in Fig. 1. Table 8 shows the results of the neutron spectrum parameters in the PN1 [13] and PN3 [14] irradiation holes at JRR-3. In the present work, PN3 irradiation position was selected.

#### (3) Counting equipment

In the present work, the system of gamma ray spectrometer with HPGe detector was used.

Its characteristics are summarized in Table 9. The geometric configuration of the detector and source support is shown in Fig. 2 and the dimensions of detector are shown in Appendix A.1.

#### (4) Experimentally determination of full-energy peak detection efficiency

The HPGe detector coupled to a PC-based 4K channel analyzer in an efficiency calibrated position with reproducible sample-to-detector geometry. The detector system had a gamma-ray energy resolution with 1.9 keV at 1332 keV of <sup>60</sup>Co. A set of point sources (<sup>241</sup>Am, <sup>109</sup>Cd, <sup>57</sup>Co, <sup>137</sup>Cs, <sup>54</sup>Mn, <sup>60</sup>Co and <sup>22</sup>Na) was used to determine the full-energy peak detection efficiency. There are two positions for this measurement; the one is at 5cm distance on top of the detector, and the other is at 15 cm distance on top of the detector. After counting the activities from point sources, the absolute efficiency of the detector was calculated, and fitting of calculated efficiency versus gamma-ray energy was carried out. Appendix A.1 shows the sources and their data for determination of efficiency of detector.

Gamma ray spectrum was obtained using Genie-2000 software. Full-energy detection efficiency of detector versus gamma ray energy was obtained and fitted to a polynomial as shown in Fig. 3.

#### 4. Determination of Impurity Elemental Concentrations in the Samples

#### 4.1 Application of ko-Standardization Method

to Determination of Elemental Concentrations in Standard Reference Materials

SRM-1577b and SRM-1633b were measured to check the precision of measurement. Their weights are 100 mg and 50 mg, respectively. The samples were irradiated at PN3 position of JRR-3 reactor during 1-5 minutes, cooling in 2-5 hours and counting in 3600 seconds at 5 cm distance on the top of the HPGe detector. Gamma ray spectrum was obtained using Genie-2000 software. Elemental concentrations in SRM-1577b and SRM-1633b were estimated by the equation (1), and results are summarized in Table 11 and Table 12. The measured values in the present work are agreed with certified values. The *Z*-score factors of all over the measured concentrations from analysis method were satisfied, i.e., -2 < Z < 2 [15], as shown in Table 10. The measured concentrations do not differ significantly from the certified values.

From the statistical evaluation procedure proposed by M. Thomson and R. Wood, the individual Z-score for the analysis of separate element is calculated as follow [see Ref. 15]:

$$Z = \frac{x - X}{\sigma^*} \tag{3}$$

where, x is the average of analyzed value which obtained from independent analysis, X is

certified value in standard research material,  $\sigma^*$  is the standard deviation from independent analysis.

#### 4.2 Application of ko-Standardization Method

to Determination of Impurity Elemental Concentrations in Molybdate Solutions

As investigated in section 4.1 above, it was proved that all of the parameters such as efficiency of detector ( $\varepsilon_p$ ), thermal/epithermal neutron flux ratio (f), deviation of epithermal neutron spectrum ( $\alpha$ ), were available. The k<sub>0</sub>-standardization method was used in this work.

Determination of impurity concentrations in molybdate solutions is the same method with Standard Reference Materials, NIST. The samples were separately irradiated at the PN3 position of JRR-3 reactor. After cooling, the samples were counted using gamma ray spectrometer with the HPGe detector at 5 cm distance on the top detector. The gamma ray spectral was obtained using Genie-2000 software. As a result, impurity concentrations were estimated by the equation (1). Impurity concentrations in three kinds of molybdate samples are summarized in Table 13, Table 14 and Table 15.

#### 5. Results and Discussions

Before gamma-ray irradiation, the impurity and major elements were identified in the powder samples. The elemental concentrations were measured and shown in Table 13. Na, Mn and W elements were measured as impurities in the samples. The existence of impurities as Ar, K and In in the molybdenum oxides is due to contamination during preparation of samples.

For the molybdate solutions after gamma-ray irradiation, Na, Ar, K, Mn and W are identified as impurities in the ammonium molybdate solution, while Na and W were found in the potassium molybdate solution. Elemental concentrations for measured impurities in the molybdate solutions are shown in Tables 14 and 15.

The accuracy of the method was validated by analyzing the Standard Reference Materials (SRM-1577b and SRM-1633b) of NIST. The measured and certified values for the elemental concentrations of NIST are shown in Tables 11 and 12. The uncertainties of measured concentrations of elements in Tables 11 and 12 are at  $\pm 1\sigma$  ( $\sigma$ : standard deviation) and they are the unweighted standard deviation of two independent measurements.

The measured values in present work are agreed with certified values. The Z-score factors of all over the measured concentrations from analysis method were satisfied, i.e., -2 < Z < 2 [15]. The measured result does not differ significantly from the certified value.

As shown in Fig. 4, in ammonium molybdate solution at circulated state, the Mn and W concentrations were the same magnitude as that of before gamma-ray irradiation, i.e.,  $\sim 0.03$ 

mg/l and ~6.5 mg/l, respectively. However, K (~31 mg/l) was appeared in this solution due to mixing water with the ammonium molybdate powder, and K was dissolved a little from wall of glass. The Na concentration was increased approximately 4 times as large as that of before gamma-ray irradiation. There is no change in molybdenum contents in this case. In stilled solution, impurities in the ammonium molybdate solution were the same magnitude of the circulated solution, but the Na concentration was increased approximately 40 times as large as that of before gamma-ray irradiation: the reason is thought to be that Na content in glass is more dissolved than that in circulated state. Under experimental conditions in this work, the impurities of stainless steel owing to corrosion were not detected by the NAA method because of the detection limit of the elements in the NAA method (see Appendix A.2). The ICP method was applied to identify impurities in the solution, and as a result, the impurities such as Cr, Fe and Ni, coming from stainless steel, were identified at very low levels of concentration.

As shown in Fig. 5, in the potassium molybdate solution after gamma-ray irradiation with 60 days at circulated state and stilled state, W (~20 mg/l) and Na (~700 mg/l) concentrations were the same magnitudes as that of before gamma-ray irradiation; Mn concentration was not found in solutions. In this case, major elemental concentration was stably staying for both stilled and circulated solutions. The impurities of aluminum alloy and stainless steel due to corrosion were measured by the ICP method, and as a result, the impurities such as Cr, Fe and Ni were also identified at very low levels of concentrations.

Fig. 6 shows the relationship between elemental concentrations in potassium molybdate solutions and gamma-ray irradiation time with stainless steel enclosed. It was clear that the content of elements was not changed and independent with gamma-ray irradiation time. For the elements such as Cr, Fe and Ni, which are thought to be dissolved from the stainless steel, very low level of concentrations were measured. As shown in Fig. 6, variety of concentration of Cr, Fe and Ni is due to error in analysis. In general, impurities concentration in both stilled and circulated molybdate solutions is stably staying and independent with gamma-ray irradiation time.

Although there are many suitable elements in stainless steel to measure by the NAA method, they are not detectable in solution under our experimental condition. It was clear that the corrosion of stainless steel in solution was too low to detect by the NAA method. Detection limit of elemental concentrations is shown in Appendix A.2. From measured results by the ICP and NAA methods, the corrosion of the stainless steel has been occurred, but very slow. In order to measure impurities from corrosion of stainless steel in molybdate solutions, corrosion test with longer time will be necessary, e.g., from one year to two years. Then, the impurities, coming from corrosion of stainless steel, would be easily measured by the NAA method.

#### 6. Conclusions

The impurity concentration in both (NH<sub>4</sub>)<sub>6</sub>Mo<sub>7</sub>O<sub>24</sub> and K<sub>2</sub>MoO<sub>4</sub> solutions, selected as advanced targets of the Mo-solution irradiation method for <sup>99</sup>Mo production, was determined by the Instrumental Neutron Activation Analysis using the k<sub>0</sub>-standardization method. As a result, it was found that Na, Mn and W are identified as impurities in the molybdate solutions. These impurity concentrations were observed at low levels for both the stilled and circulated molybdate solutions. However, Na concentration in potassium molybdate solution was high level. It must be careful to design the radiation shielding because <sup>24</sup>Na and <sup>22</sup>Na were formed with high energy gamma ray. The impurities such as Cr, Fe and Ni were almost coming from corrosion of the stainless steel about two months with very low values in concentration. In order to obtain the high quality of <sup>99</sup>Mo production, the impurities in the molybdate solution should be removed, and this will be studied in next steps. From obtained data, it is concluded that the choice of the molybdate solution for production of <sup>99</sup>Mo radioisotope is suitable and useful in irradiation targets.

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		Production methods	
Items	Fission method- $(n, f)$ method	Neutron capture m	ethods - (n, y) method
		Solid irradiation method	M-SUIMIT
<irradiation target=""></irradiation>	Enriched <sup>235</sup> U: HEU	Natural Mo	Natural Mo
• Chemical type	• U-Al alloy, UO <sub>2</sub>	MoO <sub>3</sub> , Metal Mo	Molybdate
• Form	• Foil, Pellet	Powder, Pellet, Metal	Aqueous solution
Quality control	Complex	Complex	Simple
<irradiation></irradiation>			
• Facility	Rabbit	Rabbit	• Solution circulated type capsule
Capsule volume	• About 30 cm <sup>3</sup>	• About 30 cm <sup>3</sup>	• About 1,700 $\rm cm^3$
Pre-irradiation preparation	• Enclose to capsule	• Enclose to capsule	Adjustment of Mo solution (easy)
• Irradiation time	• 5-7 days	• 5-7 days	• 5-7 days
• Collection of <sup>99</sup> Mo	• Batch collection	• Batch collection	Continuous collection
<post-irradiation process=""></post-irradiation>	Isolation in cell	Dissolution in cell	No special treatment
	(Complex)	(Relatively simple)	
<characteristics <sup="" generated="" of="">99Mo&gt;</characteristics>			
• Specific activity	• 370 TBq/g-Mo	• 37-74 GBq/g-Mo	• 37-74 GBq/g-Mo
<ul> <li>Activation by products</li> </ul>	Quite many	• <sup>92m</sup> Nb	• <sup>92m</sup> Nb
<mo adsorbent=""></mo>	Alumina (2 mg-Mo/g-Al <sub>2</sub> O <sub>3</sub> )	PZC (280-340 mg-Mo/g-PZC)	PZC (280-340 mg-Mo/g-PZC)
<radioactive waste=""></radioactive>			
Capsule structural material	• Generation at each irradiation	Generation at each irradiation	Generation per capsule exchange
Waste solution	• Quite a number of a and $\gamma$ nuclides	• A few y nuclides	• A few y nuclides
<domestic in="" japan="" production=""></domestic>	Difficult	Possible	Possible

Table 1Comparison of <sup>99</sup>Mo production methods assuming in JMTR

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Items		Criteria *1	$(n, f)^{*2}$	$(n, \gamma)^{*2}$
<sup>99m</sup> Tc yield (%)		60 ~ 110	> 80	> 80 ~ 90
Radioactive impurity content		< 5%	< 5 (µCi/mCi <sup>99m</sup> Tc)	< 1 (µCi/mCi <sup>99m</sup> Tc)
			Unit: µCi/mCi <sup>99m</sup> Tc	Unit: µCi/mCi <sup>99m</sup> Tc
$^{99}\mathrm{Mo}$			< 0.15	< 0.003
131 <b>I</b>			< 0.05	_
$^{103} m Ru$		< 0.015%	< 0.05	_
$^{89}\mathrm{Sr}$			< 0.006	_
$^{90}\mathrm{Sr}$			< 0.0006	_
Other radionuclide			< 0.1	_
Radiochemistry purity (%)			> 95	> 99
pH		$4.5 \sim 7.0$	$4.5 \sim 7.0$	$4.5 \sim 7.0$
Sterility		Cleared	Cleared	Cleared
Apyrogenicity			Cleared	Cleared
				Unit: µg/ml
Non-radioactive	- Al			< 0.02
impurity content	- Mo	< 10 ppm	< 10 µg/ml	< 0.14
	- Zr			< 0.01

 Table 2
 Inspection standard sodium pertechnetate (99mTc) as medicine

 $^{*1}$  The drugs, cosmetics and medical instruments act [16].

\*2 Inspection standard in pharmaceutical [17].

Sample Name	Chemical Formulas	Weight (mg)	Maker
MO201	MoO <sub>2</sub>	20.7	KO
MO202	$MoO_2$	20.0	AL
MO301	$MoO_3$	20.9	KO
MO302	MoO <sub>3</sub>	22.5	ТА
AM000	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub>	22.0	KA
AM100	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub>	20.9	ТА
PO000	K <sub>2</sub> MoO <sub>4</sub>	21.4	WA

 Table 3
 Prepared powder samples for neutron activation analysis

 Table 4
 Prepared molybdate solutions at circulated state

Sample name	Chemical formulas	Degree of dissolution	Sampling volume (ml)	Weight (mg)	Maker
CA60S	(NH4)6M07O24	1	0.1	31.52	KA
CK60S	K <sub>2</sub> MoO <sub>4</sub>	2.5	0.05	20.82	WA

 Table 5
 Prepared molybdate solutions at stilled state

Sample name	Chemical formulas	Degree of dissolution	Sampling volume (ml)	Weight (mg)	Maker
AH60S	$(\mathrm{NH}_4)_6\mathrm{Mo}_7\mathrm{O}_{24}$	1	0.1	30.31	TZ A
AH60A	(NH4)6M07O24	1	0.1	30.14	
KH10S	K <sub>2</sub> MoO <sub>4</sub>	2.5	0.05	19.63	
KH30S	K <sub>2</sub> MoO <sub>4</sub>	2.5	0.05	20.63	1174
KH60S	$K_2MoO_4$	2.5	0.05	19.77	WA
KH60A	$K_2MoO_4$	2.5	0.05	19.81	

Sample*	Solution	Material	Irradiation time (d)	Gamma dose (Gy)	Average temperature (°C)	pH	$\begin{array}{c} \text{Mo} \\ \text{concentration} \\ (g/\ell) \end{array}$
CA60S	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub>	SUS304	64.4	1.0×10 <sup>7</sup>	80.2	7.94	181.9
CK60S	K <sub>2</sub> MoO <sub>4</sub>	SUS304	61.9	$9.9 \times 10^{6}$	79.9	10.50	419.4

 Table 6
 Solution samples after gamma irradiation (Circulated solution irradiation)

 Table 7
 Solution samples after gamma irradiation (Stilled solution irradiation)

Sample*	Solution	Material	Irradiation time (d)	Gamma dose (Gy)	Average temperature (°C)	pH	$\begin{array}{c} \text{Mo} \\ \text{concentration} \\ (g/\ell) \end{array}$
AH60S		SUS304	60.6	1.4×107	80.0	7.69	173.9
AH60A	(NH4)6M07O24	Alumite processed A6063	60.6	1.4×10 <sup>7</sup>	79.6	7.60	176.3
KH60A		Alumite processed A6063	60.6	1.4×10 <sup>7</sup>	79.9	9.97	398.2
KH10S	K <sub>2</sub> MoO <sub>4</sub>		9.8	$2.2 \times 10^{6}$	80.6	10.08	405.3
KH30S		SUS304	32.0	$7.3 \times 10^{6}$	80.3	10.00	409.2
KH60S	KH60S		60.6	1.4×107	79.9	9.99	399.1

\*In Table 6 and Table 7:

- -"S" at the right side end of sample name means a piece of stainless steel in solution during gamma-ray irradiation.
- -"A" at the right side end of sample name means a piece of aluminum alloy in solution during gamma-ray irradiation.

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D	Irradiation position			
Parameters	PN1	PN3		
$\Phi_{th} (\mathrm{cm}^{-2}.\mathrm{s}^{-1})$	$4.709 \times 10^{13}$	$1.5 \times 10^{13}$		
$T_n(\mathbf{K})$	296	-		
f	207	2561		
α	0.1151	0.09088		

Table 8	Neutron spectrum	parameters of PN1	and PN3,	JRR-3 research reactor
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### Table 9Characteristics of the gamma-ray spectrometer system at INAA-Lab, JRR-3

Quantitative	Parameter
• Model	GX1519-7500 SL
• Series number	2891667
• MCA	3502 (4096 channels)
• Shaping time constant	4 µs
• FWHM	1.9 keV (at 1332 keV of <sup>60</sup> Co)
• Relative efficiency	18.8%

**Table 10**Conditions of Z-score for measured results

Condition	Status
-2< Z<2	The measured result does not differ significantly from the certified value.
2 <  Z  < 3	It is not clear whether the measured result differs significantly from the certified value.
Z  > 3	The measured result is significantly different from the certified value.

	Concentrat	tion (ppm)	ZCoorro	
Element	Measured Certified		Z Score	
Na	$2095.00 \pm 74$ $2010 \pm 30$		1.15	
Κ	$19754\pm715$	$19500\pm300$	0.36	
Sc	$39 \pm 6$	41	-0.25	
Mn	$132.8\pm5.1$	$131.8\pm1.7$	0.21	
Ga	$52.15 \pm 2.30$	_	_	
As	$128.3 \pm 4.9$	$136.2 \pm 2.6$	-1.60	
Ba	$596 \pm 60$	$709 \pm 27$	-1.86	
$\mathbf{Sr}$	$1043 \pm 86$	$1041 \pm 14$	0.03	
La	$87 \pm 5$	94	-1.51	
Sm	$19.30\pm0.73$	20	-0.96	
Eu	$4.7 \pm 0.8$	4.1	0.74	
Dy	$17.6 \pm 2.8$	17	0.22	
W	$5.9 \pm 1.6$	5.6	0.23	

 Table 11
 Measured elemental concentration in NIST SRM-1633b

Table 12Measured elemental concentration in NIST SRM-1577b

Element	Concentra	70		
Element	Measured Certified		Z-Score	
Cl	$2753\pm52$	$2780 \pm 60$	-0.52	
Na	$2286\pm69$	$2420\pm60$	-1.94	
Mg	$563 \pm 48$	$601 \pm 28$	-0.79	
K	$9923 \pm 29$	$9940 \pm 20$	-0.59	
Mn	$9.6 \pm 0.6$	$10.5\pm1.7$	-1.5	
Cu	$149 \pm 8$	$160 \pm 8$	-1.4	
Br	$9.22 \pm 2.2$	9.76	-0.25	

Sample Chemical		Concentration, µg/g (mg/1)*							
name	formulas	Na	Ar	К	Mn	Mo	In	W	
MO201	MoO <sub>2</sub>	10.54	_	_	1.38	$7.51 \times 10^{5}$	14.55	82.74	
MO201		(3.24)			(0.42)	$(2.31 \times 10^5)$	(4.47)	(25.40)	
MO202	$MoO_2$	11.89	—	51.21	0.64	$7.53 \times 10^{5}$	_	130.01	
MO202		(3.57)		(15.40)	(0.19)	$(2.26 \times 10^5)$		(39.00)	
MO201	$MoO_3$	14.36	2.27	_	0.50	$6.58 \times 10^{5}$	_	114.02	
M0301		(4.44)	(0.71)		(0.15)	$(2.03 \times 10^5)$		(35.23)	
MO202	$MoO_3$	41.88	—	_	0.07	$7.35 \times 10^{5}$	_	125.72	
MO302		(13.6)			(0.02)	$(2.39 \times 10^5)$		(40.860	
	$(\mathbf{NII})\mathbf{M}_{\mathbf{c}}\mathbf{O}$	5.74	_	_	0.10	$5.49 \times 10^{5}$	_	20.49	
AMUUUU	(INIT4/61/107024	(1.84)			(0.03)	$(1.76 \times 10^5)$		(6.56)	
AM100	$(\mathbf{NH}) \cdot \mathbf{M}_{2} = \mathbf{O}_{1}$	0.96	_	_	_	$5.81 \times 10^{5}$	-	46.83	
AM100	(INIT4/61/107024	(0.30)				$(1.80 \times 10^5)$		(14.50)	
PO000	K-MoO.	694.92	_	$3.23 \times 10^{5}$	-	$3.79 \times 10^{5}$	-	17.4	
PO000	<b>K</b> 21 <b>V</b> 10 <b>U</b> 4	(743.56)		$(3.46 \times 10^5)$		$(4.06 \times 10^5)$		(18.60)	

 Table 13
 Elemental concentration in powder samples before gamma-ray irradiation

\* Estimated from 0.1 m/solution after dissolute with pure water.

 Table 14
 Elemental concentration in molybdate solutions (at circulated state)

Sample	NAA method (Unit: mg/1)					ICP m	ethod (I	Unit: mg/1)	
name	Na	Ar	K	Mn	Mo	W	Cr	Fe	Ni
CA60S	7.52	5.02	30.91	0.04	$1.94 \times 10^{5}$	6.15	0.14	7.24	0.29
CK60S	795.72	_	$3.35 \times 10^{5}$	_	$4.00 \times 10^{5}$	24.98	0.17	0.22	< 0.01

 Table 15
 Elemental concentration in molybdate solutions (at stilled state)

Sample	NAA method (Unit: mg/1)						ICP m	ethod (Unit:	mg/1)
name	Na	Ar	K	Mn	Mo	W	Cr	Fe	Ni
AH60S	80.22	3.86	21.50	0.06	$1.72 \times 10^{5}$	6.34	0.78	< 0.01	0.32
AH60A	70.94	3.81	18.48	0.09	$1.78 \times 10^{5}$	6.03	—	_	_
KH60A	724.33	—	$3.32 \times 10^{5}$	—	$3.83 \times 10^{5}$	20.64	—	_	_
KH10S	719.40	—	$3.39 \times 10^{5}$	_	$3.99 \times 10^{5}$	21.92	0.18	< 0.01	0.03
KH30S	701.94	—	$3.27 \times 10^{5}$	—	$4.16 \times 10^{5}$	24.88	0.38	0.49	0.38
KH60S	726.96	_	$3.23 \times 10^{5}$	_	$3.93 \times 10^{5}$	22.00	0.25	< 0.01	0.03



Fig. 1 Location of the PN1 and PN3 irradiation hole in JRR-3 research reactor.



Fig. 2 Geometric configuration of detector and source support.



Fig. 3 Efficiency of detector HPGe at 5 cm and 15 cm distances measured with point sources Am-241, Cd-109, Co-57, Mn-54, Cs-137, Co-60 and Na-24.



Fig. 4 Comparison of elemental concentrations in ammonium molybdate solution before and after gamma ray irradiation during 60 days with stainless steel enclosed. - AM000: powder sample before gamma ray irradiation;

- CA60S: circulated solution; - AH60S: stilled solution.





- PO000: powder sample before gamma ray irradiation;

- CK60S: circulated solution; - KH60S: stilled solution.



**Fig. 6** Elemental concentrations in potassium molybdate solution versus gamma ray irradiation times with stainless steel enclosed.

### Appendixes

#### A.1 Detector and Standard Radioisotope Sources Used in the Experiments

At the INAA-Lab, JRR-3, a system of gamma ray spectroscopy with HPGe detector was used to measure of activities of the samples. The knowledge of detector's parameters was important to determine of full-energy peak detection as well as effective angle solids. Table A.1.1 and Table A.1.2 are shown the parameters of detector and data of standard radioisotope sources used in the experiments, respectively.

Material/Density (Dim.: kg/m <sup>3</sup> )	Thickness (Dim.: mm)
• Crystal : Germanium/5350	1. Crystal radius/24.0
• Detector can: Beryllium/1850	2. Crystal height/46.0
• Top dead layer: Lithium/534	3. Core/cavity radius/4.0
• Support: PMMA/1180	4. Core/cavity height/33.0
• Contact layer: Boron/2370	5. Contact layer/0.0004
• Other: Polyimide/1500	6a. Det. Cover/1.0+10.0
	6b. Source holder/3.0
	7. Detector can./0.5
	8. Top dead layer/1.6971
	A. Position/1(0), 2(20), 3(70), 4(170), 5(270)
	A1. Air layer/14
	A2. Vacuum gap/11.33

Table A.1.1 Parameters of the HPGe detector at INAA-Lab, JRR-3

Isotope	Energy (keV)	Activities (Bq)	Reference date	Half-time (year)	Measurement date	Activities (Bq)
Am-241	59.54	$3.97{ imes}10^4$	01/09/92	432.02	06/01/09	$3.87 \times 10^{4}$
Cd-109	88.03	$4.76 \times 10^{5}$	01/03/96	1.271	06/01/09	$4.20 \times 10^{2}$
Co-57	122.06	$3.94 \times 10^{5}$	01/03/01	0.744	07/01/09	$2.52 \times 10^{2}$
Cs-137	661.65	$4.66 \times 10^{4}$	01/09/92	30.174	07/01/09	$3.20 \times 10^{4}$
Mn-54	834.83	$4.61 \times 10^{5}$	01/03/01	0.855	07/01/09	$7.67 \times 10^{2}$
Co-60	1173.24	$4.14 \times 10^{4}$	01/03/96	5.279	07/01/09	$7.61 \times 10^{3}$
Na-22	1274.54	$3.81 \times 10^{5}$	01/03/96	2.602	07/01/09	$1.23 \times 10^{4}$

#### A.2 Minimum Detectable Concentration

Mass-detection limit was presented by equation (Lloyd A. Curie, *Analytical Chemistry*, Vol. 40, No. 3, 1968):

$$m_D = \frac{k^2 + 2k \left[\mu_b + \sigma_b^2\right]^{1/2}}{P(\Sigma) S(\lambda, t_i) T(\lambda, t_d, t_m) \varepsilon_p(x)}$$
(A.2.1)

where

*P* = production rate (nuclei/g-sec);

 $S = \text{saturation factor} = 1 - e^{-\lambda t_i}$ (A.2.2)

$$T = \left( e^{-\lambda t_{d}} / \lambda \right) \left( 1 - e^{-\lambda t_{m}} \right)$$
 (sec.) (A.2.3)

 $\varepsilon_p$  = detection efficiency.

 $\Sigma$  and  $\lambda$  are characteristic of the nuclear reaction being utilized; they present the reaction cross section (cm<sup>2</sup>) and product decay constant (sec<sup>-1</sup>), respectively;  $t_i$ ,  $t_d$  and  $t_m$  are the times (sec) for activation, decay and counting, respectively.

 $\mu_b = b.t_m$ ; b = background rate. k = 10 with confidence level of 95%.

Applying to determine detection limit for some elements was done at INAA-Lab, JRR-3. Table A.2 is shown the detection limit of 9 elements in the present work.

Element	Detection Limit (mg/1)					
Element	Irradiation time >> $T_{1/2}$	Irradiation time = 5 minutes				
Al	1.38	1.75				
Na	$2.45 \times 10^{-2}$	6.35				
K	$1.67 \times 10^{-2}$	3.56				
Cr	$4.02 \times 10^{-4}$	4.62				
Mn	$1.62 \times 10^{-3}$	$7.31 \times 10^{-2}$				
Fe	$1.96 \times 10^{-2}$	$3.63 \times 10^{2}$				
Co	$8.20 \times 10^{-4}$	$5.90{ imes}10^2$				
Ni	$2.00 \times 10^{-2}$	$8.82 \times 10^{-1}$				
W	$9.52 \times 10^{-4}$	$3.91 \times 10^{-1}$				

Table A.2 Minimum detectable concentrations at Lab-INAA, JRR-3 reactor (Counting position: 5 cm; Counting time: 1 hour; Decay time = 0)

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表1.SI基本単位					
甘木里	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	А			
熱力学温度	ケルビン	К			
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	単位の例
AI 立 H I 基本単位	
名称	記号
面 積 平方メートル	m <sup>2</sup>
体 積 立法メートル	m <sup>3</sup>
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 <sup>2</sup>
波 数 毎メートル	m <sup>-1</sup>
密度, 質量密度 キログラム毎立方メートル	kg/m <sup>3</sup>
面 積 密 度 キログラム毎平方メートル	kg/m <sup>2</sup>
比体積 立方メートル毎キログラム	m <sup>3</sup> /kg
電 流 密 度 アンペア毎平方メートル	A/m <sup>2</sup>
磁 界 の 強 さ アンペア毎メートル	A/m
量 濃 度 <sup>(a)</sup> , 濃 度 モル毎立方メートル	mol/m <sup>3</sup>
質量濃度 キログラム毎立法メートル	kg/m <sup>3</sup>
輝 度 カンデラ毎平方メートル	cd/m <sup>2</sup>
屈 折 率 <sup>(b)</sup> (数字の) 1	1
比 诱 磁 率 <sup>(b)</sup> (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 action of the action and a state of the action of the ac (b)

表3. 固有の名称と記号で表されるSI組立単位

			SI 組立単位	
組立量	名称	記号	他のSI単位による	SI基本単位による
	- (44 (F3)	10.2	表し方	表し方
平 面 角	ラジアン <sup>(b)</sup>	rad	1 <sup>(b)</sup>	m/m
立 体 角	ステラジアン <sup>(b)</sup>	$\mathrm{sr}^{(\mathrm{c})}$	1 <sup>(b)</sup>	$m^{2/}m^2$
周 波 数	ヘルツ <sup>(d)</sup>	Hz		s <sup>-1</sup>
力	ニュートン	Ν		m kg s <sup>-2</sup>
压力, 応力	パスカル	Pa	$N/m^2$	$m^{-1}$ kg s <sup>-2</sup>
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	С		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	$\mathbf{S}$	A/V	$m^{2} kg^{1} s^{3} A^{2}$
磁東	ウエーバ	Wb	Vs	$m^2 kg s^2 A^1$
磁 束 密 度	テスラ	Т	Wb/m <sup>2</sup>	$kg s^2 A^1$
インダクタンス	ヘンリー	Η	Wb/A	$m^{2} kg s^{2} A^{2}$
セルシウス温度	セルシウス度 <sup>(e)</sup>	°C		K
光東	ルーメン	lm	$cd sr^{(c)}$	cd
照度	ルクス	lx	$lm/m^2$	m <sup>-2</sup> cd
放射性核種の放射能 (「)	ベクレル <sup>(d)</sup>	$\mathbf{Bq}$		s <sup>-1</sup>
吸収線量,比エネルギー分与,	ガレイ	Gy	J/kg	$m^2 c^{-2}$
カーマ		Gy	0/115	III S
線量当量,周辺線量当量,方向	2 ( ( g )	Sv	I/lea	m <sup>2</sup> c <sup>-2</sup>
性線量当量, 個人線量当量		50	9/Kg	m s
酸素活性	カタール	kat		s <sup>-1</sup> 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

(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)剤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、ベクレルは放射性接種の統計的過程についてのみ使用される。
 (e)セルジロ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。
 (e)セルシウス度はケルビンの特別な名称で、セルシウス温度器を表す気値に見合いたましても同じである。
 (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制造2(CI-2002)を変照。

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

	SI 組立単位			
組立量	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 <sup>-1</sup> kg s <sup>-1</sup>	
カのモーメント	ニュートンメートル	N m	$m^2 kg s^2$	
表 面 張 九	ニュートン毎メートル	N/m	kg s <sup>-2</sup>	
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 <sup>-3</sup>	
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)	$m \text{ kg s}^{-3} \text{ K}^{-1}$	
体積エネルギー	ジュール毎立方メートル	J/m <sup>3</sup>	m <sup>-1</sup> kg s <sup>-2</sup>	
電界の強さ	ボルト毎メートル	V/m	m kg s <sup>-3</sup> A <sup>-1</sup>	
電 荷 密 度	クーロン毎立方メートル	C/m <sup>3</sup>	m <sup>-3</sup> sA	
表 面 電 荷	クーロン毎平方メートル	C/m <sup>2</sup>	m <sup>-2</sup> 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 卒	ファラド毎メートル	F/m	${ m m}^{-3}{ m kg}^{-1}{ m s}^4{ m A}^2$	
透 磁 率	ヘンリー毎メートル	H/m	$m \text{ kg s}^{-2} \text{ A}^{-2}$	
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 <sup>-1</sup> 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 <sup>2</sup> m <sup>-2</sup> kg s <sup>-3</sup> =kg s <sup>-3</sup>	
酵素活性濃度	カタール毎立方メートル	kat/m <sup>3</sup>	m <sup>3</sup> s <sup>1</sup> mol	

表 5. SI 接頭語						
乗数	接頭語	記号	乗数	接頭語	記号	
$10^{24}$	<b>э</b> 9	Y	$10^{-1}$	デシ	d	
$10^{21}$	ゼタ	Z	$10^{-2}$	センチ	с	
$10^{18}$	エクサ	Е	$10^{-3}$	ミリ	m	
$10^{15}$	ペタ	Р	$10^{-6}$	マイクロ	μ	
$10^{12}$	テラ	Т	$10^{-9}$	ナノ	n	
$10^{9}$	ギガ	G	$10^{-12}$	ピ =	р	
$10^{6}$	メガ	М	$10^{-15}$	フェムト	f	
$10^3$	キロ	k	$10^{-18}$	アト	а	
$10^2$	ヘクト	h	$10^{-21}$	ゼプト	z	
$10^1$	デ カ	da	$10^{-24}$	ヨクト	у	

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°=(п/180) rad		
分	,	1'=(1/60)°=(п/10800) rad		
秒	"	1"=(1/60)'=(п/648000) rad		
ヘクタール	ha	$1ha=1hm^{2}=10^{4}m^{2}$		
リットル	L, 1	1L=11=1dm <sup>3</sup> =10 <sup>3</sup> cm <sup>3</sup> =10 <sup>-3</sup> m <sup>3</sup>		
トン	t	$1t=10^{3}$ kg		

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表7.	SIに属さないが、	SIと併用される単位で、	SI単位て
	まとして米にた	パロア あんしょ 但 と し ア よ の	

衣される奴値が実験的に侍られるもの				
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 <sup>-19</sup> J		
ダルトン	Da	1Da=1.660 538 86(28)×10 <sup>-27</sup> 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 <sup>11</sup> 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	-	ア	bar	1 bar=0.1MPa=100kPa=10 <sup>5</sup> Pa	
水銀	柱ミリメー	トル	mmHg	1mmHg=133.322Pa	
オン	グストロ・	- L	Å	1 Å=0.1nm=100pm=10 <sup>-10</sup> m	
海		里	М	1 M=1852m	
バ		ン	b	$1 \text{ b}=100 \text{fm}^2=(10^{-12} \text{cm})2=10^{-28} \text{m}^2$	
1	ッ	ŀ	kn	1 kn=(1852/3600)m/s	
ネ		パ	Np	の形法しの教徒的な阻係は	
ベ		N	В	↓ S1単位との数値的な関係は、 対数量の定義に依存。	
デ	ジベ	N	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 <sup>-7</sup> J			
ダイン	dyn	1 dyn=10 <sup>-5</sup> N			
ポーアーズ	Р	1 P=1 dyn s cm <sup>-2</sup> =0.1Pa s			
ストークス	St	$1 \text{ St} = 1 \text{ cm}^2 \text{ s}^1 = 10^4 \text{ m}^2 \text{ s}^1$			
スチルブ	$^{\mathrm{sb}}$	$1 \text{ sb} = 1 \text{ cd} \text{ cm}^{-2} = 10^4 \text{ cd} \text{ m}^{-2}$			
フォト	$_{\rm ph}$	1 ph=1cd sr cm $^{-2}$ 10 <sup>4</sup> lx			
ガル	Gal	1 Gal =1cm s <sup>-2</sup> =10 <sup>-2</sup> ms <sup>-2</sup>			
マクスウェル	Mx	$1 \text{ Mx} = 1 \text{G cm}^2 = 10^{-8} \text{Wb}$			
ガ ウ ス	G	$1 \text{ G} = 1 \text{Mx cm}^2 = 10 \ ^4\text{T}$			
エルステッド <sup>(c)</sup>	Oe	$1 \text{ Oe} \triangleq (10^{3}/4\pi) \text{A m}^{-1}$			

(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	ユ	IJ	ĺ	Ci	1 Ci=3.7×10 <sup>10</sup> Bq
$\boldsymbol{\nu}$	ント	、ゲ	$\sim$	R	$1 \text{ R} = 2.58 \times 10^{-4} \text{C/kg}$
ラ			F	rad	1 rad=1cGy=10 <sup>-2</sup> Gy
$\scriptstyle  u$			Д	rem	$1 \text{ rem}=1 \text{ cSv}=10^{-2} \text{Sv}$
ガ	ン	/	7	γ	1 γ =1 nT=10-9T
フ	x	ル	11		1フェルミ=1 fm=10-15m
メー	ートル系	ミカラ	ット		1メートル系カラット=200 mg=2×10-4kg
Þ			ル	Torr	1 Torr = (101 325/760) Pa
標	準ナ	、気	圧	atm	1 atm = 101 325 Pa
力		IJ	_	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)
Ξ	ク		$\sim$	μ	$1 \mu = 1 \mu m = 10^{-6} m$

この印刷物は再生紙を使用しています