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On Performance Experience and Measurements with Ningyo Waste Assay System (NWAS)

Naoki ZAIMA, Shin'ichi NAKASHIMA, Koji KANEDA and Kazumi KADO

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We developed uranium mass assay systems for 200-litter wastes drums applied neutron and gamma measurements by NDA method. In this intermediate report we will describe measurement systems and trial data. The systems are composed of the 16 pieces of helium-3 proportional counters for neutron detection and a large sized NaI(Tl) scintillation detector for gamma ray detection. The extensive testing trials using the calibrated uranium sources with different enrichment and some kinds of matrices in drums were performed. Through the one year testing the useful experiences of this system concerning neutron and gamma ray measurements for uranium mass were obtained. Almost all instruments and software were so good performance as is designed. As the next step we are going to schedule to try measurements for actual wastes that are stored in the Uranium Refining and Conversion Plant at Ningyo-toge, and put practical uses near future. Our research was accomplished with the support of LANL.

Keywords : Uranium Mass Assay, Neutron and Gamma Measurement, NDA, Helium-3 Proportional Counters, U-234(α,n)Reaction, Spontaneous Fission of U-238, Large Sized NaI(Tl) Detector, 200-litter Wastes Drum

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NWAS の導入と測定経験について

日本原子力研究開発機構 人形峠環境技術センター
環境保全技術開発部

在間 直樹，中島 伸一，金田 弘司，門 一実

（2010 年 12 月 6 日 受理）

200 リットルドラム缶に封入されたウラン廃棄物の NDA 測定を中性子及びγ線を用いて測定する装置の開発試験を行ったので、その状況を報告する。測定装置は中性子線測定用として16 本のヘリウム-3 比例計数管とγ線測定用として大口径 NaI(Tl)シンチレーション検出器を兼ね備えている。種々のマトリックスと異なる化学形・濃縮度のウラン線源を 200 リットルドラム缶に装荷して試験を行った。1 年に亘る試験の結果、装置の特性を把握することができ、近々人形峠環境技術センター製錬転換施設に貯蔵されているウラン廃棄物ドラム缶の測定を開始する予定である。本研究は米国ロスアラモス国立研究所との共同研究に基づくものである。

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人形峠環境技術センター：〒708-0698　岡山県苫田郡鏡野町上齋原 1550

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1. Introduction

The primary purpose of the Ningyo Waste Assay System (NWAS) is to provide a determination of the total uranium mass in 200-litter wastes drums from dismantling operations in the Uranium Refining and Conversion Plant (URCP) at the Ningyo-Toge Environmental Engineering Center of JAEA. The NWAS was introduced under the cooperation study between DOE-JAEA bilateral safeguards cooperation agreement, under Action Sheet 51, "NDA Study for a waste assay system at Ningyo-Toge", toward which effective measurements for uranium fluorides may be possible. LANL had taken charge of design and composition on NWAS, JAEA had achieved a series of testing. [Ref.-1], [Ref.-2]

The features of neutron detection are unique, it is the accepted view that the neutron passive measurement for uranium is not usually applicable, however we have tried to prove its applicability. This system is composed of the two kind of measurements detectors, one is 16 set of helium-3 proportional counters for neutron detection and the other is high sensitivity NaI(Tl) detector for gamma-ray detection, assays are performed simultaneously but independently.

The passive measurement of neutrons are intended to detect the emanating from spontaneous fission of U-238 and neutrons emanating (α,n) reaction against fluorine atoms emanating from U-234's α-particles. Simultaneously the passive detection of gamma ray emitting from U-235 and Pa-234m as an U-238's progenies are performed.

Each of these measurements provides an independent determination of the total uranium mass within the drum, from which either, both, or the average mass can be reported.

In this paper we will report on the performance experiences to date with the NWAS and summarize measurements of drums containing uranium standards sources in the various matrices. Additionally we also discuss a few aspects of the system which are optimal and for which improvements could be made in possible future developments of this measurement concept.

2. Structure and Measurements Methodology

The main structures of NWAS are reviewed below in detail. The **Figure-1** shows the conceptual design of assay systems with additional shielding devices of NWAS. The **Figure-2** shows the inner view of NWAS and the **Figure-3** shows the outer view of NWAS. The total weight of the system amount to 500kg including additional shielding devices, however every part is capable to separate to each unit and easy to move to other places. The **Figure-4** shows the outer view of the personal computer as controller of NWAS. The **Figure-5** shows the outer view of HV supply and amplifier tools for both detectors of NWAS.

Thus the features of measurements methodology of NWAS are summarized below.

The 900mm long and 25.4mm diameter of 16 unit of helium-3 proportional counters which are embedded into the two slab-shape aluminum boxes in a straight line with 8 units respectively, and those boxes are set up on 90 degree clockwise and are to be faced with 200-litter wastes drum. The detectors, those amplifier and control system (JSR-12/12N) are

supplied by Canberra Corporations.

The 5 inch diameter and 5 inch long of NaI(Tl) detector with 20mm thickness of tungsten annular cylinder as the gamma ray collimator is settled between two neutron detectors boxes at the central level of 200-litter wastes drum. The detector, its amplifier and control system (DART) are supplied by Ortec Corporations.

The drum rotation system with 450kg weight capability are prepared, measurements may usually be performed with rotation for geometrically uniform detection.

For neutron measurements are based on two different mechanism of nuclear reaction. One is spontaneous fission neutron derived from U-238 emanations, however those emissions rates are too low to use the determination uranium mass by itself. The neutron emission rate is assumed 0.0136 [neutrons/sec/gU] approximately. [ref.3]

The other is neutron emanating from (α,n) reaction which α-particles from U-234 would be captured by low-Z elements, especially fluorine atoms have particularly large reaction cross section. [Ref.-4]

Furthermore the neutron emission rate of (α,n) reaction will grow up according to increase of uranium enrichment, so totally it will be much larger contribution than spontaneous fission.

The neutron energy of those emitted thus are so higher energy (approximately up to 2MeV), therefore it is required to thermalize neutron energy in order to detect helium-3 proportional counters. In the aluminum boxes the 80mm thickness of high density polyethylene slabs are installed inside of drum-side as moderator and otherwise 20mm thickness of high density polyethylene slabs are installed rear-side as reflector. Furthermore in order to decrease neutron background derived from the ambient uranium sources or cosmic rays, the 100mm thickness of high density polyethylene slabs are installed for four directions all. In addition so as to capture thermal neutrons generated from the outer polyethylene slab the 0.1mm of cadmium foils are attached outside of the aluminum boxes.

For gamma measurements in order to decrease the background level from ambient uranium sources the additional shielding slab with 50mm thickness of lead is installed toward the opposite side of NaI(Tl) detector.

Those additional shielding devices are also shown in **Figure-6,7.**

The **Figure-8** shows the control scheme of NWAS over which are controlled by the personal computer

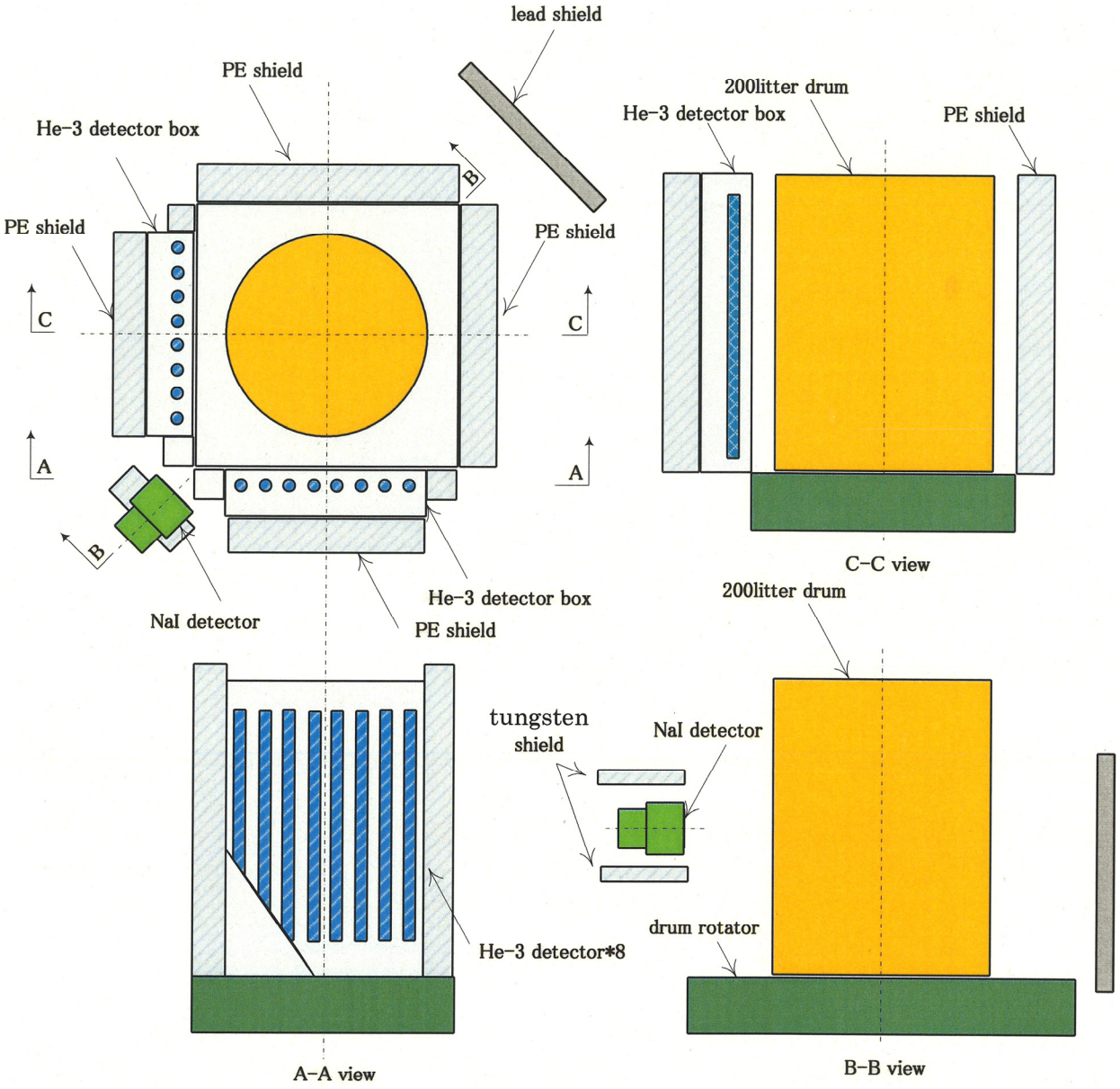


Figure-1 Conceptual design of NWAS system

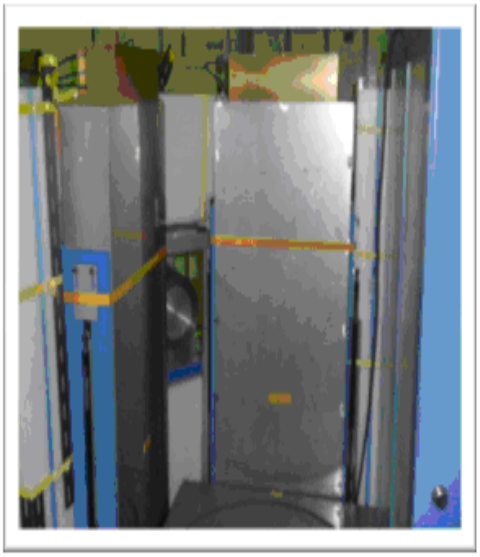


Figure-2 The inner view of NWAS

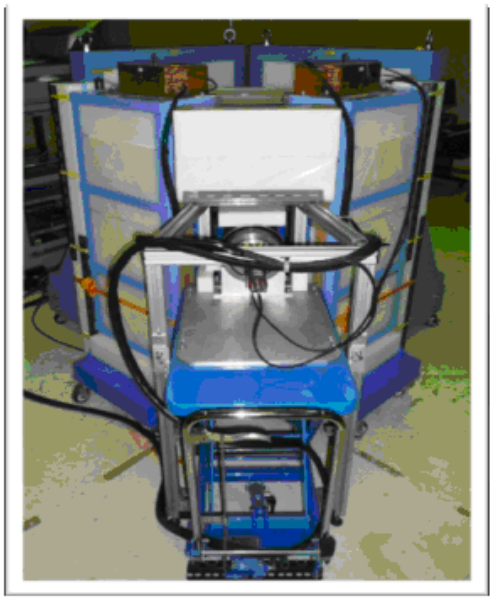


Figure-3 The outer view of NWAS

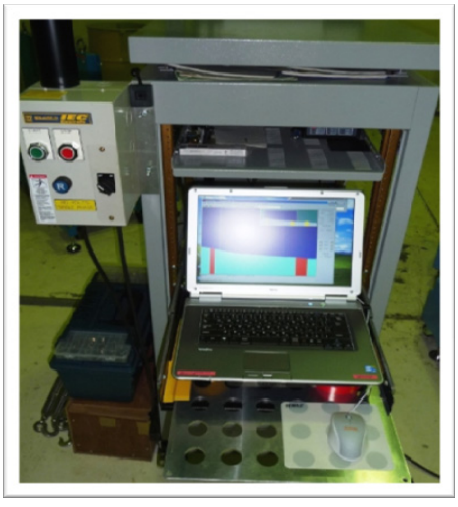


Figure-4 The controllers of NWAS

Figure-5 The HV supply and amplifier

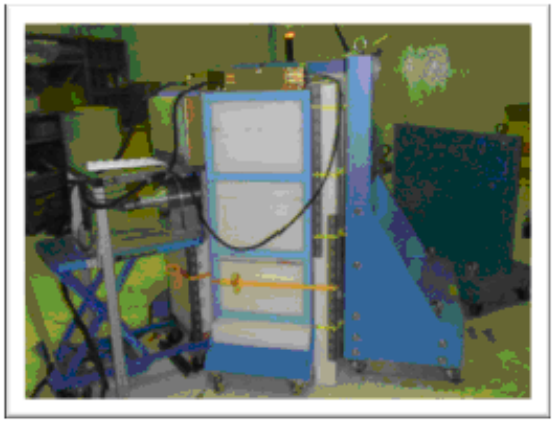


Figure-6 The additional polyethylene shielding

Figure-7 The additional lead shielding

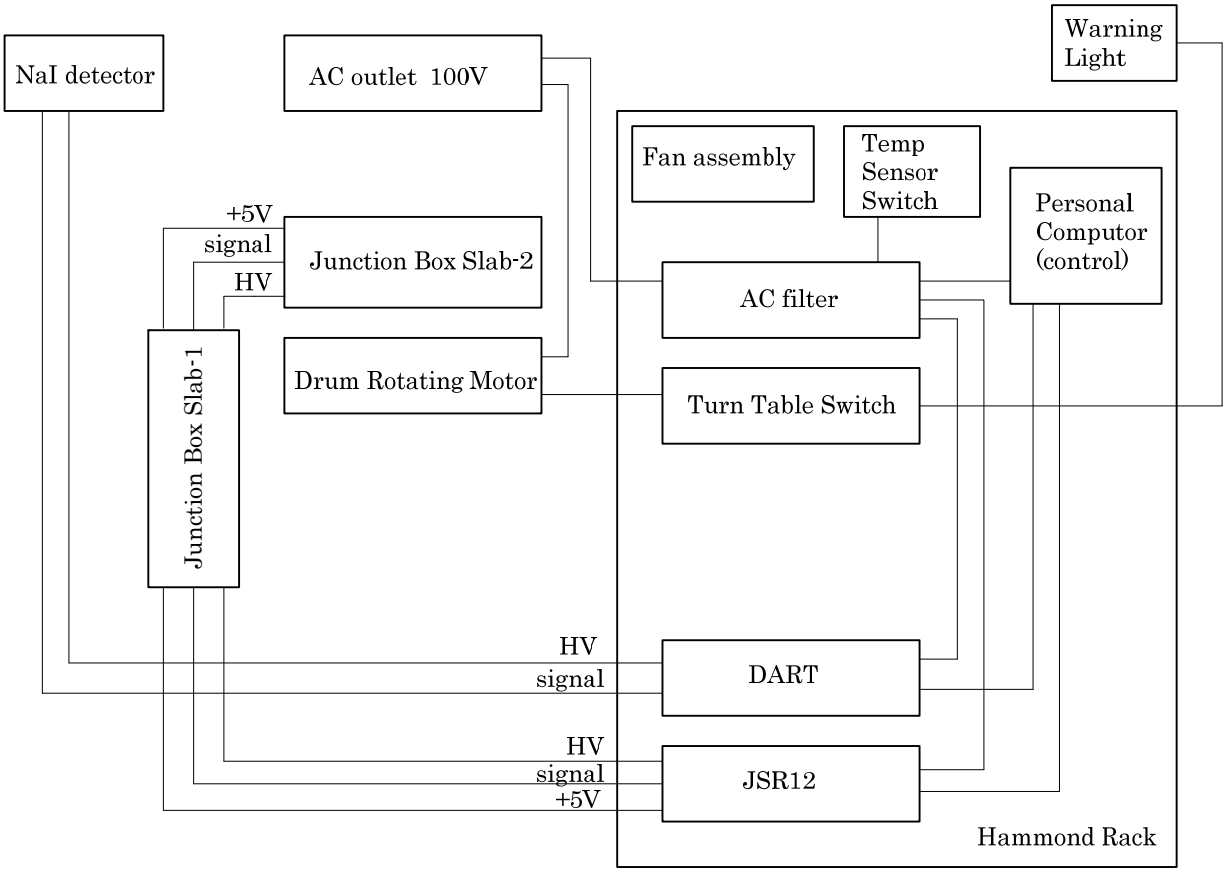


Figure-8 Control scheme of NWAS

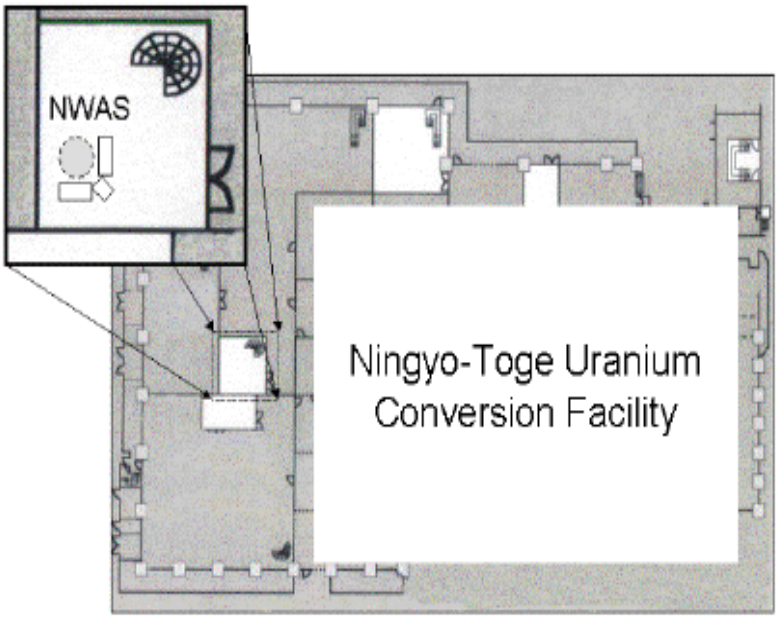


Figure-9 The room location of NWAS in the facility

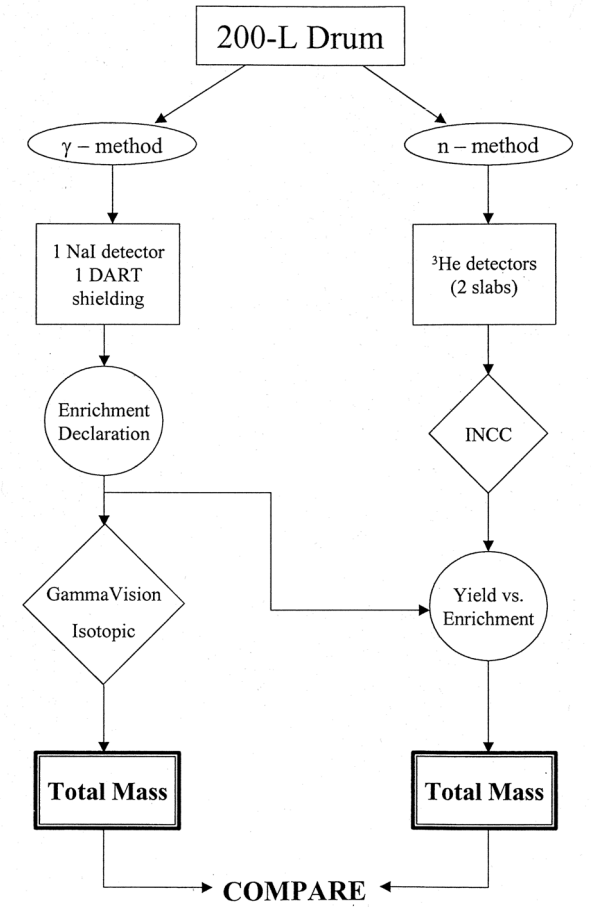


Figure-10 The original schemes of NWAS

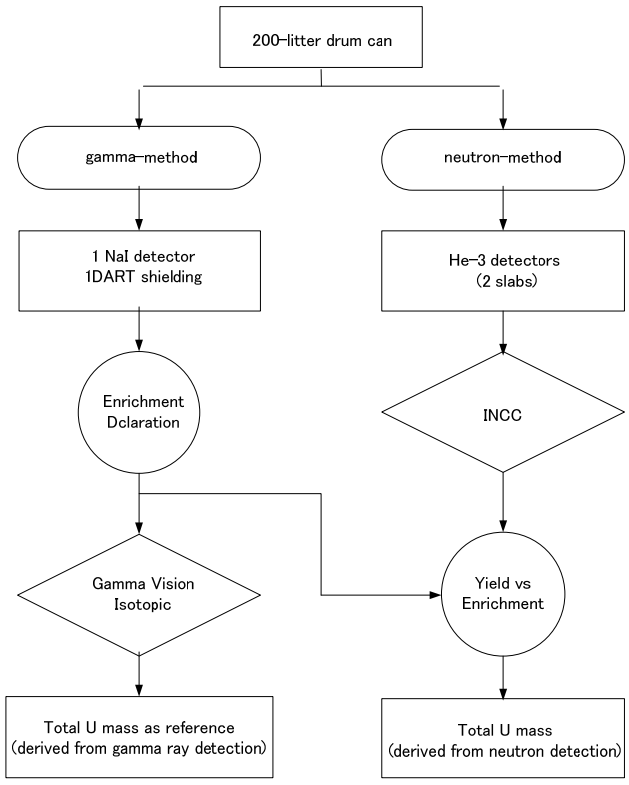


Figure-11 The revised schemes of NWAS

3. In-Plant Installation

The NWAS is designed to provide a determination of the total uranium mass in 200-litter wastes drums. It is intended for use by the facility operator to characterize and categorize uranium-bearing wastes and excess inventory materials from the dismantled.

Therefore NWAS was installed in the "yellow cake solving room" located in the radiation controlled area on the ground floor of URCP at the Ningyo-Toge Environmental Engineering Center. The location suggests an advantage for drum handlings, is illustrated in **Figure-9**.

After some first trials by the engineer of LANL in 2003, the testing and second trial to the actual operation had been suspended. Up to in 2009, the reconfirmation and development tests were restarted.

The room where NWAS was installed has 10m of square space and a concrete floor and 30cm thickness of two concrete walls, the other two walls and ceiling, however, are not concrete, but are more thin gypsum wall and metallic slab. Furthermore so many wastes drums are now stored in every next room. Therefore it is required more shielding against those surrounding radiation environments.

4. Measuring Approach and Analyzing Programs

4.1 Scope

The NWAS consists of passive neutron/gamma-ray detectors for the measurement of natural, depleted or low-enriched uranium wastes in 200 litter drums. The original concept of schematic measuring approach was shown in **Figure-10**, that is to say, after the two separate measurement simultaneously a total uranium mass within each drum will be calculated. Both two results are then compared and can be combined. From each technique, the total uranium mass (and error) can be evaluated.

To our knowledge, this was the first case that these types of hybrid/combined techniques have been applied to the passive measurement of uranium-bearing wastes.

However we have changed the measuring approach because following some reasons.

At first the gamma measurements data by gamma spectrometry have revealed it's higher background level and relatively large counting error, therefore it was not so easy to determine U-235 mass from gamma ray energy spectrum, especially in case of the drums with relatively high density matrices.

Secondly at the present time the region of U-235 enrichment index is limited up to 1.3% in URCP and we have the several records concerning U-235 enrichment data for each waste drum by process knowledge and dismantlement records. Therefore for the moment, the facility operator will declare U-235 enrichment index from stored data in case of existed right data, if not will use the fixed value.

Furthermore the uranium assay from gamma ray had indicated 50-60% of counting errors which were far larger than neutron assay as will be shown later.

The revised concept of schematic measuring approach was shown in **Figure-11**, that is to say, the uranium determination will be performed only by neutron detection only. The gamma ray

measurements had been positioned as a reference.

Several programs are prepared for measuring and analyzing. The characteristics of each program are describe in APPENDIX.

(1) "INCC" developed by LANL for neutron detection and analysis

(2) "Gamma Vision" developed by Ortec for gamma ray detection and analysis

(3) "ISOTOPIC" developed by Perkin Elmer for analysis of uranium mass assay from gamma ray spectrometry.

(4) "V3 macro program of EXCEL" by LANL incorporated for data collection, comparison and combination

4.2 Background Measurements

Since NWAS passively measures very low level of thermal neutron and gamma ray emanating from waste drums, it is important to determine the backgrounds detected and how to account for and subtract them appropriately.

Neutron background

The analysis of the neutron background rate is important in the point of view of "signal to background ratio" for NWAS. Furthermore the measured background rate, although fairly stable throughout the measurement periods, is affected by the presence of the waste drum being measured.

Long time measurements (usually 72000 seconds) were performed periodically so that we may confirm background rate variance. Until now the average of neutron background is 5.4 $\pm$0.009 cps (based on 20 times measurements) However during the testing of the NWAS, there was considerable difficulty assessing the correct (and appropriate) background count rate, which changed depending on the presence of a matrices drum.

When drums with metals (mainly steel) were placed on the rotation platform, the effective background rate appeared to increase (by about 10% on average) in the neutron detector. This is due to the increase in cosmic ray spallation background neutrons created by the presence of the high-Z materials in the drum. Conversely, when drums with combustibles or empty were placed on the rotation platform, the effective background appeared to decrease (by about 10% on average) in the background neutrons by the moderating low-Z matrix. Therefore prior the series of the testing by using the different matrix, the background rate was certainly measured correspondingly so that a correction will be applied to the measured background and net neutron count rate that is based on the matrix material (low-Z or high-Z materials) within the drum itself.

The typical background data of neutron detector are shown in **Table-1**.

Table-1 The neutron background rate data (example)

matrix	time(sec)	counts (cps)	error(cps)	relative
empty	72000	4.124	0.008	0.0019
combustibles	72000	5.345	0.009	0.0017
NaF	72000	4.487	0.008	0.0018
Alumina	72000	3.881	0.007	0.0018
steel	72000	5.709	0.009	0.0016

Gamma ray Background

The detection of the gamma ray background rate is also important in the point of view of "signal to background ratio" for NWAS. Especially as for utilizing gamma ray spectrometry, it is notable that the direct detection of uranium gamma rays (186keV from U-235 and 1001keV from Pa-234m) from waste drums were interfered by gamma rays (1460keV from K-40) originated concrete elsewhere in the facility.

Long time measurement (usually 72000 seconds) were performed periodically, same as in neutron measurement, to check for the presence of peaks in the energy regions of interest above the background continuum.

Two regions of interest (ROIs) are shown outlined in the blue shaded boxes. These ROIs represent the regions for the 186keV peak from U-235 and 1001keV peak from Pa-234m. There are no easily discernible peaks in the background spectrum except for the 1460keV background peak from K-40 and two small peaks between 500-600keV, one of which is the 511keV annihilation peak. There is also a shoulder appearing in background of the 1001keV ROI, which could be from 1001keV gamma rays but certainly not of any quantity to be concerned. Furthermore, the ROI at 186 keV is observed to be free of any noticeable peaks.

It is notable to not be observed matrix dependence of the background level by contraries to neutron measurements. As a reference the two sample of gamma ray backgrounds are shown in **Figure-12,13**.

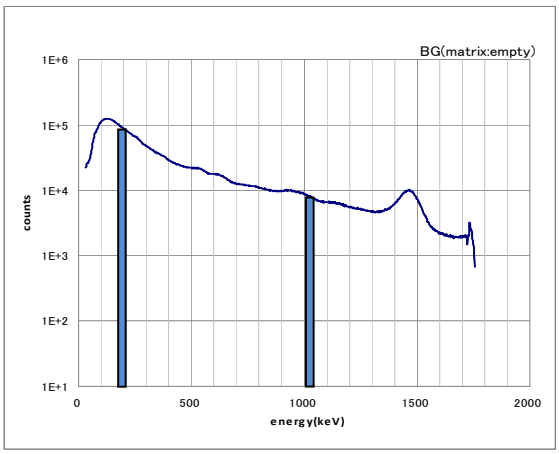


Figure-12 The background gamma ray spectrum (72000sec, matrix:air)

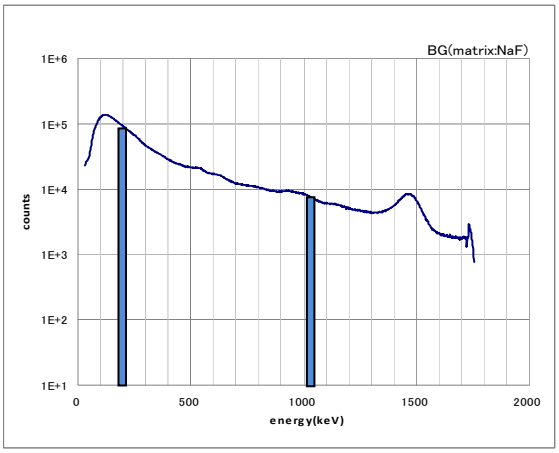


Figure-13 The background gamma ray spectrum (72000sec, matrix:NaF)

4.3 Detector Calibration

Routine calibrations are necessary for neutron and gamma ray detectors.

Neutron calibration

For neutron detectors, 100,000 neutrons/sec traceable source intensity of Cf-252 checking source (approximately 1MBq) is used for calibration, and the counting efficiency is checked periodically. (**Figure-14**) The checking source is settled at the center of drum position without matrix. The NWAS is supplied with a Cf-252 source holder that can be placed in the center hole of the drum rotation platform. This source holder with Cf-252 source mounted on the drum rotation system. (**Figure-15**) The measured counting efficiency are (5.4～5.6 ± 0.03) % in average. The precise data are showed in **Table-2**, those errors are derived from the counting uncertainty and source intensity definition error.

Table-2 Calibrated neutron counting efficiency (example)

	efficiency	error	relative
1	0.0553	0.0024	0.0427
2	0.0546	0.0027	0.0500
3	0.0552	0.0028	0.0500

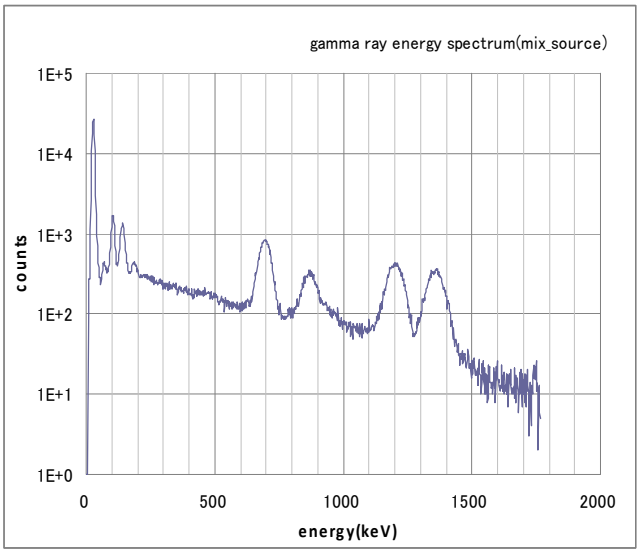
Figure-14 Cf-252 neutron standard source

Figure-15 Cf-252 source holder

Gamma ray calibration

For gamma detectors, energy calibration and counting efficiency calibration are checked periodically. The mixed checking source including 10 gamma ray peaks is used for energy calibration, the checking source is settled at the top of NaI(Tl) detector position without drum.

The typical gamma ray spectrum is shown **Figure-16.**



calibration source surface type (MX-421)			
nuclide	E(keV)	branch	activity(Bq)
Cd-109	---		26800
Co-57	122	0.856	1744
Ce-139	166	0.799	1742
Cr-51	320	0.0992	44750
Sr-85	514	0.96	2322
Cs-137	662	0.851	2201
Mn-54	835	1	2417
Y-88	898	0.937	2637
Co60	1173	1	2946
Co60	1333	1	2946

Figure-16 The energy calibration gamma ray spectrum for NaI(Tl) detector

5. Measurement procedure

5.1 Preparation for Standard source

For the purpose of performing benchmark measurements, many standard samples were prepared. Those samples were small glass vials contained of uranium powders, each one weighed one gram of uranium as metal content. The reason why prepared many small samples was that the homogenous distribution were needed for benchmark measurements. Especially in order to verify the difference of neutron emission rates, the plural chemical forms and plural uranium enrichment (IE=index of enrichments) were prepared. The standard materials prepared are the following;

i) uranium tetrafluorides with IE=1.08%

ii) uranium tetrafluorides (natural)

iii) tri-uranium octa-oxides with IE=1.11%

iv) tri-uranium octa-oxides (natural)s

5.2 Preparation for Testing Tools

As the mocked-actual wastes drums, in which some kinds of matrices are filled up, 200-litter drums were prepared. Now the dismantling works have been continued in URCP, several kinds of wastes were generated as a result, also there remained so many kinds of wastes by plant operation. Therefore the five matrices were selected as is likely exist with practical use among them in URCP.

As the mocked-actual wastes drums, in which some kinds of matrices are filled up, 200-litter drums were prepared. The five matrices were selected as is likely exist with practical use in URCP.

i) empty state as a reference for any other matrices that is the base with no attenuation by inner materials

ii) combustibles as the mocked-actual drum contained light media such as paper towel, vinyl gloves, filter media so on

iii) sodium fluoride (NaF) pellets which are usually generated wastes in URCP as off-gas trap media (density is 1.0 g/cc approximately)

iv) alumina pellets (Al_2O_3) which are also usually generated wastes in URCP as off-gas trap media (density is 0.8 g/cc approximately)

v) steel bars or blocks which are accounted the major part of wastes generated mainly dismantled in URCP (averaged density is limited up to 1.0 g/cc)

In case of each matrix nine pipes were inserted in which are capable to set optionally the small glass vials contained one gram of uranium in 200-litter drum. Testing tools are shown in **Figure-17 (a)(b)(c)(d)(e).**

Using these testing tools, many experiments were performed. The source distributions were basically symmetrical as mocked a homogeneous distributions. In some cases mocked up heterogeneous distributions were tried for the purpose of the influence by maldistribution of sources. (**Figure-18**)

The uranium powder sources in small glass vials and attached to nine bars at equal distance were distributed into the pipes.

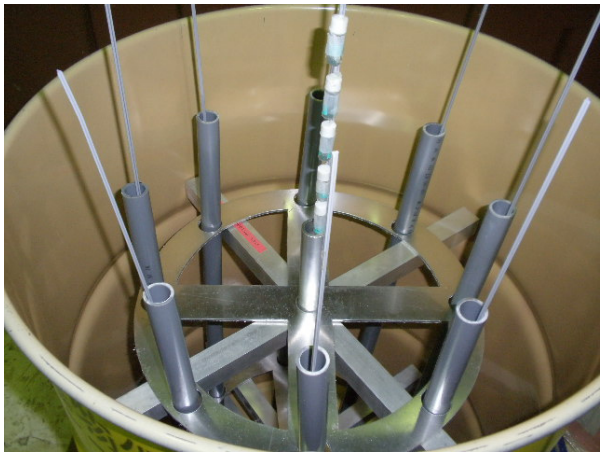


Figure-17(a) Testing tools with empty drum

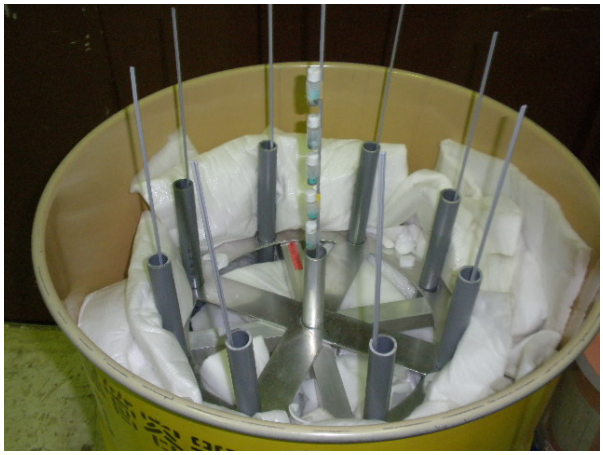


Figure-17(b) Testing tools with combustibles in drum

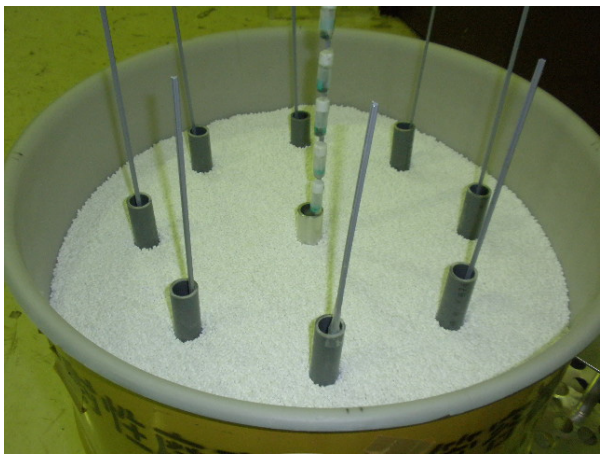


Figure-17(c) Testing tools with NaF in drum

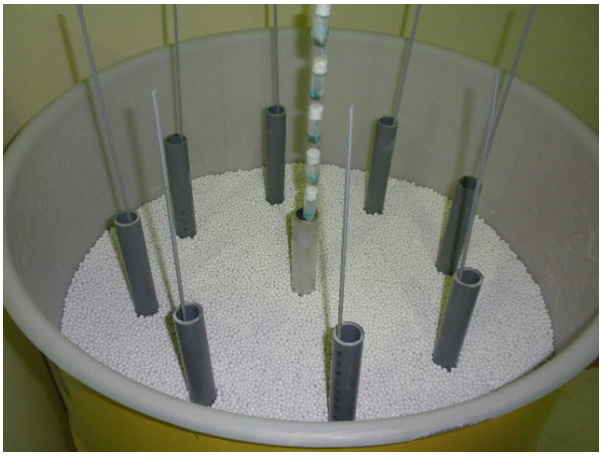


Figure-17(d) Testing tools with alumina in drum

Figure-17(e) Testing tools with steel bars in drum

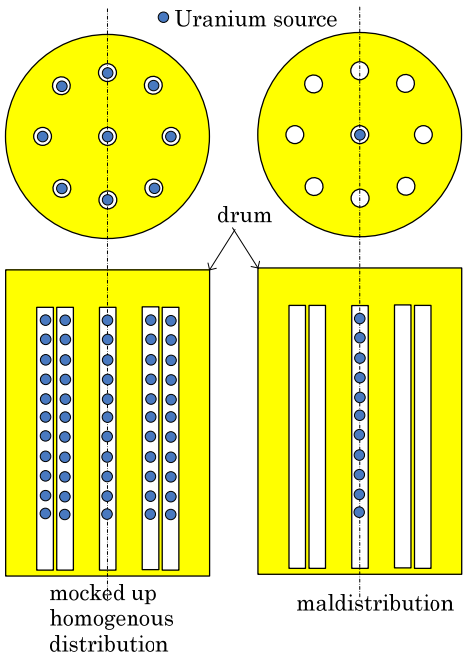


Figure-18 Image of testing tools for maldistribution with air drum

5.3 Uranium Mass Estimation Methods

Through two independent measurements uranium mass is determined by the independent estimation methods as is described below;

for neutron detection

The neutron assay is performed by the following formula based on the thermal neutron counting. The important point is that the neutron emission rates differ from the chemical form of uranium and the enrichment of uranium.

$$M = \frac{n_S - n_B}{\varepsilon \cdot Y(E)} \qquad \text{---- (Equation-1)}$$

$$Y(E) = 0.136 + F \cdot IE$$

where M : uranium mass calculated (gU)

n_S : measured background-subtracted single rate for sample (cps)

n_B : measured background single rate for empty condition (cps)

ε : detection efficiency (-)

Y(E) : neutron emission yield depended of uranium enrichments (n/s/gU)

IE : uranium enrichment (U-235 enrichment %)

0.0136 : neutron emission rates of spontaneous fission (n/s/gU)

F : weighing factor of neutron emission rates of (α,n) reaction depended on chemical form or matrix (n/s/gU)

for gamma ray detection

The gamma ray assay is performed the following formula based on the peak counting of each energy region. The important point is that mass of uranium are calculated as gU-235 or gU-238 respectively, finally both are summarized

$$M = \frac{A_n \cdot (A_t)}{\lambda \cdot A_V} \qquad A_n = \frac{P_A \cdot CF}{\varepsilon \cdot B_\gamma} \qquad \text{---- (Equation-2)}$$

where M : uranium mass calculated (gU-235 or gU-238)

A_n : uranium activity (Bq)

A_t : atomic number

λ : decay constant

A_V : mass number

P_A : peak counts of 186keV or 1001keV(cps)

CF : conversion factor for 186keV or 1001keV corresponding matrix

ε : detection efficiency for 186keV or 1001keV (-)

B_γ : gamma ray emission branch of 186keV or 1001keV

5.4 Mocked-up Testing

Over 200 measurement trials were performed on multiple complex conditions concerning uranium mass, chemical form of uranium and enrichment. The overview of testing conditions are summarized in **Table-3.**

Table-3 The overview of testing conditions

chemical form	EU/NU	Empty (a)	combusti-bles (b)	NaF (c)	Alumina (d)	Steel (e)
UF_4	EU	27gU, 45gU or 81gU				
UF_4	NU	27gU, 45gU, 81gU or 162gU				
U_3O_8	EU	32gU				
U_3O_8	NU	45gU, 99gU or 169gU				

Note: (b) density=0.1g/cc, (c)density=1.0g/cc, (d)density=0.8g/cc, (e)density=1.0g/cc

Every data was purchased in the same conditions, so as to 3600 seconds of counting time with rotation, three cycles toward the same conditions as possible.

6. Results of Trial

for neutron measurement

The trials of neutron measurements were performed by “rate only” mode of INCC which are capable to detect by time division method and to decrease relative errors.

Through trials it was found that weighing factor of “F” value does not necessarily indicate the definite value in Equation-1, because it is assumed that neutron emission rate derived from (α,n) reaction are depended on chemical form of uranium source and neutron attenuation also depended on the materials of matrices.

Therefore in order to purchase the weighing factor of “F” value, the fitting calculation between the declared uranium mass and calculated uranium mass toward each matrix were tried.

The estimated weighing factor “F” values are shown in **Table-4**. These values are not defined theoretically but experimentally, so further verification would be needed.

Table-4 The weighing factor “F” depended on chemical form and matrix

chemical form	EU/NU	Empty (a)	combusti-bles (b)	NaF (c)	Alumina (d)	Steel (e)
UF_4	EU	0.23	0.20	0.09	0.11	0.30
UF_4	NU	0.29	0.34	0.09	0.11	0.31
U_3O_8	EU	0.20	0.31	0.10	0.12	0.41
U_3O_8	NU	0.32	0.29	0.10	0.12	0.14

Note:(a)density=0.1g/cc, (b)density=1.0g/cc, (c)density=0.8g/cc, (d)density=1.0g/cc

The variances of these factors shows the differences depended on the chemical form of uranium. It was expected that the weighing factor "F" of uranium fluorides are greater than the that of uranium oxides. The relationship between raw data of neutron counts rate versus the declared uranium mass is shown in **Figure-21(a)(b)(c)(d)(e)(f)**. Those data suggested no conclusive differences between fluorides and oxides.

According to (Equation-1) uranium mass were calculated for all trial cases, whose data are presented numerically in **Table-5(a)(b)(c)(d)(e)(f)** and graphically in **Figure-22(a)(b)(c)(d)(e)(f)**.

Furthermore in order to confirm the repeatability the recycle measurements for neutron (without matrix) on the same conditions were performed. At least the repeatability was kept within 25%.

for gamma ray measurement

The trials of gamma ray measurements were performed by "acquire/save/report" mode of Gamma Vision, which will be to accumulate peak counts and to perform peak analysis. According to (Equation-2) uranium mass were calculated for all trial cases, whose data are presented numerically also in **Table-5(a)(b)(c)(d)(e)(f)** and graphically in **Figure-23 (a)(b)(c)(d)(e)(f)**.

Figure-19 shows a typical gamma energy spectrum (3600 seconds) measured drum used air as matrix, 186keV peak and 1001keV peaks are observed clearly. However in the case of used alumina or NaF as matrix there often arose which the 1001keV peak had not indicated clearly, so unable to estimate uranium mass, especially **Figure-20** shows a typical gamma energy spectrum (3600 seconds), no clear peak observed except K-40.

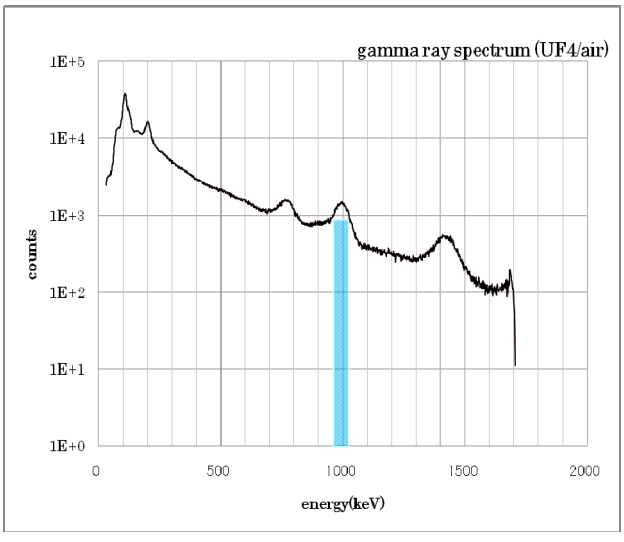


Figure-19 The typical gamma ray spectrum (matrix:empty)

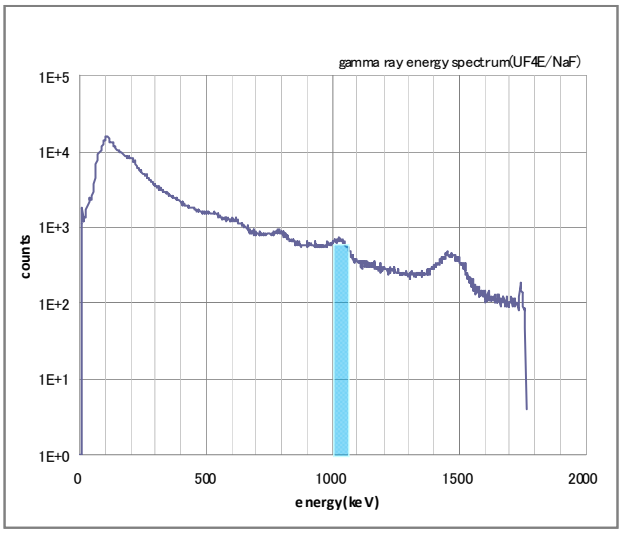


Figure-20 The typical gamma ray spectrum (matrix:NaF)

Table-5(a) The numerical data summary of neutron and gamma ray measurements

empty/homo		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	85	593	12	7116	1.389	0.031	4.350	0.009	1.080	0.0546	0.266	95	7	0.6	0.3	52	30
UF4/E	81	295	12	3540	1.211	0.048	6.442	0.011	1.080	0.0546	0.266	83	7	ND			
UF4/E	81	295	12	3540	1.185	0.048	6.442	0.011	1.080	0.0546	0.266	81	7	ND			
UF4/E	81	297	12	3564	1.325	0.048	6.442	0.011	1.080	0.0546	0.266	91	8	ND			
UF4/E	45	294	12	3528	0.575	0.046	6.442	0.011	1.080	0.0546	0.266	39	5	0.3	0.2	46	27
UF4/E	27	275	12	3300	0.619	0.042	4.611	0.008	1.080	0.0552	0.266	42	5	ND			
UF4/E	18	298	12	3576	0.351	0.037	4.611	0.008	1.080	0.0552	0.266	24	4	ND			
UF4/E	9	299	12	3588	0.297	0.040	4.611	0.008	1.080	0.0552	0.266	20	4	ND			
UF4/N	162	290	12	3480	2.117	0.051	6.544	0.010	0.711	0.0546	0.221	175	13	1.2	0.7	165	97
UF4/N	90	298	12	3576	0.993	0.047	6.544	0.010	0.711	0.0546	0.221	82	8	0.7	0.4	92	54
UF4/N	90	297	12	3564	0.978	0.047	6.544	0.010	0.711	0.0546	0.221	81	8	ND			
UF4/N	45	297	12	3564	0.614	0.046	6.544	0.010	0.711	0.0546	0.221	51	6	0.3	0.2	44	26
UF4/N	45	298	12	3576	0.834	0.046	6.544	0.010	0.711	0.0546	0.221	69	7	ND			
UF4/N	45	292	12	3504	0.808	0.047	6.544	0.010	0.711	0.0546	0.221	67	7	ND			
UF4/N	27	296	12	3552	0.387	0.044	6.098	0.009	0.711	0.0546	0.221	32	5	0.3	0.2	45	27
UF4/N	27	292	12	3504	0.310	0.044	6.098	0.009	0.711	0.0546	0.221	26	5	0.3	0.2	44	26
UF4/N	27	294	12	3528	0.461	0.044	6.098	0.009	0.711	0.0546	0.221	38	6	ND			
UF4/N	45	296	12	3552	0.642	0.039	4.611	0.008	0.711	0.0552	0.221	53	6	0.3	0.2	46	27
UF4/N	27	297	12	3564	0.476	0.039	4.611	0.008	0.711	0.0552	0.221	39	5	0.2	0.1	28	16
UF4/N	18	297	12	3564	0.219	0.038	4.611	0.008	0.711	0.0552	0.221	18	4	ND			
UF4/N	9	299	12	3588	0.074	0.040	4.611	0.008	0.711	0.0552	0.221	6	4	ND			
U3O8/E	32	289	12	3468	0.538	0.046	6.544	0.010	1.113	0.0546	0.241	41	6	0.2	0.1	33	19
U3O8/E	16	296	12	3552	0.130	0.044	6.544	0.010	1.113	0.0546	0.241	10	4	ND			
U3O8/N	198	293	12	3516	2.461	0.050	6.098	0.009	0.711	0.0546	0.240	187	13	ND			
U3O8/N	99	297	12	3564	1.587	0.047	6.320	0.010	0.711	0.0546	0.240	121	10	0.7	0.4	101	59
U3O8/N	45	271	12	3252	0.672	0.048	6.442	0.011	1.113	0.0546	0.368	33	4	ND			
U3O8/N	45	298	12	3576	0.545	0.046	6.442	0.011	1.113	0.0546	0.368	27	4	ND			

Table-5(b) The numerical data summary of neutron and gamma ray measurements

empty/hetero		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	45	299	12	3588	0.840	0.040	4.309	0.029	1.080	0.0546	0.281	55	5	0.5	0.3	46	27
UF4/E	81	299	12	3588	1.342	0.045	4.611	0.008	1.080	0.0552	0.281	87	7	0.9	0.5	83	49
UF4/E	27	292	12	3504	0.587	0.038	4.611	0.008	1.080	0.0552	0.281	38	4	0.3	0.2	28	16
UF4/E	18	292	12	3504	0.427	0.039	4.611	0.008	1.080	0.0552	0.281	28	4	ND			
UF4/E	9	296	12	3552	0.189	0.037	4.611	0.008	1.080	0.0552	0.281	12	3	ND			
UF4/N	45	299	12	3588	0.582	0.038	4.361	0.018	0.711	0.0546	0.298	36	4	0.4	0.2	52	31
UF4/N	81	299	12	3588	1.200	0.037	4.611	0.008	0.711	0.0552	0.298	73	6	0.9	0.5	83	49
UF4/N	27	295	12	3540	0.472	0.039	4.611	0.008	0.711	0.0552	0.298	29	4	0.3	0.2	28	16
UF4/N	18	298	12	3576	0.343	0.041	4.611	0.008	0.711	0.0552	0.298	21	4	ND			
UF4/N	9	280	12	3360	0.128	0.039	4.611	0.008	0.711	0.0552	0.298	8	3	ND			
U3O8/E	32	297	12	3564	0.654	0.045	4.309	0.029	1.113	0.0546	0.325	37	4	0.3	0.2	23	14
U3O8/N	75	299	12	3588	0.675	0.049	6.512	0.01	0.711	0.0546	0.212	58	7	ND			

Table-5(c) The numerical data summary of neutron and gamma ray measurements

combustibles		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	45	299	12	3588	0.766	0.030	4.480	0.008	1.080	0.0546	0.266	53	5	0.5	0.3	43	25
UF4/E	81	299	12	3588	1.191	0.043	5.420	0.009	1.080	0.0546	0.266	82	7	0.6	0.3	80	47
UF4/E	27	296	12	3552	0.343	0.038	4.658	0.008	1.080	0.0552	0.266	23	4	ND			
UF4/E	18	298	12	3576	0.262	0.038	4.658	0.008	1.080	0.0552	0.266	18	3	ND			
UF4/E	9	299	12	3588	0.121	0.037	4.658	0.008	1.080	0.0552	0.266	8	3	ND			
UF4/N	76	299	12	3588	0.969	0.029	4.432	0.009	0.711	0.0546	0.242	73	6	1.0	0.6	74	44
UF4/N	100	295	12	3540	1.432	0.041	4.628	0.008	0.711	0.0546	0.242	108	9	ND			
UF4/N	162	293	12	3516	2.086	0.050	5.339	0.012	0.711	0.0546	0.242	158	12	1.2	0.7	159	94
UF4/N	81	270	12	3240	1.051	0.047	5.339	0.012	0.711	0.0546	0.242	79	8	0.6	0.3	80	47
UF4/N	45	298	12	3576	0.446	0.045	5.339	0.012	0.711	0.0546	0.242	34	5	0.3	0.2	44	26
UF4/N	27	295	12	3540	0.252	0.041	5.339	0.012	0.711	0.0546	0.242	19	4	0.2	0.1	27	16
UF4/N	18	273	12	3276	0.098	0.038	4.658	0.008	0.711	0.0552	0.242	7	3	ND			
UF4/N	9	297	12	3564	0.064	0.037	4.658	0.008	0.711	0.0552	0.242	5	3	ND			
U3O8/E	32	299	12	3588	0.694	0.032	4.361	0.018	1.113	0.0546	0.355	36	3	0.6	0.3	52	31
U3O8/N	45	299	12	3588	0.501	0.028	4.480	0.008	0.711	0.0546	0.220	42	4	0.3	0.2	36	21
U3O8/N	75	299	12	3588	0.880	0.029	4.350	0.009	0.711	0.0546	0.220	73	6	0.9	0.5	119	70

Table-5(d) The numerical data summary of neutron and gamma ray measurements

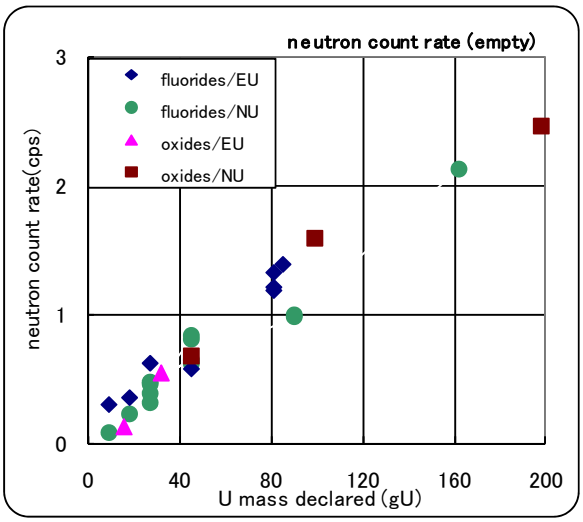
NaF		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	81	295	12	3540	0.640	0.045	6.206	0.011	1.080	0.0546	0.113	104	13	ND			
UF4/E	81	299	12	3588	0.527	0.048	6.206	0.011	1.080	0.0546	0.113	86	12	ND			
UF4/E	45	298	12	3576	0.144	0.044	6.206	0.011	1.080	0.0546	0.113	23	8	ND			
UF4/E	45	297	12	3564	0.137	0.045	6.206	0.011	1.080	0.0546	0.113	22	8	ND			
UF4/N	162	294	12	3528	0.658	0.043	4.286	0.009	0.711	0.0546	0.085	141	16	ND			
UF4/N	162	291	12	3492	0.778	0.045	4.286	0.009	0.711	0.0546	0.085	167	18	ND			
UF4/N	162	298	12	3576	0.739	0.045	4.286	0.009	0.711	0.0546	0.085	158	18	ND			
UF4/N	81	295	12	3540	0.351	0.048	5.825	0.009	0.711	0.0546	0.085	75	14	ND			
UF4/N	81	296	12	3552	0.316	0.042	5.825	0.009	0.711	0.0546	0.085	68	12	ND			
UF4/N	81	299	12	3588	0.319	0.040	5.825	0.009	0.711	0.0546	0.085	68	12	ND			
U3O8/E	32	295	12	3540	0.436	0.035	4.153	0.008	1.111	0.0546	0.127	63	8	ND			
U3O8/E	32	294	12	3528	0.225	0.034	4.153	0.008	1.111	0.0546	0.127	32	7	ND			
U3O8/E	32	296	12	3552	0.171	0.038	4.153	0.008	1.111	0.0546	0.127	25	7	ND			
U3O8/N	169	294	12	3528	0.848	0.039	4.487	0.008	0.711	0.0552	0.086	178	17	ND			
U3O8/N	169	294	12	3528	0.754	0.039	4.487	0.008	0.711	0.0552	0.086	158	16	ND			
U3O8/N	169	297	12	3564	0.795	0.039	4.487	0.008	0.711	0.0552	0.086	167	17	ND			
U3O8/N	81	298	12	3576	0.579	0.042	5.825	0.009	0.711	0.0552	0.086	122	15	ND			
U3O8/N	81	299	12	3588	0.621	0.047	5.825	0.009	0.711	0.0552	0.086	130	16	ND			
U3O8/N	81	291	12	3492	0.504	0.043	5.825	0.009	0.711	0.0552	0.086	106	14	ND			

Table-5(e) The numerical data summary of neutron and gamma ray measurements

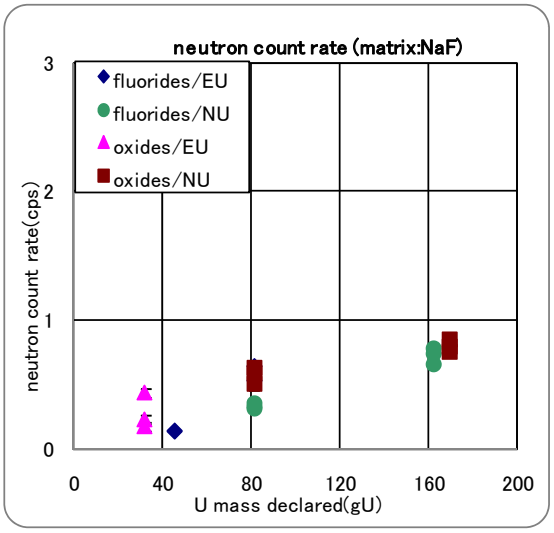
alumina		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	81	294	12	3528	0.906	0.036	4.286	0.009	1.080	0.0546	0.152	109	10	ND			
UF4/E	81	296	12	3552	0.677	0.039	4.286	0.009	1.080	0.0546	0.152	81	9	ND			
UF4/E	81	296	12	3552	0.733	0.039	4.286	0.009	1.080	0.0546	0.152	88	9	ND			
UF4/E	45	291	12	3492	0.205	0.039	5.100	0.009	1.080	0.0552	0.152	24	6	ND			
UF4/N	162	296	12	3552	0.742	0.043	5.100	0.009	0.711	0.0552	0.105	128	14	ND			
UF4/N	162	292	12	3504	0.691	0.044	5.100	0.009	0.711	0.0552	0.105	119	14	ND			
UF4/N	162	296	12	3552	0.634	0.039	5.100	0.009	0.711	0.0552	0.105	110	12	ND			
UF4/N	45	296	12	3552	0.208	0.038	4.428	0.008	0.711	0.0552	0.105	36	8	ND			
UF4/N	45	297	12	3564	0.273	0.037	4.428	0.008	0.711	0.0552	0.105	47	9	ND			
UF4/N	45	297	12	3564	0.219	0.035	4.428	0.008	0.711	0.0552	0.105	38	8	ND			
UF4/N	162	294	12	3528	0.841	0.036	4.124	0.008	0.711	0.0546	0.105	147	14	ND			
UF4/N	162	291	12	3492	0.931	0.041	4.124	0.008	0.711	0.0546	0.105	162	15	ND			
UF4/N	162	297	12	3564	0.886	0.039	4.124	0.008	0.711	0.0546	0.105	154	15	ND			
U3O8/E	32	294	12	3528	0.732	0.038	4.132	0.009	1.111	0.0546	0.146	37	4	ND			
U3O8/E	32	274	12	3288	0.580	0.040	4.132	0.009	1.111	0.0546	0.146	29	3	ND			
U3O8/E	32	296	12	3552	0.685	0.038	4.132	0.009	1.111	0.0546	0.146	34	4	ND			
U3O8/N	99	296	12	3552	0.482	0.036	4.428	0.008	0.711	0.0552	0.098	89	11	ND			
U3O8/N	99	292	12	3504	0.563	0.039	4.428	0.008	0.711	0.0552	0.098	104	12	ND			
U3O8/N	99	299	12	3588	0.502	0.040	4.428	0.008	0.711	0.0552	0.098	92	12	ND			

Table-5(f) The numerical data summary of neutron and gamma ray measurements

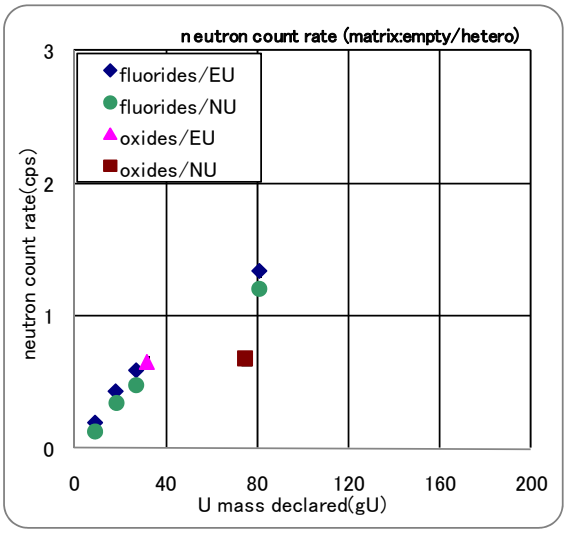
steel bars		Neutron Assay											Gamma Assay			
source	declared mass (gU)	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting effi-ciency	neutron emission	Neutron Assay (gU)	gU Err	Gamma Assay U-235(g)	gU Err	Gamma Assay U-238(g)	gU Err
UF4/E	81	297	12	3564	1.186	0.045	5.709	0.008	1.080	0.0546	0.341	64	6	0.4	0.2	38	23
UF4/E	81	295	12	3540	1.016	0.045	5.709	0.008	1.080	0.0546	0.341	55	5	0.6	0.3	54	31
UF4/E	45	296	12	3552	0.613	0.043	5.709	0.008	1.080	0.0546	0.341	33	4	0.4	0.2	37	21
UF4/E	45	298	12	3576	0.633	0.043	5.709	0.008	1.080	0.0546	0.341	34	4	0.3	0.2	25	15
UF4/E	27	293	12	3516	1.131	0.044	5.709	0.008	1.080	0.0546	0.341	61	5	0.3	0.2	26	15
UF4/E	27	295	12	3540	0.973	0.044	5.709	0.008	1.080	0.0546	0.341	52	5	0.4	0.2	35	21
UF4/E	18	297	12	3564	0.492	0.043	5.709	0.009	1.080	0.0546	0.341	26	4	0.3	0.2	26	24
UF4/E	18	298	12	3576	0.570	0.043	5.709	0.009	1.080	0.0546	0.341	31	4	0.2	0.1	22	13
UF4/E	81	296	12	3552	1.511	0.046	5.709	0.009	1.080	0.0546	0.341	81	7	0.4	0.3	39	23
UF4/N	54	292	12	3504	0.669	0.044	5.823	0.009	0.711	0.0546	0.236	52	6	0.3	0.2	42	25
UF4/N	90	293	12	3516	1.182	0.045	5.823	0.009	0.711	0.0546	0.236	92	8	0.6	0.4	89	52
U3O8/E	32	296	12	3552	0.827	0.044	5.709	0.008	1.111	0.0546	0.468	32	3	0.6	0.3	51	30
U3O8/N	198	296	12	3552	1.957	0.047	5.709	0.008	0.711	0.0546	0.111	324	24	0.7	0.4	96	56
U3O8/N	169	297	12	3564	1.016	0.042	4.142	0.008	0.711	0.0552	0.111	167	15	1.3	0.7	175	103
U3O8/N	99	296	12	3552	0.670	0.037	4.142	0.008	0.711	0.0552	0.111	110	12	ND			
U3O8/N	54	292	12	3504	0.377	0.038	4.142	0.008	0.711	0.0552	0.111	62	9	ND			



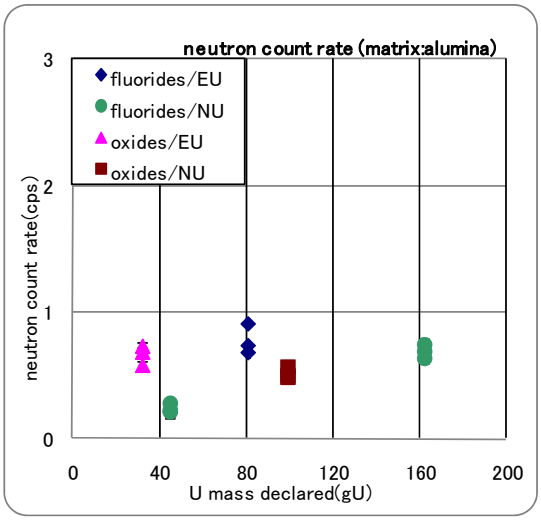
(a) matrix : empty



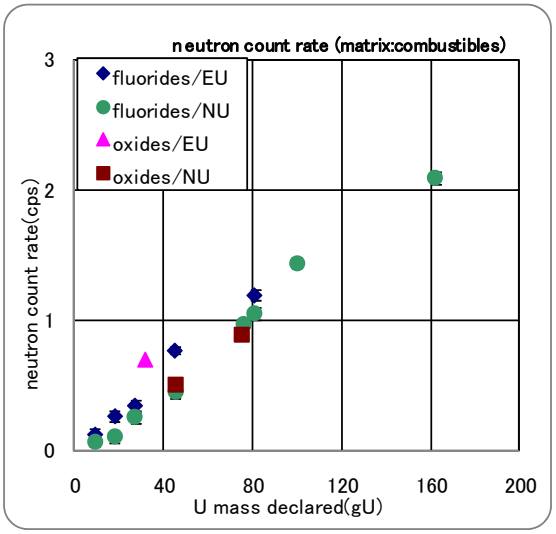
(d) matrix : NaF(1.0g/cc)



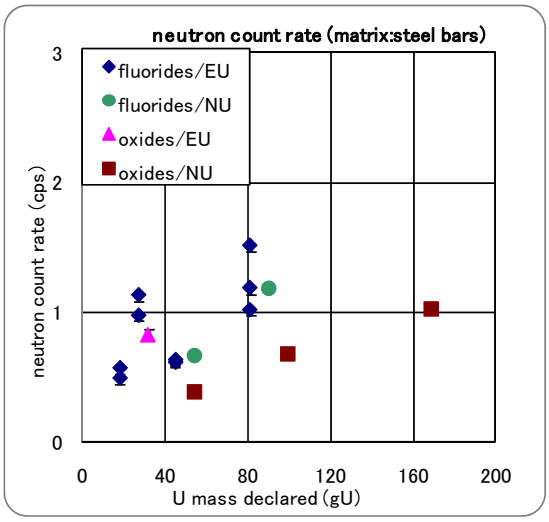
(b) matrix : empty/hetero



(e) matrix : alumina(0.8g/cc)

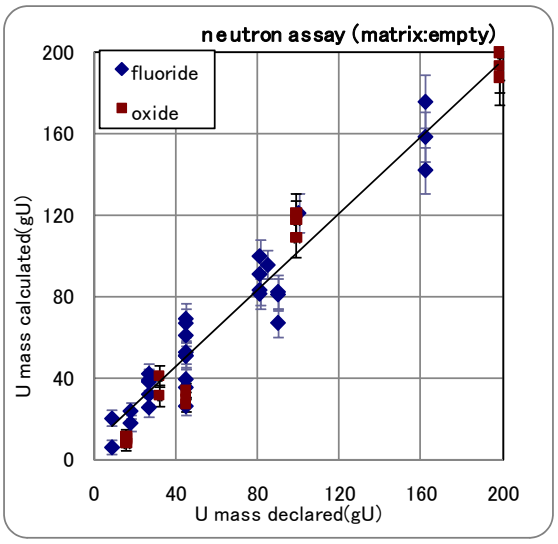


(c) matrix : combustibles

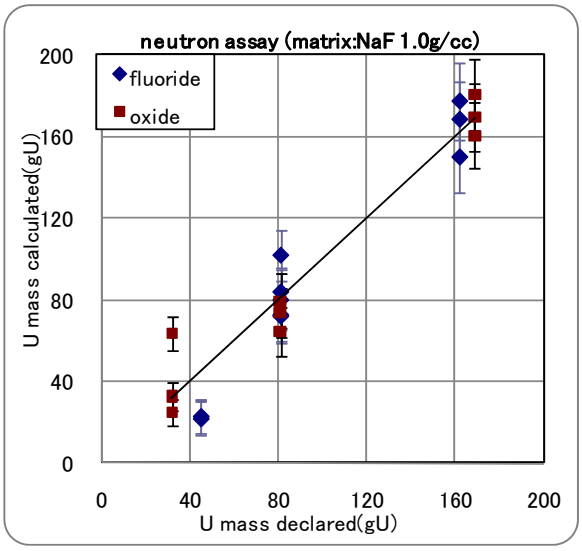


(f) matrix : steel (1.0g/cc)

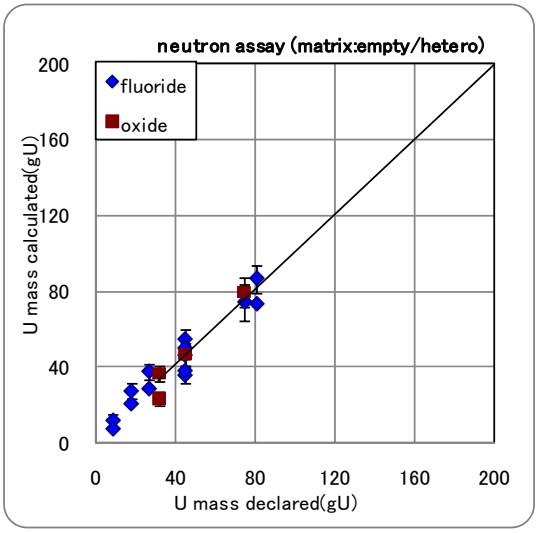
Figure-21 The response data of neutron detector



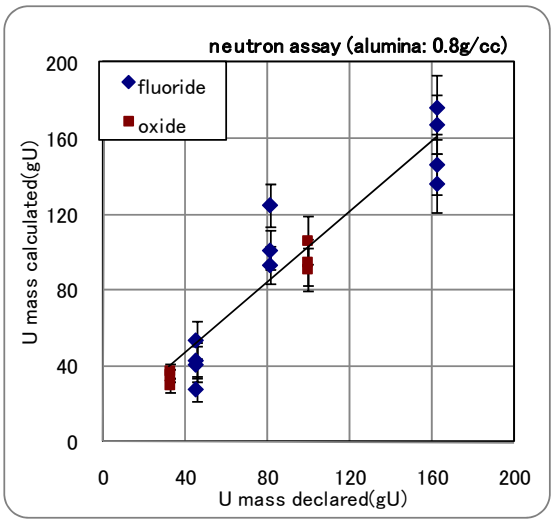
(a) matrix : empty



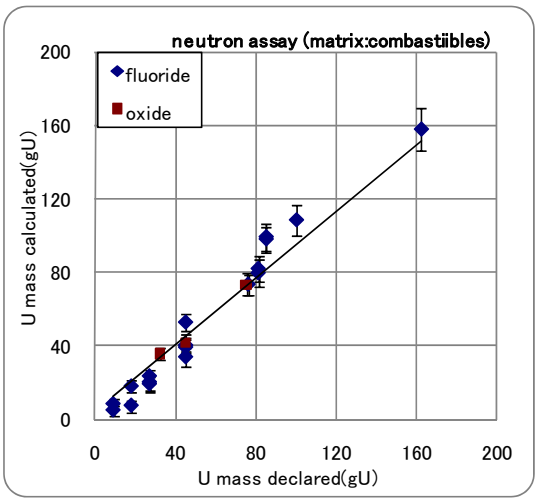
(d) matrix : NaF (1.0g/cc)



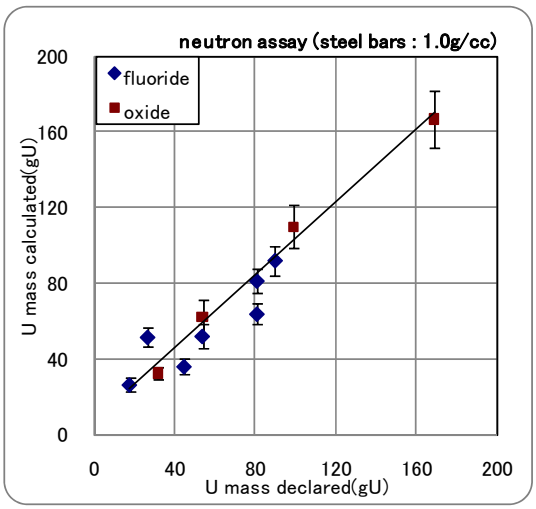
(b) matrix : empty/hetero



(e) matrix : alumina(0.8g/cc)

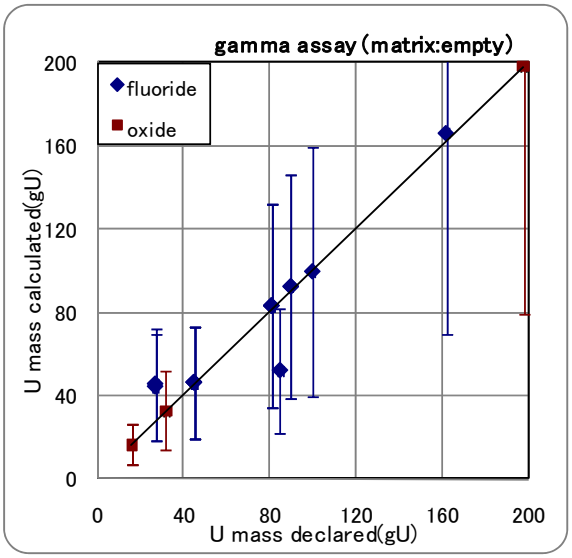


(c) matrix : combustibles

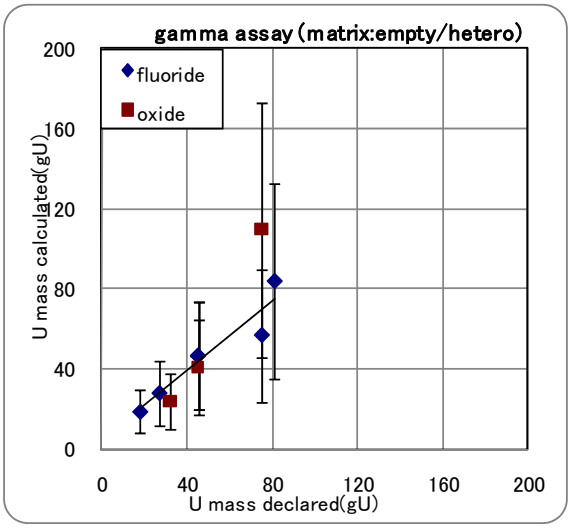


(f) matrix : steel bars (1.0g/cc)

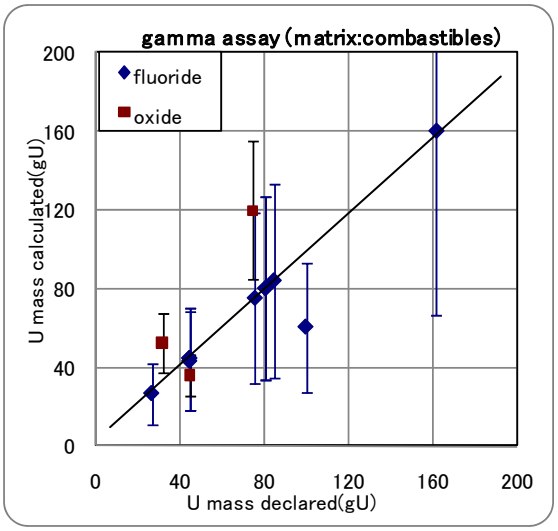
Figure-22 The example data of neutron measurements



(a) matrix : empty



(b) matrix : empty/hetero



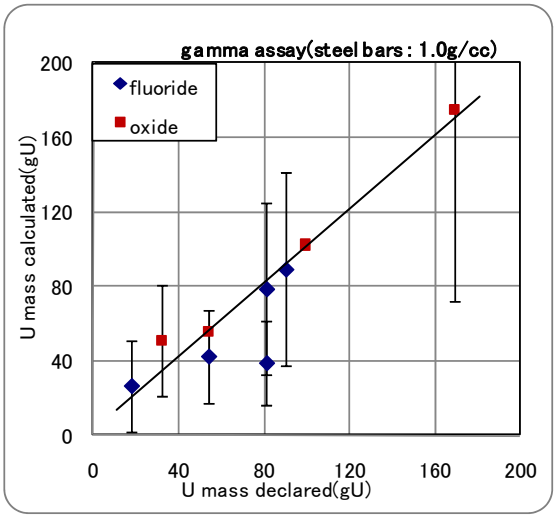
(c) matrix : combustibles

Not detected

(d) matrix : NaF (1.0g/cc)

Not detected

(e) matrix : alumina(0.8g/cc)



(f) matrix : steel bars (1.0g/cc)

Figure-23 The example data of gamma ray measurements

7. Estimation for Detection Limit of This Method

Detection limits of the radiation measurement system are defined from the background rates, the counting time and parameter with statistical uncertainty. For the purpose of estimation of the detection limit of this method, we used the following formula which is so popular in Japan.

for neutron detection

The 3σ method was used as follows.

$$ALD_{mass} = \frac{n_D}{\varepsilon \cdot Y(E)}$$

$$n_D = \left(\frac{k}{2}\right) \times \left[\frac{k}{t_s} + \sqrt{\left(\frac{k}{t_s}\right)^2 + 4n_B\left(\frac{1}{t_b} + \frac{1}{t_s}\right)}\right]$$

where n_D : minimum net detectable counting rate (cps)

n_B : background rates (cps)

t_T : counting time for sample (cps)

t_B : counting time for background (cps)

k_{MDA} : factor of multiple standard deviation (k=3 means 99.7% reliability)

η : counting efficiency

Y(E) : neutron emission yield depended of uranium enrichments (n/s/gU)

for gamma detection

The Currie method was used as follows.

$$ALD_{mass} = \frac{ALD_{act} \cdot (A_t)}{\lambda \cdot A_V}$$

$$ALD_{act} = \frac{n_D \cdot CF}{\varepsilon \cdot B_\gamma}$$

$$n_D = \frac{\frac{k_{MDA}^2}{t_T} + 2k_{MDA}\sqrt{n_B\left(\frac{1}{t_T} + \frac{1}{t_B}\right) + r_1^2 n_B^2}}{1 - k_{MDA}^2 r_2^2}$$

where n_D : minimum net detectable counting rate (cps)

n_B : background rates (cps)

t_T : counting time for sample (cps)

t_B : counting time for background (cps)

k_{MDA} : factor of multiple standard deviation (k=3 means 99.7% reliability)

r : relative error derived from background level variance

ε : counting efficiency

The typical detection limit estimated by above method is shown in **Table-6.** Regarding neutron assay detection limit as uranium mass it was assumed 6～12gU for light matrices, 13～28gU for relatively heavy matrices and 6～15gU for steels which indicate well penetration by neutron for 60minutes measurement time. If be shortened measurement time, detection limit will raise accordingly. The variances are based on uranium enrichment from 0.711 to 1.3%, which are most likely case in URCP.

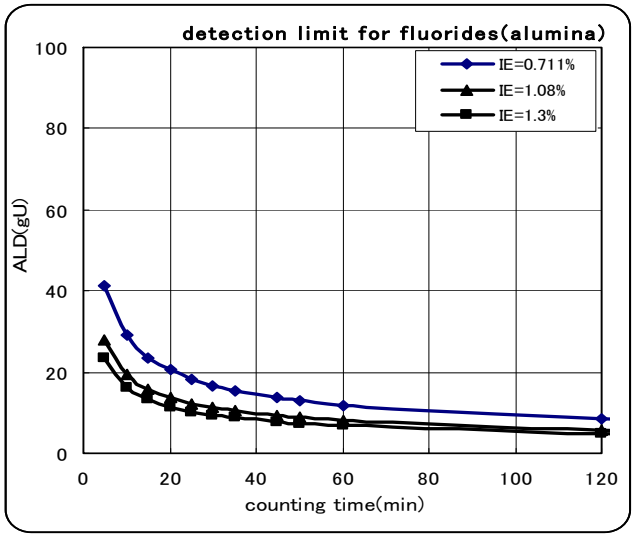


Figure-24 Detection limit for neutron assay

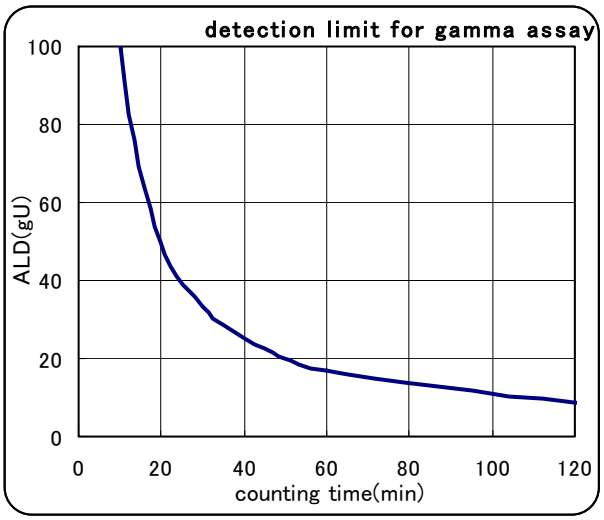


Figure-25 Detection limit for gamma assay

Table-6 The typical detection limit data

detection method	Source and matrix	measured time (min)		
		20	40	60
neutron detection	fluorides in combustibles	11～20	8～14	6～11
neutron detection	oxides in combustibles	11～20	8～14	7～12
neutron detection	fluorides in alumina	23～39	16～28	13～23
neutron detection	oxides in alumina	28～48	20～34	16～28
neutron detection	fluorides in steel bars	11～20	8～14	6～12
neutron detection	oxides in steel bars	15～26	10～18	9～15
gamma detection	all cases	50	25	17

[unit ： gU]

8. Discussion

The features and possibility for practical use on NWAS had been well operated as was designed from some point of view. As a whole there had few trouble on hardware, no more additional devices are needed for practical use.

Nevertheless there remain several problems on NWAS in operation performances.

The most important problem is that the absolute counting efficiency for neutron indicated too

low to detect so far low level counting. In addition, the background level is not enough low level, on the contrary in a range of these testing conditions the signal/noise ratio are less than 1.0 as is shown in **Figure-26.** Therefore the detection limit level of NWAS have been forced to 10～50 grams of uranium at present (20～60 minutes detection) in neutron detection. The higher background level would be caused by that the measured room is surrounded the uranium wastes drums. The improvements for measuring condition, so as to add shielding or to change the measurement place, are required. Further improvements are required.

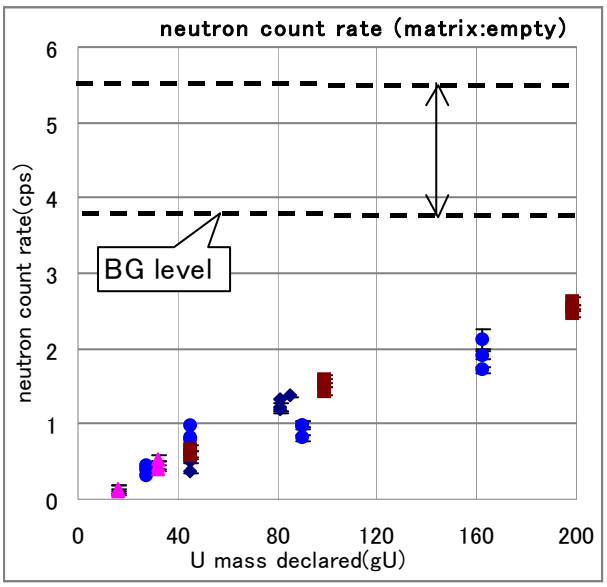


Figure-26 The consideration for signal/noise ratio of neutron detection

Furthermore the fluctuation of background level is not negligible, whose reasons are assumed not only by matrix dependence mentioned above but also by cosmic ray dependence. As for cosmic ray some reports suggest seasonal fluctuation, therefore frequent background measurements than we have done will be required.

Next the high background rate of NaI(Tl) detector prevented the uranium assay by gamma ray detection with accuracy. In fact the counting errors of a series of assay by gamma ray detection was 50-60% approximately. Furthermore the high background rate of NaI(Tl) detector also prevented the estimation for uranium enrichment by comparing 186keV and 1001keV peak counts. As was shown in **Figure-23,** it was difficult to make an approximation line. To our regret it seemed that 20mm of tungsten shield was not enough, an additional shielding would be considered.

As was described above the weighing factor "F" depended from chemical form of uranium source or matrices various conditions are thought to be suggested the degree of neutron emission rate. Nevertheless some reports said that the neutron emission rate of uranium fluorides is far greater than that of uranium oxides, but our results suggested slight differences between them. It seemed quite important to investigate the theoretical values of the neutron emission rate in a sense, however the targets of our measurement systems should be the actual

wastes drums whose chemical form are not pure but fluorides /oxides complex. Accordingly we will not choose the way but to take mean values measured in trials.

As for matrices several kinds of matrices used in testing were existed among actual wastes drums, so the classifications above are available.

10. Further Study

NWAS is not complete system at present. In order to solve some problems described above more challenges are needed.

Finally we will detail those problems specifically below.

(1) The decrease of the background level both for neutron detection and gamma ray detection would be urgent assignment

(2) There remains many manual data handling in several process, improvement of the software for automatic handling would be required

(3) The weighing factor "F" used above is merely derived from experimental, strict theoretical benchmark would be needed such as the simulation used MCNP Monte Carlo calculation code. [Ref.-5]

(4) AAS method which is known as effective estimation method for neutron attenuation in matrix is available to NWAS. Basic testing would be needed.

(5) It is desirable to measure the actual waste drums which are stored in URCP. Now in URCP over 10000 wastes drums are stored, the uranium assay against those would be expected as urgent business.

Acknowledgments

The authors are gratefully thankful to all staffs of URCP and Mr Masato Murata who was the predecessor manager of URCP at the Ningyo-Toge Environmental Engineering Center and suggested us useful advices. Also special thanks would be given to Dr. D.H.Beddingfield and Dr. D.T.Vo who were the researchers of the Safeguards Science and Technology section of LANL, engaged in developments NWAS and kindly brought us the useful informations about NWAS's technical performances.

REFERENCES

[Ref.-1] LA-CP-03-0552, Rev.2 Ningyo-Toge Uranium Refining and Conversion Plant Waste Assay System (NWAS) Operating and Users Manual

[Ref.-2] LA-CP-05-0312 Performance Experience and Measurement with the Ningyo Waste Assay System (NWAS)

[Ref.-3] LA-13642-MS Low-Activity Solid Waste measurements at Tokai Works

[Ref.-4] JAERI 1324, Data book for Calculating neutron yields from (α,n) reaction and spontaneous fission (1992)

[Ref.-5] LA-CP-00-0318 Monte Carlo Calculations of Conceptual for a Drum/Crate Waste Assay System

APPENDIX

The NWAS uses four separate software programs to collect and analyze the data. The methods and components of these software programs needed to process the NWAS data will be described in detail later in this manual in the sections entitled "User Procedures" and "Data Interpretation and Analysis." Therefore, only an introduction to each will be presented here. Additionally, as three of the four programs are available commercially, their user and operation manuals will be separately supplied.

A1. INCC

The neutron data acquisition program INCC is used to acquire and process signals from the NWAS neutron detectors. INCC is a standard data acquisition and analysis program of the IAEA. Although INCC was developed and is maintained by LANL, it is also available from several commercial vendors.

The NWAS has been designed to detect totals neutrons from the waste samples. As such, most of the elaborate analysis routines within INCC are not necessary to process and interpret the neutron signals. Generally speaking, only two functions of INCC are necessary to acquire the data : the "Background measurement", and the "Rates Only measurement". The background function will be used to subtract the contribution to the total signal rate from background sources of neutron radiation such as cosmic-ray events and the remaining inventory of waste drums at the Plant. The "Rates Only function" will be used to acquire the net count rate during the actual drum (or crate) assay.

A2. Gamma Vision

The gamma-ray spectra will be acquired with the commercially available software program Gamma Vision. Gamma Vision is very similar to the Ortec Maestro program that is commonly used in the safeguards community to acquire gamma-ray data. However, GammaVision incorporates peak-fitting and efficiency routines to determine absolute activities of isotopes in the sample. Although GammaVision was designed for the acquisition of HPGe data, it is adequate for use with NaI detectors and can be used to generate the reports necessary for inclusion into the Isotopic code.

In general, it will be necessary for the user to verify the energy calibration (and re-calibrate if necessary), acquire assay spectra, and ensure that two regions of interest (ROI) are set around the 186keV and 1001keV peaks in the spectrum. Information from these ROIs will be used in further processing for input into the Isotopic program. *(Note that the gamma-ray peak-fitting requirement has been eliminated from the NWAS operation. This function proved too difficult and unreliable for routine use in a production environment.)*

A3. Isotopic

The report generated by Gamma Vision is entered into the Isotopic program for further

analysis. Isotopic is a commercially available program with a simple data analysis procedure for the calculation of total quantities of nuclear material. It will be necessary for the user to be somewhat familiar with this program in order for it to be operated correctly.

The user will load in the analysis report from Gamma Vision and then fill in the appropriate assay information in order to proceed. The assay information necessary include, for example, source and detector distances (these should be fixed for the NWAS), the container information (example 200-L drums, waste crates), and matrix and sample information such as net weight, density, material, composition (different for each drum). At the end of the process, it will be necessary for the user to *declare the enrichment* by manual entry into the Isotopic results screen.

A4. NWAS Data Compilation (V3 compiled on EXCEL)

This program is a LANL-generated MS-Excel spreadsheet program with Visual Basic macros to compile gamma ray and neutron data and present a final numerical report for each waste drum assay. This program imports data from INCC and Isotopic, correlates and analyzes the neutron and gamma ray data, and maintains a database of previous measurements.

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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	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
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	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
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 ≙ $(10^3/4\pi)$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

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