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

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

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A uranium mass assay systems for 200-litter wastes drums applied neutron and gamma measurements by NDA method was developed. In this report, the measurement experiences followed by the previous report is described. The system consists of the 16 pieces of Helium-3 proportional counters for neutron detection with 100mm thickness polyethylene shield and a Germanium Solid State Detector (Ge-SSD) for gamma ray detection. The neutrons generated from U-234 (α,n) reaction and spontaneous fission neutrons from U-238 are measured, as well as gamma spectroscopy with Ge-SSD are used for verifying uranium enrichment. The extensive tests using a mock up drum containing the known amount of uranium with different enrichment and various kinds of matrices were performed. In addition, the measurement and determination of uranium mass in the actual uranium wastes drums accumulated in the Uranium Refining and Conversion Plant at Ningyo-toge, were also carried out. The actual uranium wastes drums are of great variety, in the point of matrix, averaged bulk density, packing condition and total uranium mass. Therefore some efforts were made to eliminate the problems, and then, it was concluded that NWAS is applicable to almost all kinds of wastes drums.

The obtained results have been informed to IAEA and it is desirable that IAEA could adopt NWAS as an inspection equipments of uranium wastes. The series of researches were accomplished with the support of DOE/LANL.

Keywords : Uranium Mass Assay, Neutron and Gamma Measurement, NDA, Helium-3 Proportional Counters, U-234(α,n)F Reaction, Spontaneous Fission of U-238, Germanium Solid-State Detector(Ge-SSD), 200-litter Uranium Wastes Drum

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NWAS の導入と測定経験について-Ⅱ

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(2012 年 5 月 24 日　受理)

200 リットルドラム缶収納の廃棄物中全ウランを定量する非破壊分析（NDA）装置を開発、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に着手して実績をあげつつあるので、前報で報告した以降の状況について報告する。測定装置は中性子線測定用として 16 本のヘリウム-3(He-3)比例計数管とγ線測定用として Ge 半導体検出器を組み合わせて使用している。廃棄物中ウランのα線と共存するフッ素元素等との U-234(α,n) 反応で生じる中性子と U-238 の自発核分裂中性子を、ポリエチレン減速材により熱中性子化し 16 本のヘリウム-3 比例計数管を用い測定する。バックグランド低減のため、検出器周囲は厚さ 100mm のポリエチレンで遮蔽する。種々の廃棄物内容物（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たモックアップ試験体を用い、前報より対象を拡大して行いそれぞれの条件に対応する較正定数を新たに求め直した。さらに、その較正定数を用いて実際のウラン廃棄物中の全ウラン定量評価を試みた。中性子発生量はウラン濃縮度依存であるため、Ge 半導体検出器による同時測定を行い U-235 の 186keV 及び Pa-234m(U-238 と平衡状態にある子孫核種)の 1001keV におけるγ線強度比をγ線エネルギースペクトル解析し濃縮度評価も行った。製錬転換施設には 200 リットルドラム缶収納のウラン廃棄物が多数保管されており、現在それらの全ウラン定量の作業を着実に進めつつある。実際のウラン廃棄物は内蔵されるマトリックス・嵩密度・収納状態・ウラン量等様々な態様を呈し、モックアップ試験で使用した模擬ドラム缶試料とは異なる測定条件となることもある。そこで、いくつかの応用的な評価手法も試み、様々な態様のウラン廃棄物に対する本 NWAS 測定装置の適用性を確認しつつある。また、その経過については IAEA に対しても逐一報告し、査察機器としての利用を目指している。本研究は米国エネルギー省(DOE)/ロスアラモス国立研究所(LANL)との共同研究によって実施された。

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Contents

目 次

Table List

Figure List

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1. Introduction

In previous report the developments process around the Ningyo Waste Assay System (NWAS) were described in detail. [Ref-1] The primary purpose of the NWAS is to provide a determination of the total uranium mass in 200-litter wastes drums generated from dismantling operations in the Uranium Refining and Conversion Plant (URCP) at the Ningyo-Toge Environmental Engineering Center of JAEA.

Commonly recognized that there are no established methods enable to determine precise total uranium mass, so it is an urgent requires developing the measurement methods with high sensitivity and accuracy. Especially over 7,000 uranium wastes drums have accumulated in URCP by the end of 2011. In order to address these difficult problems the new measurement system was developed.

Many tests were strenuously carried out in order to identify the characteristics of NWAS, and to obtain many parameters that would be utilized for uranium assay. NWAS consists of the two kinds of detectors, one is 16 of Helium-3 proportional counters for neutron detection and the other is high sensitivity Germanium solid-state detector (Ge-SSD) for gamma ray detection. The assays are performed simultaneously but independently. The passive neutrons measurement is intended to detect the neutrons emanating from spontaneous fission of U-238 and (α,n) reaction between a fluorine atoms and α-particles emanating from U-234. Simultaneously the gamma rays emitting from U-235 and Pa-234m, which is a progeny nuclide of U-238 are detected.

We say regarding the development several methods for analyzing the actual uranium wastes drums which are of great variety in terms of the kind of matrices, averaged bulk density, packing condition, chemical compositions and total uranium mass. Through these experiences we have established the firm procedure the uranium assay.

Additionally we also discuss a few aspects regarding optimal system for which improvements could be made in terms of possible future developments of this measurement concept.

In this report we have added deeper considerations and discussions compared with previous report.

2. Process Developments

All the equipments described below were originally supplied by U.S. Los Alamos National Laboratory (LANL) in 2003 under a joint study program. 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 room where NWAS was installed has 8 m of square space with concrete floor and 20 cm thickness of two concrete walls. Other two walls and the ceiling are not concrete, but are thinner gypsum wall and metallic slab. This room has an advantage for drum handlings,

however, it was found that so many wastes drums stored in every next room increased the radiation background level in the room. So it is required to intensify additional shielding.

The developments of NWAS performed as a cooperative study defined in Action Sheet 51 (AS-51) under the bilateral safeguards cooperation agreement between JNC (currently JAEA) and .U.S. Department of Energy (US-DOE). LANL had taken charge of design and composition of NWAS, and JAEA had achieved a series of test in this cooperative study. **[Ref.-2]**

The design concept was called "hybrid measurements", which is intended it for the two way uranium assays through simultaneous measurements neutron (Helium-3 proportional counter) and gamma ray (NaI(Tl) scintillation detector). However it found that the gamma ray background was high in spite that the large sized NaI(Tl) scintillation detector was shielded by tungsten metal. Therefore Ge-SSD with high gamma ray energy resolution was installed instead of NaI(Tl) scintillation detector.

Detection response of neutron against uranium mass is with no doubt superior to that of gamma ray, therefore we have decided to adopt neutron measurement only for uranium assay. On the other hand, gamma spectroscopy was adopted for uranium enrichment check.

3. System Structure and Measurements Methodology

The conceptual design of NWAS system is shown in **Figure-1,** and the bird view of NWAS system is shown in **Figure-2**. Key policies of the measurements methodology regarding NWAS are high sensitivity and accuracy, simple analysis scheme. Not only neutron detectors but also gamma detector are installed, the latter is intended a complementary function. Ge-SSD has been selected as the gamma detector instead of NaI(Tl) scintillation detector, which had been described in previous report.

3.1 Neutron Measurement

The neutron detectors in NWAS can be used to determine the total uranium mass by measurement of the neutron emission rate from uranium wastes drum and the enrichment determined by gamma spectroscopy. The neutrons emitted from a particular wastes drum are the spontaneous fission neutron from U-238 and generated by the (α,n) reaction between α-particles from U-234 and low-Z elements especially fluorine atoms with particularly large cross section. **[Ref.-3]**

The number of emitted neutrons per second from spontaneous fission in uranium per unit mass is well known, 0.0136 n/s of gram of U-238. **[Ref.-2]** However the number of neutrons per second per gram from (α,n) reactions is dependent on two factors, the chemical composition of uranium compounds and the U-235 enrichment. Therefore it is important to know not only the uranium enrichment but also the chemical composition of

the uranium in the drum.

The neutron energy of both spontaneous fission and (α,n) reactions are approximately 2MeV and neutron emissions are very low, so it is required the high sensitivity detector with little difference derived from source position dependence.

The heart of NWAS consists of two large sized polyethylene-moderated Helium-3 proportional counters aluminum Helium-3 detector slab boxes. Each Helium-3 detector slab box contains eight 4atm, 25.4mm diameter and 914mm active length of Helium-3 proportional counters on a 3.8cm pitch, supplied by GE Reuter Stocks (model number:RS-P4-0836-201). Each box has two pre-amplifiers which are attached to four Helium-3 proportional counters.

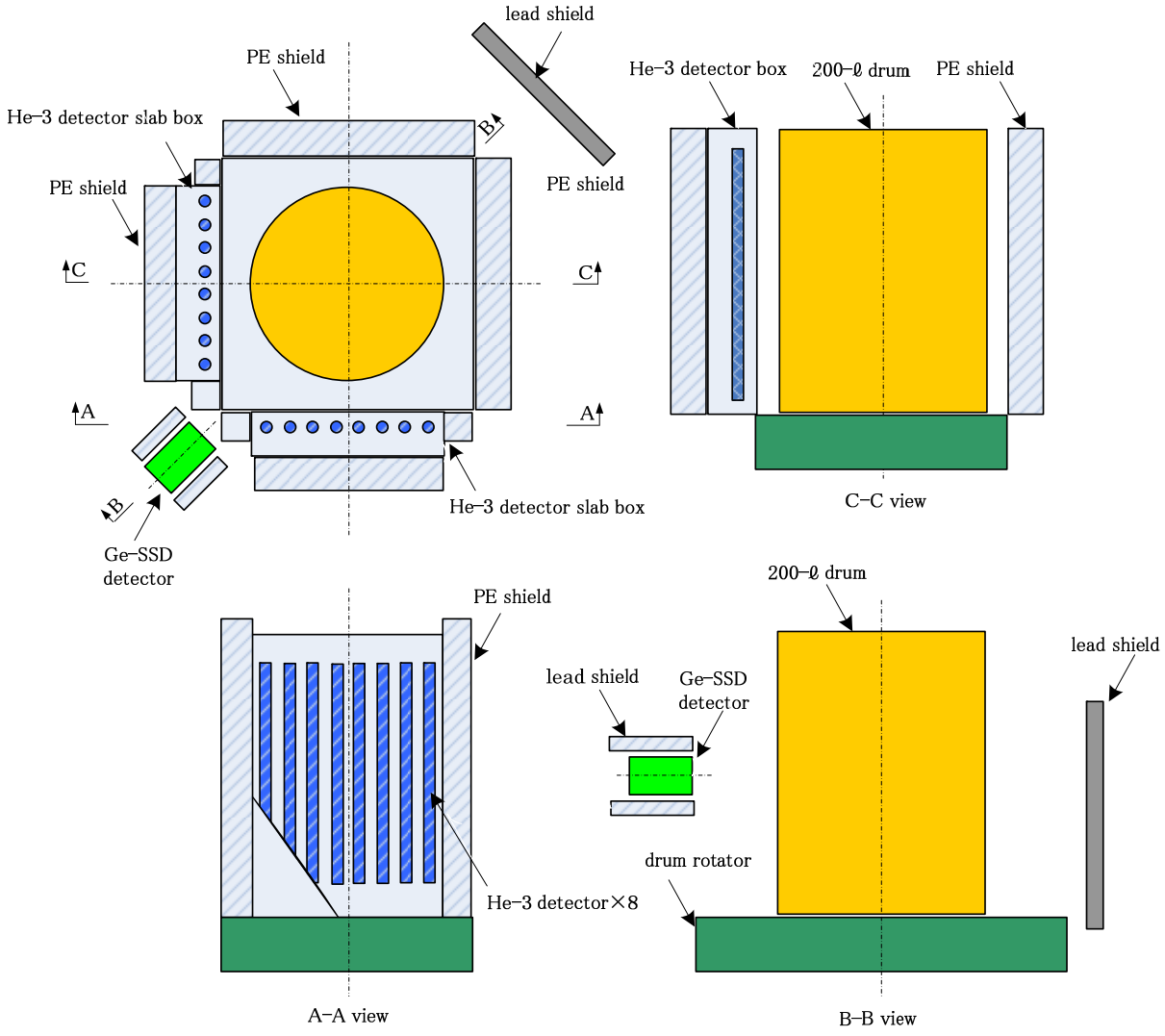


Figure-1 Conceptual design of NWAS system

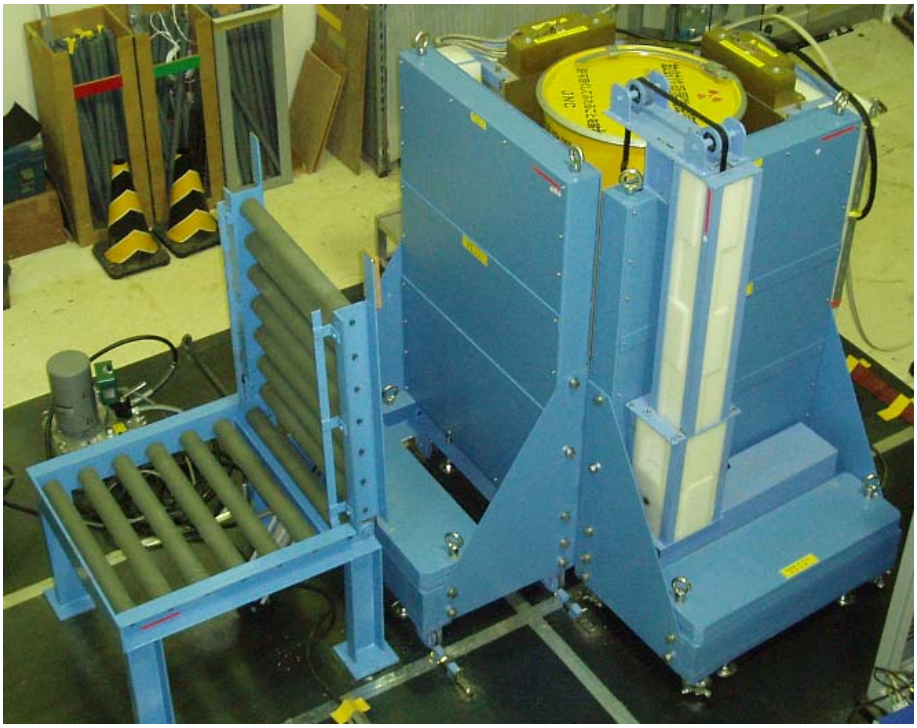


Figure-2　Bird view of NWAS system

Figure-3　The inner view of NWAS

Figure-5　The external view of NWAS

Figure-4　The controllers of NWAS

Figure-6 The personal computer for control

Figure-7 Additional Source Transport Tool

Figure-8　Setup of Ge-SSD with Shield

Figure-9　Additional Gamma Shielding

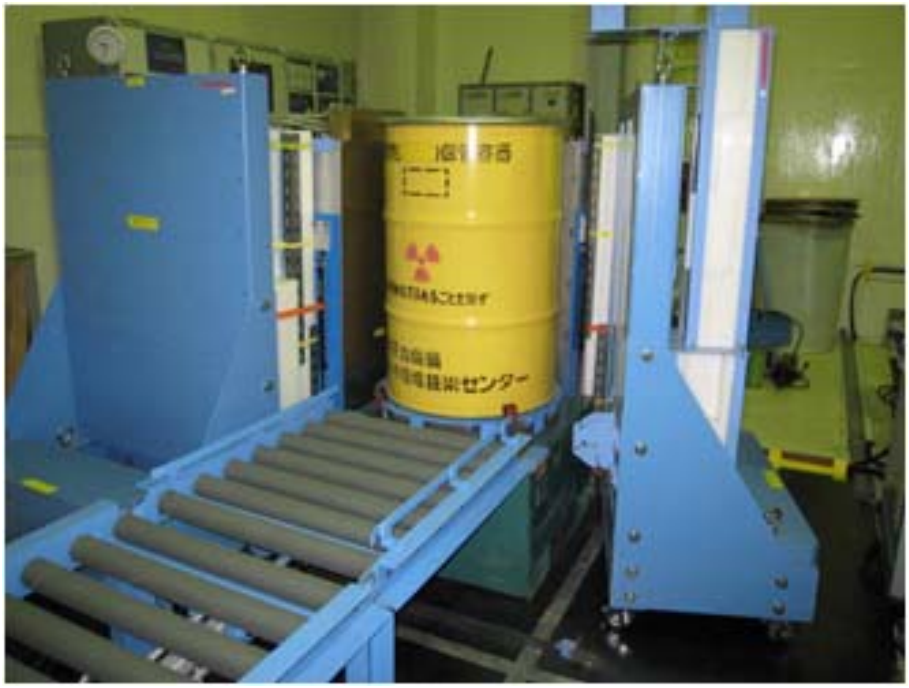


Figure-10　The Drum Rotation and Transport System

The Helium-3 detector slab boxes contain 10.2 cm of polyethylene moderator and a 2.54cm thick of borated polyethylene (5% of boron by weight) back shield to reduce background neutron detection. The eight of Helium-3 proportional counters are placed 2.54cm from front surface (nearest drum) of the polyethylene arranged in a straight rows respectively. Those Helium-3 detector slab boxes are set up on 90 degree clockwise and are to be faced with 200-litter wastes drum shown in **Figure-3**. The amplifier and control system (Shift Register JSR-12/12N) shown in **Figure-4**, were supplied by Canberra Corporations. Additional shield slabs composed of 100mm thickness of polyethylene for four sides in order to decrease ambient neutron background. One of the four slabs are movable for drum loading and un-loading. The 0.01mm of cadmium foil was wrapped outside of aluminum slab boxes including Helium-3 proportional counters as an additional neutron absorber, in order to decrease ambient neutron background.

The external view of NWAS is shown in **Figure-5**. These structures may realize good thermal neutron detection. Cf-252 source transport tool for the AAS (Added-A-Source) measurement method is shown in **Figure-7**, which is capable to handle remotely and safely. The details of the AAS measurement method is discussed later in this report.

3.2 Gamma Spectroscopy

A 77 mm diameter of high purity Ge-SSD with 40mm thickness of lead shield is settled between two neutron detectors Helium-3 detector slab boxes at the central level of 200-litter wastes drum. The gamma ray detection aims for analyzing uranium enrichments by measurement both 186keV/1001keV energy peaks. The detector, its amplifier, and the control system are supplied by Canberra Corporations, shown in **Figure-8**. Additional shield 50mm thickness lead placed at the opposite side of the gamma detector intends to reduce ambient gamma background shown in **Figure-9**.

3.3 Utilities

(1) Drum transport system

In principle, the measurements are performed rotating the drum at 2.5 rpm of speed. The drum rotation system withstands up to 450 kg of drum weight. Originally it was not so easy and not so convenient that we moved to the actual drums on the drum rotator by using drum handling porter. For the purpose of easy and safe drum handling, a drum transport system connecting with the drum rotator with rubber shown in **Figure-10,** had been introduced.

The drum transport system contains horizontal drum transport rollers and flip-up style transport rollers that moved by hydraulically-powered driving, both are connected

directly and flatly when loading a drum. The system enabled us to move drums easily and conveniently.

(2) Personal computer

NEC personal computer (Versa Pro installed Microsoft Windows XP) shown in **Figure-6** is currently installed for the control the shift register and data acquisition.

(3) Software

Supreme "INCC" for neutron data acquisition program is used, which was provided by LANL **[Ref.-4]**. It has been fulfilled not only to acquire counting but also to exclude the sudden burst pulses, which are mainly derived from cosmic rays.

INCC's characteristics are that the procedure which enable to reduce the relative counting errors by comparing series cycle counting rates in shortly. Implemental explanation says the following up stochastic check (so called QC check) enable to exclude some counting values as was over standard deviation. The main policy of QC check is described in the followings.

Measurements normally consist of repeat cycles, for our example, 300 cycles of 12 seconds each for low uranium mass samples. The accidentals/singles test compares the singles rate with the accidental coincidence rate at the end of each cycle. If the neutron source rate is constant during the cycle, then, within statistical errors, the accidentals rate should equal the square of the singles rate times the gate length. If the rates do not agree within statistical errors and the quality control tests are turned on, then the cycle is rejected and another is made automatically. The limit of acceptance is set by the parameter "Accidentals/singles test outlier limit (sigma)", which is the limit expressed in standard deviations. The usual limit is 3 standard deviations.

Convenient and commercially provided "Gennie 2000" for gamma ray acquisition program is used. Gennie 2000's has the multi functions which include of analyzing gamma rays spectroscopy and evaluate peak counts and its errors.

4. Measuring Approach

4.1 Background Measurements

Since NWAS can make passive measurements of very low level of thermal neutron and gamma ray emanating from wastes drums, it is important to determine the backgrounds, how to account then, and to calculate appropriately.

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 still affected by the presence of the wastes drum being measured.

Long time background measurements (usually 72,000 seconds) were performed periodically so that background rate variance was identified and confirmed. Until now,

by aggressive efforts the average of neutron background was improved down to 4.2 cps compared with the average that was previously reported. However during the test of NWAS, considerable difficulty was found in assessing the correct (and appropriate) background count rate, which changed depending on the presence of matrices. (In this report various substances packing in drum are defined to be called “matrices”)

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 was due to the increase in cosmic ray spallation 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 rate appeared to decrease (by about 10% on average) in the background neutrons by the moderating low-Z matrix. Therefore the prior series of the test 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.

However, the above problem is not so important. Because the backgrounds often vary more than a little, and they are considered by the influence of humidity in the detector Helium-3 detector slab boxes. In order to address the humidity problem, the maintenance procedure was improved, including frequent exchanging the silica gels are needed based on the recommendation by LANL **[Ref-2].**

For practical purposes in actual use, we came to conclusion that the just previous value would be adopted the measured value of every matrix as the background. The typical background data obtained by the neutron detector is shown in **Table-1**. There is no great distinction among them, but steel drums show slightly higher backgrounds than others.

Table-1 Typical Background Data of Neutron Detector (example)

matrix	time (sec)	counts (cps)	error (cps)	relative error
none	72,000	4.391	0.008	0.0018
empty	72,000	4.444	0.008	0.0018
NaF pellets	72,000	4.104	0.008	0.0019
alumina pellets	72,000	4.283	0.152	0.0355
steel pieces(0.5g/cc)	72,000	4.561	0.008	0.0018
steel pieces(0.9g/cc)	72,000	4.570	0.010	0.0022

4.2 Detector Calibration

Routine calibrations are necessary for neutron and gamma ray detectors.

For neutron detectors, 117,000 neutrons/sec traceable source intensity of Cf-252 checking source (approximately 1MBq) is used for calibration, and the counting efficiency is checked periodically. The checking source is settled at the center position of empty drum. A Cf-252 source holder is installed in NWAS, so that it can be placed in the center hole of the drum rotation platform. This source holder and Cf-252 source were mounted on the drum rotation system.

The measured counting efficiency is 5.434 % in average. This condition remains unchanged after our previous report. The latest precise data is shown in **Table-2**. The errors are derived from the counting uncertainties and the source intensity definition error. (Approximate 5% uncertainty according to the certificate of the source)

Table-2 Calibrated Neutron Counting Efficiency (example)

	Date	Elapsed Time (days)	Average count rate (cps)	Counting efficiency (%)
1	2011/8/30	561	4.184E+3	5.349
2	2011/9/8	570	4.182E+3	5.381
3	2011/10/6	598	4.166E+3	5.468
4	2011/11/1	624	4.128E+3	5.521
5	2011/12/5	658	4.047E+3	5.546
average				5.434

[note] Cf-252 source was certificated on 15/Feb/2010

Some parameters were determined for normal operations of NWAS. The extracts are shown in **Table-3.** [**Ref-2**].

Table-3 Operating Parameters for NWAS Neutron Detectors.

	Item	Set values
1	Operating high voltage	1680V
2	Die-Away Time	54 μ sec
3	Gate Width	64 μ sec
4	DT correction A	2.444 μ sec
5	DT correction B	0.788 μ sec^2

5. Summary of Mockup Tests

5.1 Preparation

As described in the previous report, many standard samples were prepared in order to perform the benchmark measurements. Those samples were small glass vials containing uranium powders, each vial contained one gram of uranium as metal content.

The reason why the many small samples were prepared was that the homogenous distribution was to be simulated for benchmark measurements. Especially, in order to verify the difference of neutron emission rates, the plural chemical compositions and plural uranium enrichment (IE=uranium enrichment) were prepared. The prepared standard materials were the following;

i) uranium tetrafluorides (UF_4) with IE=1.08%

ii) uranium tetrafluorides(UF_4) with IE=0.711%

iii) tri-uranium octa-oxides (U_3O_8) with IE=1.11%

iv) tri-uranium octa-oxides (U_3O_8)with IE=0.711%

As the mockup wastes drums, 200-litter drums, in which different matrices are filled up, were prepared. Now the dismantling works have been continued in URCP, several kinds of wastes were generated. In addition, there remained so many kinds of wastes by the past plant operation. Therefore, the seven different matrices were selected as representative of likely exist where it would be used practically in URCP.

As a mockup wastes drum, in which some kinds of matrices are filled up, a 200-litter drum was prepared. Five different matrices were selected as is likely exist with practical use in URCP.

i) empty state as a reference, with no attenuation by inner materials, source distribution was homogenous

ii) sodium fluoride (NaF) pellets which are usually generated in URCP wastes as off-gas trap media (averaged bulk density was arranged as 1.0 g/cc approximately)

iii) alumina pellets (Al_2O_3) which are also usually generated in URCP wastes as off-gas trap media used subsequent stage of NaF (averaged bulk density was arranged as 0.8 g/cc approximately)

iv) steel bars or pipes, which are accounted the major part of wastes, generated mainly through dismantle work in URCP (averaged bulk density was arranged as 0.5 g/cc approximately)

v) reinforcing bars, which are simulated as the dismantled relatively heavy waste (averaged bulk density was arranged as 0.9 g/cc approximately).

vi) calcium fluorides powders (CaF_2), which are also usually generated wastes in URCP wastes as precipitates, deals with wastes water. (Averaged bulk density was arranged as 1.5 g/cc approximately, however as is described later, actual wastes drums filled with calcium fluorides powders in URCP, are not pure, and

included some impurity.)

The reinforcing bars and calcium fluorides powders have been added from the previous report. Aimed at verifying the neutron response of the detectors by 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. The overview of mockup test conditions are summarized in **Table-4** and the mockup test tools are shown in **Figure-11.**

The source distributions in a drum was basically assumed symmetrical as a homogeneous distributions as is shown in **Figure-12.** The uranium powder sources in the small glass vials, which are attached to nine bars pitched at equal distances from center, were distributed into the pipes.

Over 300 measurement changing standard source and/or matrices were performed on multiple complex conditions concerning uranium mass, chemical composition of uranium and enrichment. Every data was obtained in the same conditions, so as to 3,600 seconds of counting time with rotation.

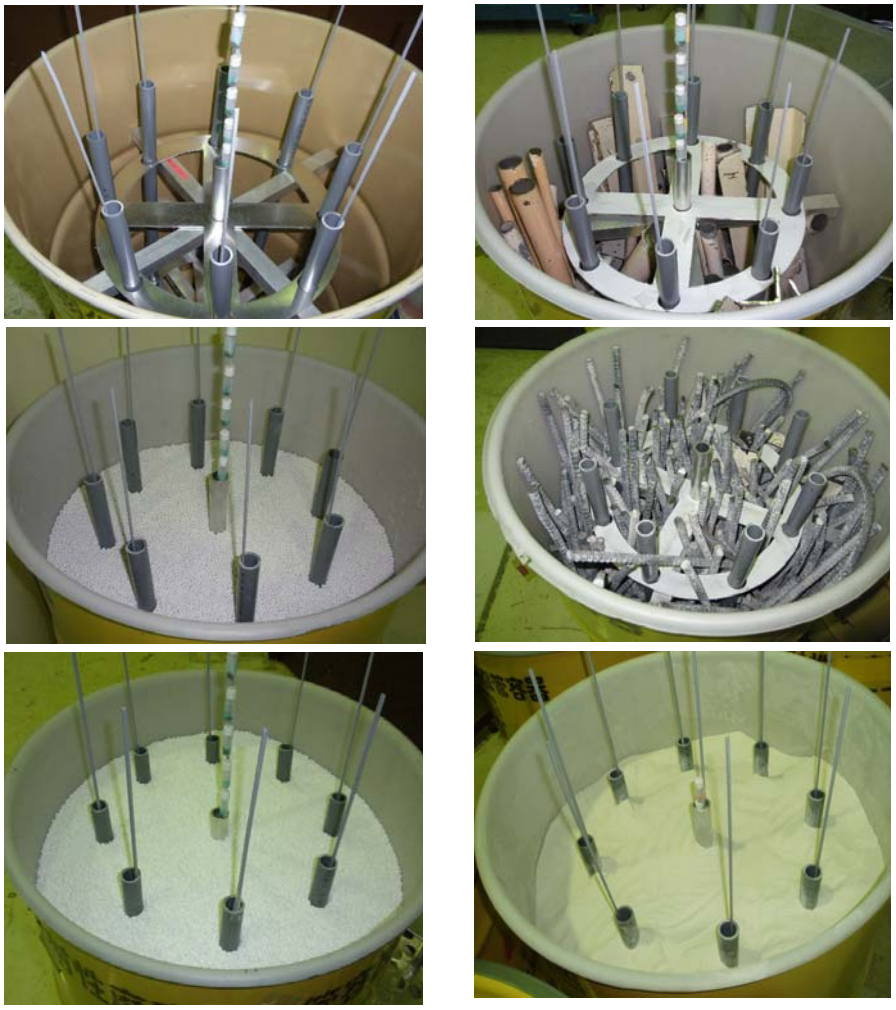


Figure-11 Mockup Test Tools

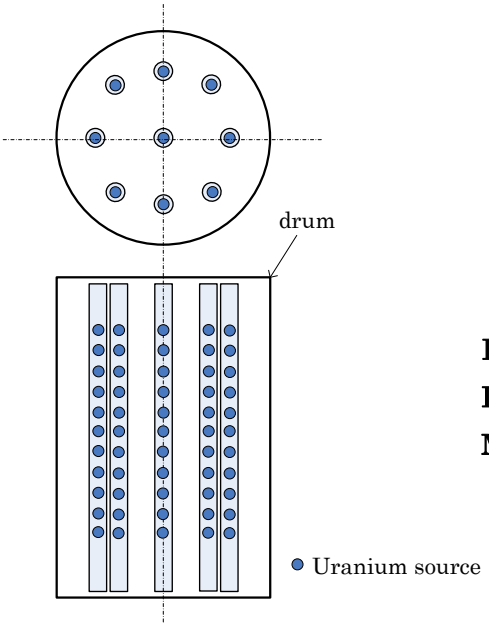


Figure-12 Source Distributions in Drum for Mockup Testing

Table-4 Overview of Mockup Test Conditions

		IE	Uranium mass use mockup tests	remarks
UF_4	EU	1.08	9gU, 18gU, 27gU up to 81gU (18gU pitch)	no more obtained
UF_4	NU	0.711	9gU, 18gU, 27gU, up to 171g(18gU pitch)	
U_3O_8	EU	1.11	8gU, 16gU, 32gU	no more obtained
U_3O_8	NU	0.711	9gU, 18gU, 27gU, up to 171g(18gU pitch)	

(note) Owning to no needs, no tests as a source of uranium oxides were tried for the mockup drums filled with calcium fluorides.

5.2 Neutron Response

The neutron measurements were performed by “rate only” mode of INCC, which are capable to acquire neutron counts from 16 Helium-3 proportional counters by time division method, normally used in 12 seconds.

Predictable outcomes suggest that there arise the results that a neutron response is difference from the kind of uranium sources and/or matrices.

The relationships of the declared uranium mass versus neutron count rate per second (=cps) was obtained. It expresses the features of the neutron emission rate based on uranium source items such as chemical composition or uranium enrichment, also expresses the characteristics of each matrix reflected neutron penetration. Those neutron response performances are summarized and shown in **Figure-13(a)(b)(c)(d)(e)(f).**

The data showed a good linearity with small counting errors, so the evaluations by extrapolations are expected surely. Furthermore the neutron response data between fluorides and oxides suggested few conclusive differences.

5.3 Evaluation Parameters

Uranium mass is determined by the following formula based on the thermal neutron counting, i.e. obviously uranium enrichment and weighing factors of "Fw" which are key factors in uranium mass determination. The important point is that the neutron emission rate which differ from the chemical composition of uranium and/or the enrichment of uranium. The formula for estimation of uranium mass are as follows.

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

$$Y(E) = 0.0136 + F_W \cdot IE$$

where M : calculated uranium mass (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 depending on uranium enrichments (n/s/gU)

IE : uranium enrichment (U-235 enrichment %)

0.0136 : neutron emission rates of spontaneous fission (n/s/gU) **[Ref-2]**

Fw : weighing factor of neutron emission rates of (α,n) reaction depending on chemical composition or matrix (n/s/gU)

The error estimation of uranium mass is necessary to include the counting error and the certification error of Cf-252 source, evaluated 5% approximately.

$$\sigma M = M \times \left(\sqrt{\left(\frac{\sigma_{ns}}{n_s - n_b} \right)^2 + \left(\frac{\sigma n_B}{n_b} \right)^2} + 0.05 \right) \qquad \text{---- (Equation-2)}$$

In the previous report, we have brought the samples of weighing factors of "Fw" derived from (α,n) reaction and neutron penetration through the matrices. But some mistakes were found afterwards, that was in the obtained experimental re-estimation of weighing factors of "Fw", and it was followed up.

The weighing factor "Fw" is obtained by the fitting calculation between the declared uranium mass and the calculated uranium mass on each matrix, i.e. it is the stochastic calculation to minimize relative errors between the experimental values and the calculated values.

The estimated weighing factor "Fw" values are shown in **Table-5**.

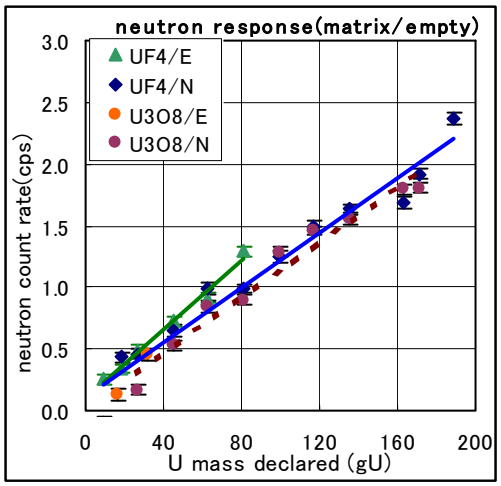
Table-5 Overview of Weighing Factor "F_w"

chemical composition	empty	NaF (d=1.0)	alumina (d=0.8)	steel (d=0.5)	steel (d=0.9)	CaF_2 (d=1.5)
UF_4	0.288	0.169	0.138	0.218	0.191	0.082
U_3O_8	0.278	0.123	0.107	0.194	0.111	0.039

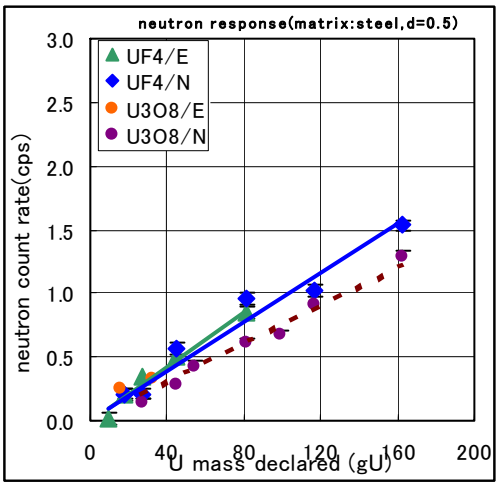
The variances of these factors reflect the differences depending on the chemical composition of uranium and/or matrices. For one example, in case of NaF as matrix, the factor "F_w" values were estimated 0.169/0.123 in regard to UF_4/U_3O_8 standard source. The results suggest that the neutron emission rate of uranium fluorides are greater than uranium oxides. For another example, in case of UF_4, a standard source, the factor "Fw" values were estimated 0.169 / 0.138 / 0.218 / 0.191 / 0.082 in regard to NaF(d=1.0g/cc) / alumina(d=0.8g/cc) / steel(d=0.5g/cc) / steel(d=0.9g/cc) / CaF_2(d=1.5g/cc) as matrices respectively. The results suggest that the neutron penetration rate through the matrices was depending on chemical components and/or averaged bulk density.

It was expected that the weighing factor "F_w" of fluorides is greater than that of uranium oxides. However, there were few conclusive differences between fluorides and oxides as source. This fact means that NWAS are expected to utilize for not only uranium-fluorides measurements but also uranium-oxides measurements

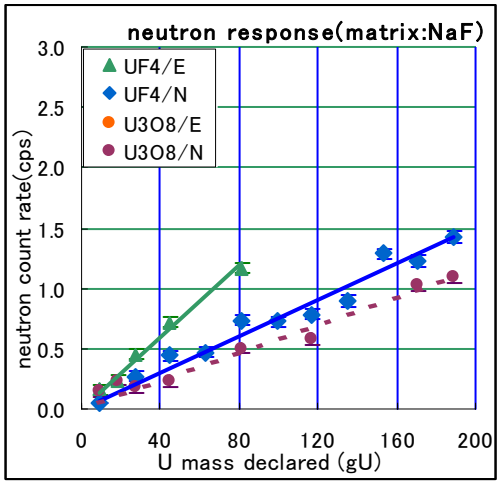
By using the weighing factor "F_w", the uranium mass was calculated according to Equation-1. Those mutual relations between the calculated uranium mass versus the declared uranium mass are summarized graphically in **Figure-14(a)(b)(c)(d)(e)(f).** The data also showed a good linearity if considering 5% error of the calibrated source, so the uranium mass determinations are possible by this method.



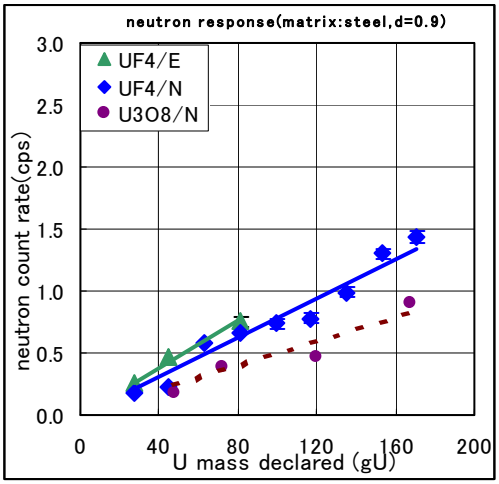
(a) matrix:empty



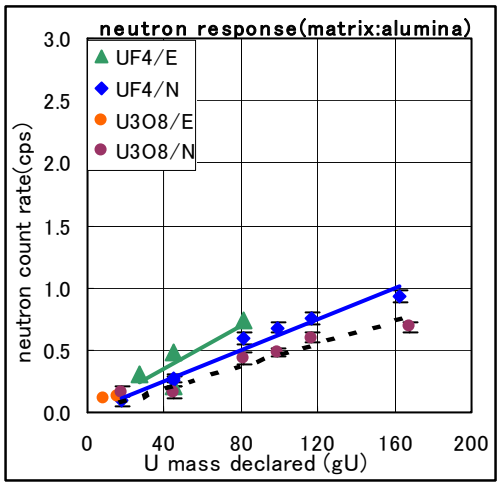
(d) matrix:steel(d=0.5g/cc)



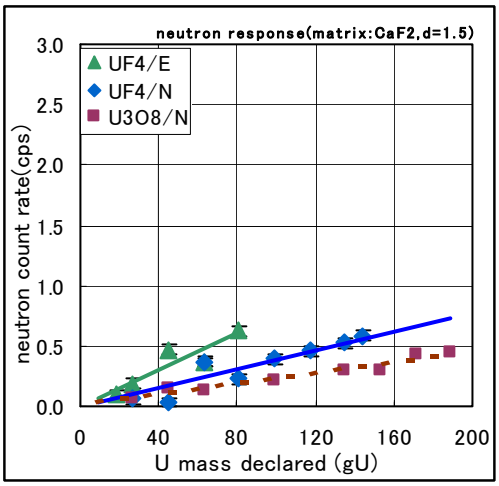
(b) matrix:NaF



(e) matrix:steel(d=0.9g/cc)

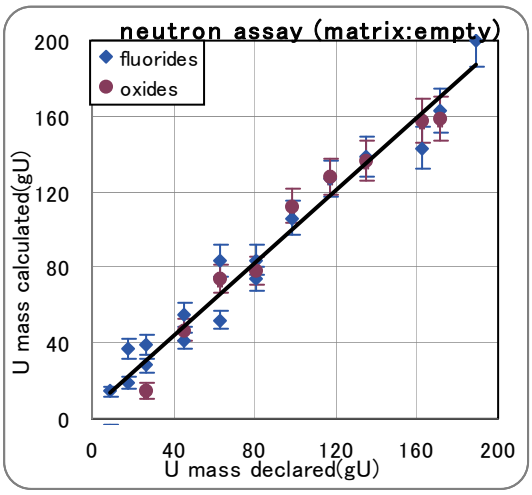


(c) matrix:alumina

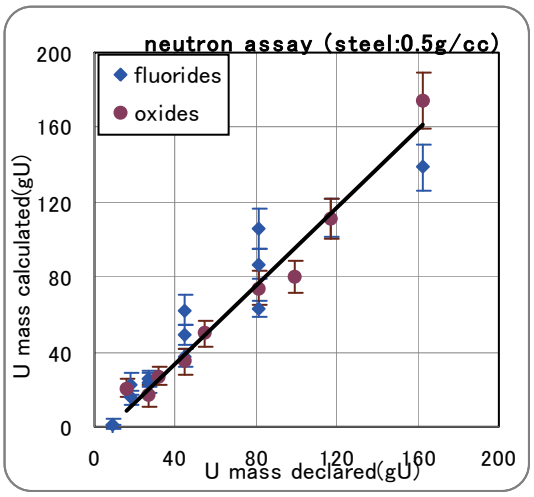


(f) matrix:CaF_2(d=1.5g/cc)

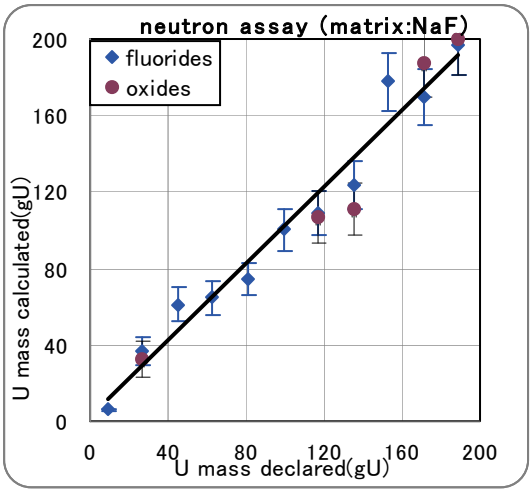
Figure-13　Neutron Response Performance



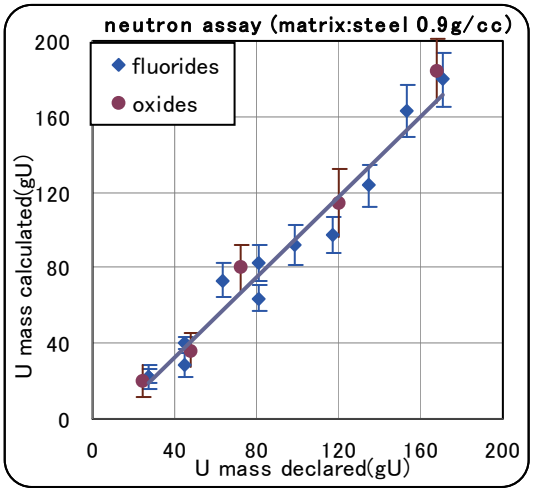
(a) empty



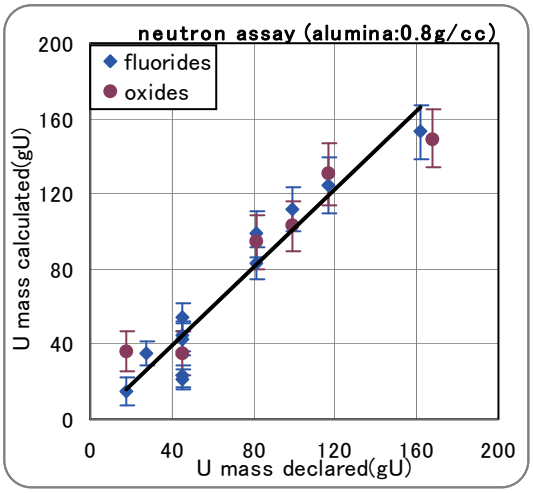
(d) steel pieces (0.5g/cc)



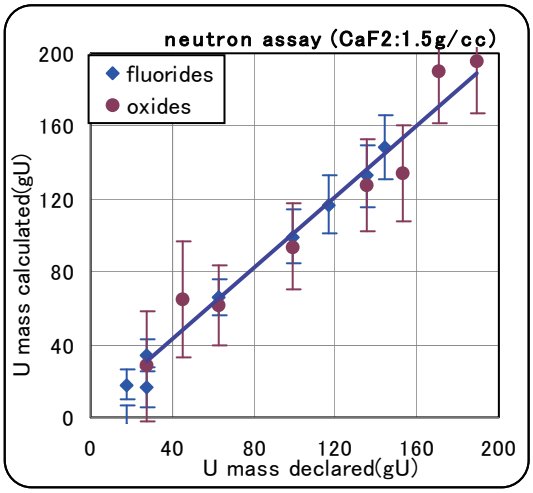
(b) NaF pellets



(e) steel pieces (0.9g/cc)



(c) alumina pellets



(f) CaF2 precipitates (1.5g/cc)

Figure-14　Relations between Calculated/Declared Uranium Mass

5.4 Verification for Source Maldistribution

It is widely known that some corrections are required against the source maldistribution in NDA measurements used gamma rays. In fact, gamma rays are generally inclined to be attenuated in matrices, especially through relatively high averaged bulk density matrices.

Contrary to this fact, such problems are relatively eliminated in NDA.used neutron methodology. In our NWAS high sensitivity and long (or tall) detectors are available. As a matter of fact, NDA.used neutron methodology has the supreme merits which suggest high penetration through matrices especially high averaged bulk density like steels, therefore less needs are required for corrections against the source maldistribution.

In order to verify the flat response toward both horizontally and vertically, the impacts of the source maldistribution was examined by changing the deposition of the Cf-252 point source on the arbitrary position horizontally and vertically. This geometry for in source maldistribution is shown in **Figure-15,** and the trend analysis is shown in **Figure-16**.

Toward horizontal direction, there also found a flat distribution within 25 cm range from the center of drum. Toward vertical direction, there found a flat distribution within 50 cm range from the center of drum.

These results confirmed that there were less impacts based on source maldistribution. In fact, it was obvious that there appeared no response deviation toward vertical direction because of the tall neutron detectors.

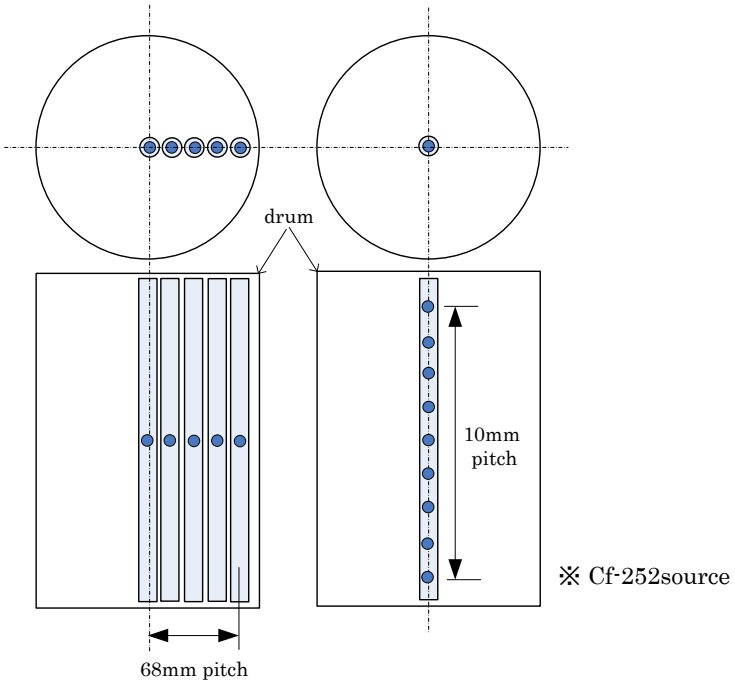
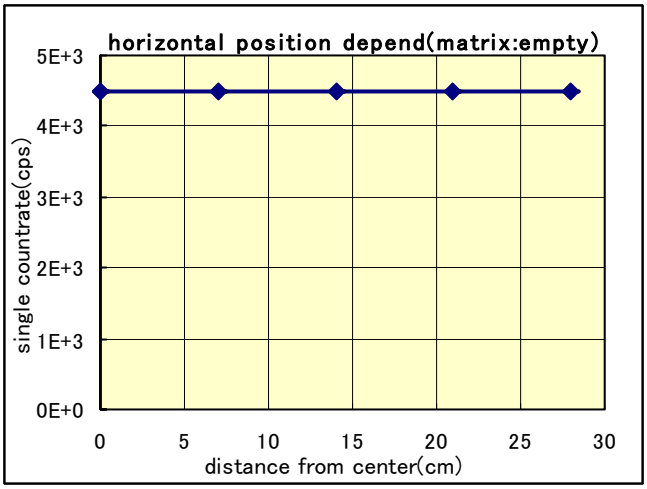
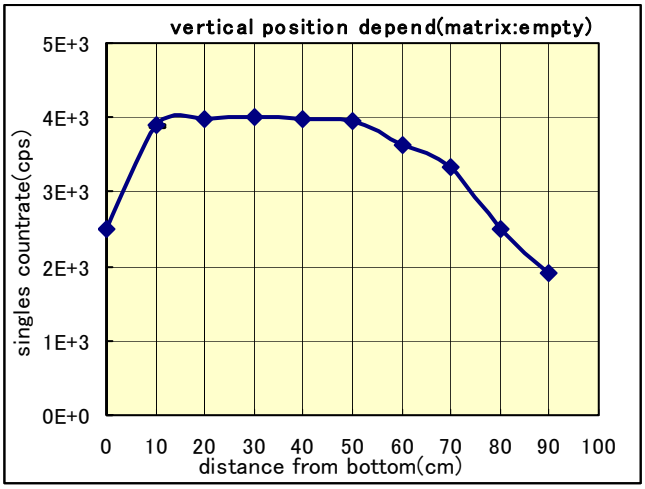


Figure-15 Maldistribution Geometry





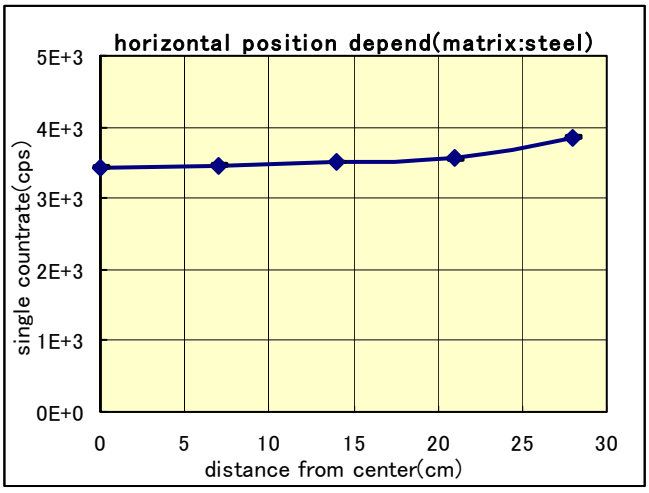


Figure-16　Trend Analysis for Maldistribution

5.5 Detection Limits Estimation

Generally the detection limits of the radiation measurement system are defined from the background rates, the counting time, and the parameters regarding statistical uncertainty. For the purpose of estimation of the detection limit for this method, the 3 σ method was applied, which is popular in Japan. The analytical formula is described in Equation-3. The second formula which calculates part of obtaining uranium mass, are equal to Equation-1.

$$MDM = \frac{n_D}{\varepsilon \cdot Y(E)} \qquad \text{---- (Equation-3)}$$

$$Y(E) = 0.0136 + F_W \cdot IE$$

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

where MDM : minimum detectable mass (gU)

n_D : minimum net detectable counting rate (cps)

ε : Cf-252 counting efficiency (-)

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

k : multiple factor against standard deviation (k=3)

n_B : background rates (cps)

t_s : counting time for sample (cps)

t_b : counting time for background (cps)

The good results regarding neutron assay detection limit as uranium mass were estimated.

The parametric conditions are listed in below.

i) The improved neutron background count rate, which is slightly different from the matrices, is used. The ranges were from 4.2 cps to 4.5 cps. In the following calculations 4.2cps as a neutron background rate were used.

ii) assumed counting time for samples were surveyed from 600 seconds to 7200 seconds

iii) actual counting time for background was determined 72000 seconds uniformly

iv) according to the 3 σ method, the definition of multiple factor against standard

deviation was determined k=3, which means 99.7% reliability.

The typical example detection limit estimated by this method is shown in **Table-6** and **Figure-17**.

The remarkable features are summarized in below.

i) in general, good detection limit values are obtained in proportion as increase of "F_W" values, as is obviously in Equation-2

ii) also good detection limit values are obtained in case of high uranium enrichment values, as is also obviously in Equation-3.

iii) long counting time provides good detection limit values, as is derived from the decrease of relative counting errors.

iv) as a matter of fact, the best detection limit values are estimated in case of wastes drums filled with steel, as was suggested to be depending on high neutron penetration for high Z elements

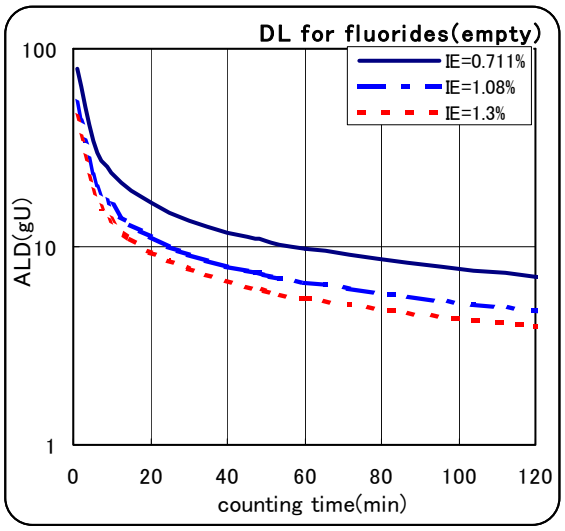
v) on the contrary, the relatively high detection limit values were estimated in case of wastes drums filled with sodium fluorides pellets or alumina pellets,

vi) As a whole, if measured in 20～60 minutes, 8～24gU approximately in wastes drums are detectable, (except for CaF_2 powder)

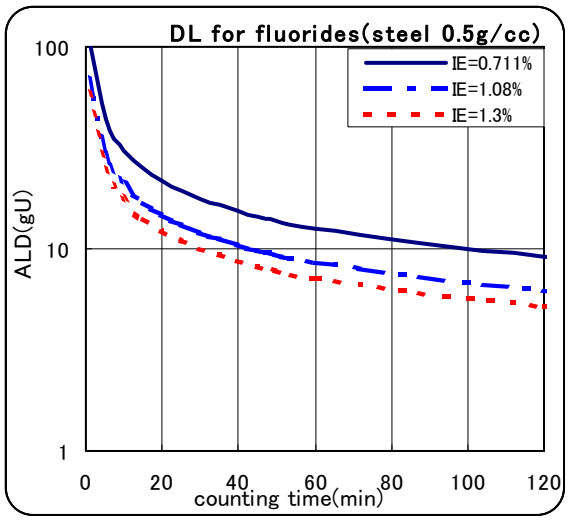
vii) these estimated values proved the measurement application to the wastes drums stored in URCP.

Table-6 Typical Detection Limit Data by Neutron Measurements

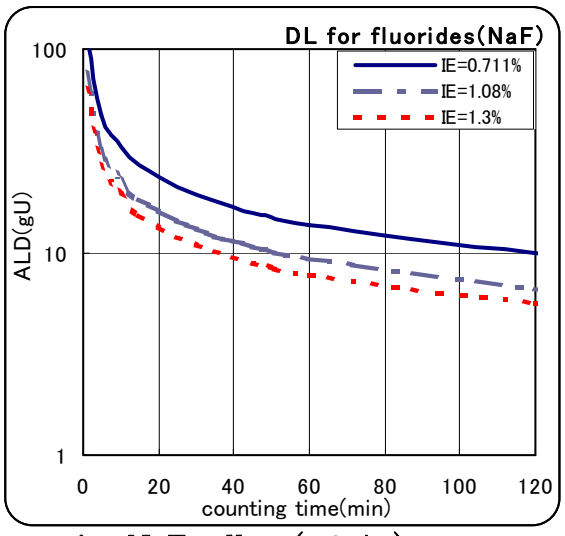
chemical composition	uranium enrich	Meas. time(min)	empty	NaF (1.0g/cc)	alumina (0.8g/cc)	steel (0.5g/cc)	steel (0.9g/cc)	CaF_2 (1.5g/cc)
UF_4	1.3%	20	9.4	13	19	12	14	30
UF_4	1.3%	40	6.7	9.4	13	8.7	10	21
UF_4	1.3%	60	5.5	7.7	11	7.2	8.1	18
UF_4	1.08%	20	11	16	23	15	17	36
UF_4	1.08%	40	8.0	11	16	10	12	25
UF_4	1.08%	60	6.6	9.2	13	8.5	9.7	21
UF_4	0.71%	20	17	23	33	22	24	51
UF_4	0.71%	40	12	17	23	15	17	36
UF_4	0.71%	60	9.8	14	19	13	14	29
U_3O_8	0.71%	20	9.8	16	24	14	23	74
U_3O_8	0.71%	40	6.9	11	17	9.7	16	53
U_3O_8	0.71%	60	5.7	9.1	14	8.0	13	43



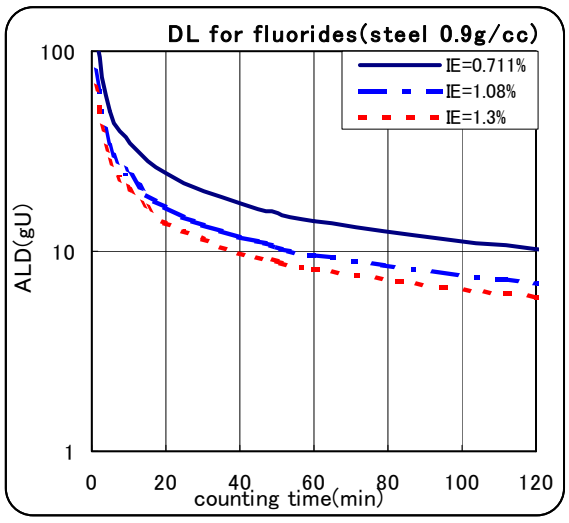
(a) matrix:empty



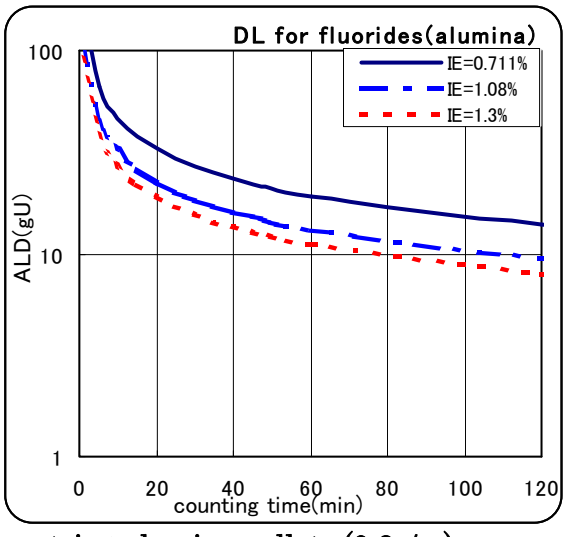
(d) matrix:steel pieces (0.5g/cc)



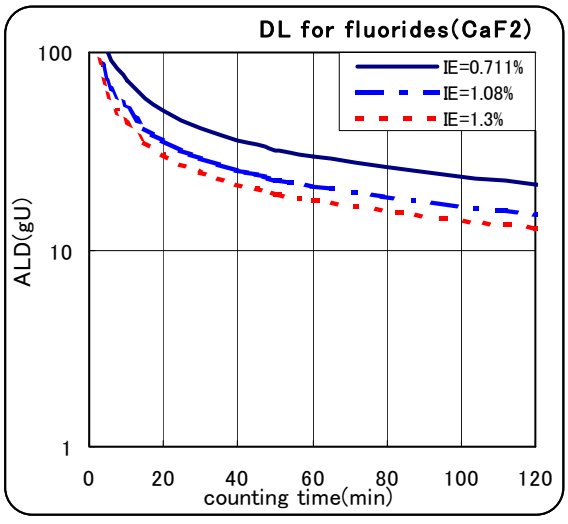
(b) matrix : NaF pellets (1.0g/cc)



(e) matrix:steel pieces (0.9g/cc)



(c) matrix : alumina pellets (0.8g/cc)



(f) matrix:CaF_2 precipitates (1.5g/cc)

Figure-17　Relations between Detection Limits

5.6 Error Estimation and Repeatability

INCC software for neutron counting acquisition and analysis has the supreme functions which would be able to control counting errors itself. Those functions, including time division counting and QC tests to exclude abnormal counting, contributed us good results regarding neutron counting errors.

It is so important to grasp the counting errors derived from nothing but neutron counting, so as to decide counting time. We had surveyed relative errors against counting time from 10min to 60min. Even in the case of 162 gU mockup sample it was repressed up to 6%. Furthermore the actual drum assumed to be involved more than 10,000gU were measured less than 0.3 % of relative error. Therefore, the data would be contributed to determine the counting time for measurement actual wastes drums. Furthermore, in order to verify the time dependence of relative error, the measurements with time variance were performed against the same mockup wastes drums with no matrix. Among them also measured repeatedly to be checked repeatability. The repeatability was kept within 5%.

The measurements data for error estimations are summarized in **Table-7, Figure-18,** and the measurements data for repeatability check are summarized in **Table-8, Figure-19.**

Table-7 Error Estimations for Neutron Detection

declared U mass	No.	time (min)	counts (cps)	error (cps)	relative error
162gUF_4 standard source	1	10	1.867	0.119	0.064
	2	20	1.831	0.084	0.046
	3	30	1.930	0.069	0.036
	4	45	2.048	0.058	0.028
	5	60	2.117	0.051	0.024

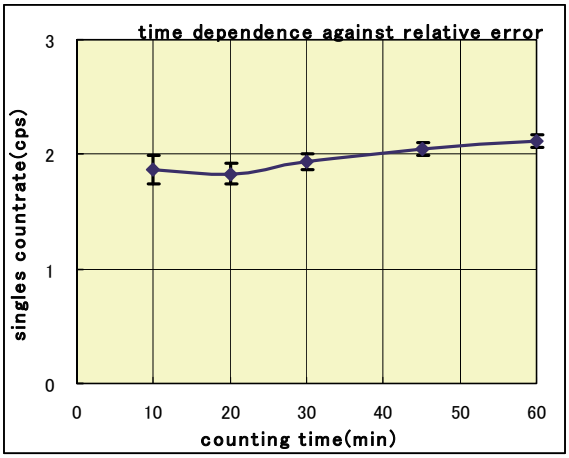


Figure-18 The Error Estimations

Table-8 Repeatability Check for Neutron Detection

declared U mass	No.	time (min)	counts (cps)	error (cps)	relative error
171gU UF_4 standard source	1	60	1.916	0.043	0.022
	2	60	2.006	0.047	0.023
	3	60	2.030	0.048	0.024
	4	60	2.042	0.048	0.024
	5	60	2.155	0.049	0.023
	6	60	2.126	0.049	0.023
average±standard deviation			2.046	0.086	

U mass unknown	No.	time (min)	counts (cps)	error (cps)	relative error
actual drum	1	60	45.57	0.121	0.003
	2	60	46.147	0.122	0.003
	3	60	45.864	0.123	0.003
	4	60	45.672	0.121	0.003
	5	60	45.906	0.122	0.003
average±standard deviation			45.832	0.224	

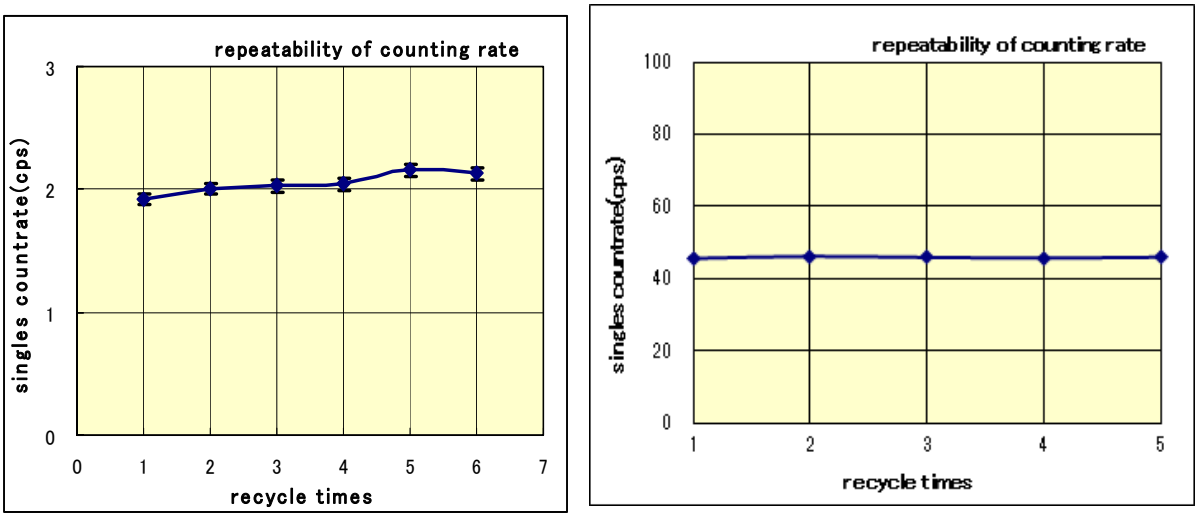


Figure-19 Repeatability Check for Neutron Detection

6. Trials for Actual Wastes Drums

6.1 Measurement's Needs

Based on the result of the mockup test, the trial measurements were performed using the actual wastes drums accumulated in URCP from last year. As was described previously, there found the great variety matrices of wastes drums, so as to sodium fluorides pellets, alumina pellets, and calcium fluorides precipitates. Each of them was the major operation waste in URCP, and steel fragments, pipes and scraps were dismantled in URCP, and so on. Over 7,000 wastes drums are now accumulated in URCP. Overwhelming requests for measuring of these drums are now expected.

At the end of 2011, over 300 trial measurements were performed, and useful data was obtained successfully.

It is necessary to accelerate these measurement works.

6.2 Characteristics of Actual Wastes Drums

As described above, several mockup test wastes drums were prepared, which conditions were considered to simulate actual wastes drums as similar as possible. However, as a matter of fact, the actual wastes drums are not monotonous characteristics. The typical samples are shown below.

i) wastes drums filled with uniform matrix and averaged bulk density, such as sodium fluorides pellets or alumina (aluminum oxides) pellets

ii) wastes drums filled with uniform matrix but non-uniform averaged bulk density, such as steel fragments and pipes generated from dismantling chemical plants

iii) wastes drums filled with almost all non-uniform matrix nor averaged bulk density, such as complex scrap pieces (steels, vinyl chloride material and so on) generated from dismantling

iv) wastes drums filled with indeterminate forms, such as calcium fluorides precipitates with so much impurity mainly generated from waste water dealings

Therefore the multiple analytical methods were required not exclusively based on the mockup test. In the next chapter, some examples for corresponding the status of actual wastes drums are discussed.

7. Analytical Approach

7.1 Fundamentals of Uranium Assay

As was described above, the uranium assay is implemented by neutron count rate of Helium-3 detectors, counting efficiency obtained from Cf-252 calibration, uranium enrichment, and the weighing factors (defined as Fw) by Equation-1, which is the same method as mockup tests. In these cases, the weighing factors "F_w" and counting efficiency are used as the constant values as was defined. This method was available to

the wastes drums filled with uniform matrix and averaged bulk density, such as sodium fluorides pellets or alumina (aluminum oxides) pellets.

These analysis methods were named ”technique-A”. The spread sheets of typical samples analyzed above are summarized in **Table-10(a)(b).**

However, in case of matrix with non-uniformity, the neutron penetration rate of each wastes drum was not constant to be inadequate to use “F_w” values. Therefore, another modified method have been required.

For example, the wastes drums filled with the dismantled fragments, often show wide range of averaged bulk density, so to be required “F_w” value corresponding each wastes drum. The modified procedures were also used as follows;

i) obtained two “F_w” values of steel against averaged bulk density of 0.5g/cc and 0.9g/cc

ii) made a graph drawn the relation “F_w” values against averaged bulk density added “F_w” values of vacant drum

iii) interpolate “F_w” values against arbitrary averaged bulk density (shown in **Figure-20**)

iv) assay uranium mass using averaged bulk density value known previously

The modified spread sheets of typical samples analyzed above are summarized in **Table-10(c).**

In these cases, the weighing factors are used as the valuables, named ”technique B”.

7.2 Application of AAS Method

In addition to provide accurate and reliable assay for uranium compounds, the perturbation correction method for neutron counting efficiency was examined in case of filled with unknown matrices by so called AAS (Add-A-Source) method using Cf-252 standard source. The main structures that we designed are shown in **Figure-21.**

The systems include 1MBq of Cf-252 standard source contained in a small vessel, one rounded belt with moving devices and 50mm thickness of polyethylene blocks used for tunnel and slab box. The 1MBq of Cf-252 standard source had been placed beside 200-littter drum at the central position used the belt conveyer handled manually. The transport route of the source is well shielded for operator’s safety.

The procedures and formulae how to estimate the attenuation rate through unknown matrices are followings. **[Ref-5]**

(1) Handling procedure

#1. Attach the Cf-252 standard source onto the tensed belt

#2. Move the Cf-252 standard source by using handle manually.

#3. Set the Cf-252 standard source beside the 200 litter drum

#4. Measure the neutron counts by using Helium-3 detectors in short time

#5. Remove the Cf-252 standard source. into polyethylene shielding Helium-3 detector slab boxes

(2) Measurement

#1. Measure the background in INCC (totals background) with an empty drum in place.

#2. Measure the empty drum with a Cf-252 source at the surface of side center with good statistics and log the empty-drum Cf-252 totals rate in 120 seconds (Cf_0)

#3. Remove the Cf-252 source from the area and measure the unknown drum using INCC as normally would do. Log the resulting totals rate (T_0)

#4. Measure the sampled drum with the Cf-252 source under the drum for the same time as the T_0 measurement in 120 seconds. Log the totals rate result (T_0 + Cf_1).

(3) Analysis

#1. Determine the value of Cf_1.

Cf_1 = (T_0 + Cf_1) - T_0 ----- (a)

#2. Determine the ratio of Cf measurements

Ratio = Cf_1/Cf_0 ----- (b)

#3. Adjust the detector efficiency in INCC

efficiency_new = efficiency_old * Ratio ----- (c)

#4. Adjust measurement result as follows

T_corrected = T_0 * Ratio (Using the original efficiency) ----- (d)

#5. Use T_corrected in combination with your calibration curve to determine the mass of uranium in the drum.

Mass_U_corrected = Mass_U_0 (from T_0) * Ratio ----- (e)

The estimated “the new efficiency” is listed in **Table-9.**

By applied above process we tried to estimate the corrected efficiency (=new efficiency). The obtained data of “the new efficiency” or the corrected efficiency were measured against actual wastes drums. The example penetration rate data verifying the effectiveness of AAS method applying each matrix are shown in **Figure-22.** In these cases, the weighing factors depending on the matrices are not used, but the values for empty drum, “new efficiency” is the parameter reflected from the matrix’s characteristics, named ”technique C”. The measurement accumulation of the actual wastes drums with inconstant averaged bulk density have found that the penetration rate by measured by AAS method against averaged bulk density was indicative of serially correlated. **(Figure-23)** The further modified spread sheets of typical samples analyzed above are summarized in **Table-10(d)(e)(f).**

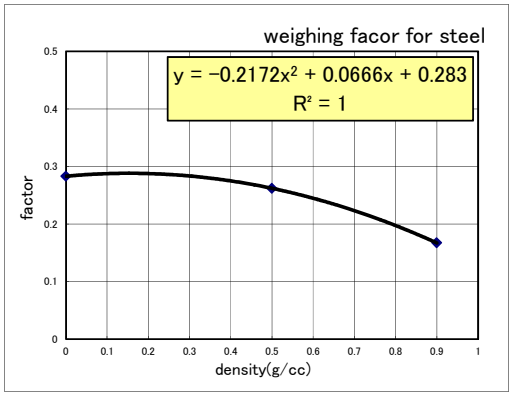


Figure-20 Interpolated Correction for Weighing Factor

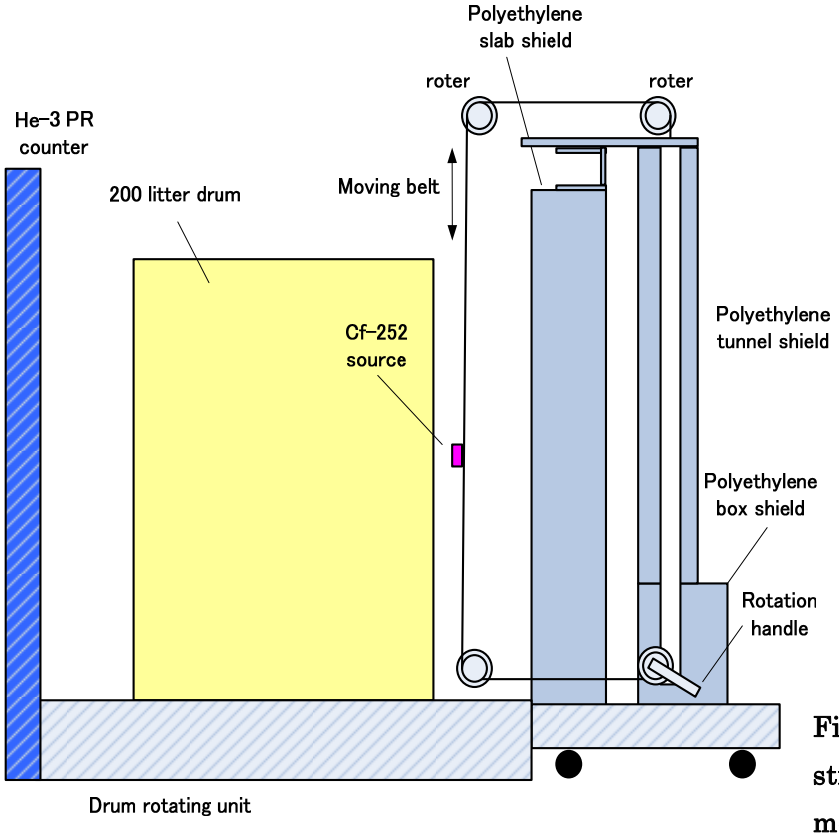


Figure-21 Main structures of AAS method

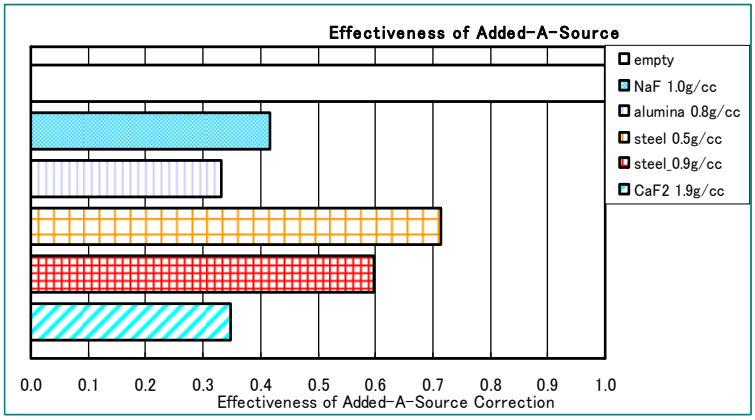
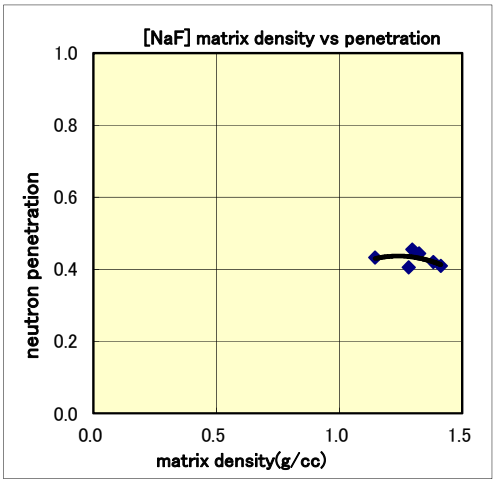
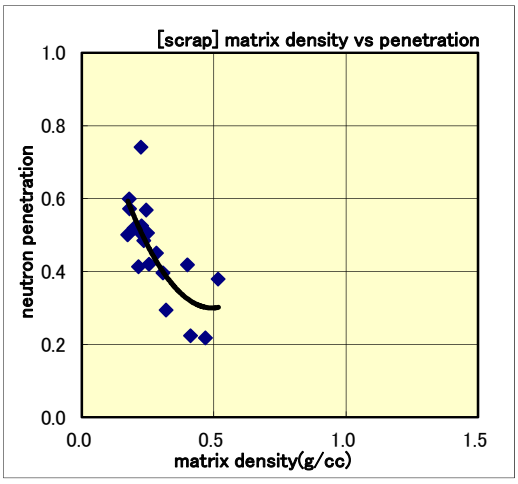


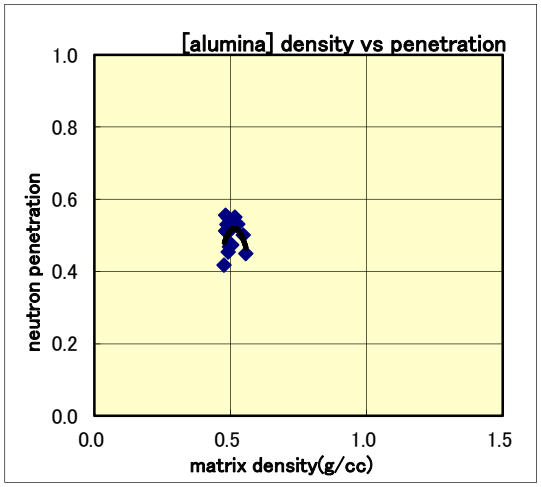
Figure-22 Effectiveness of AAS method



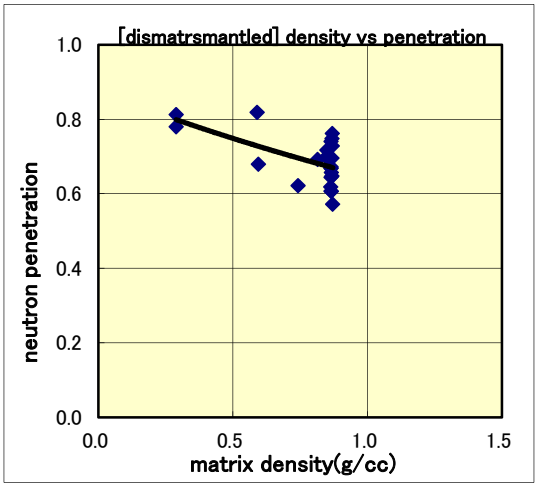
(a) matrix : NaF pellets



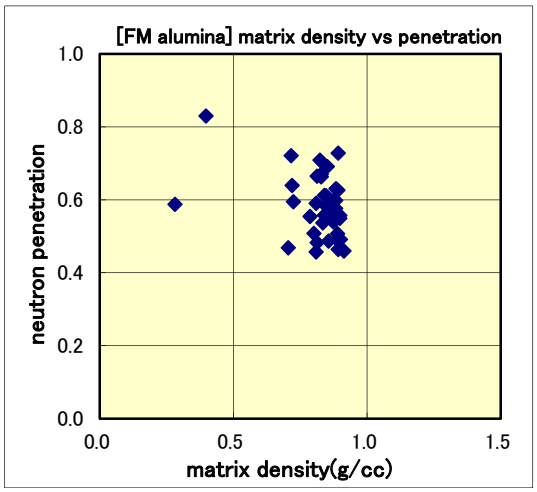
(d) matrix : scrap pieces



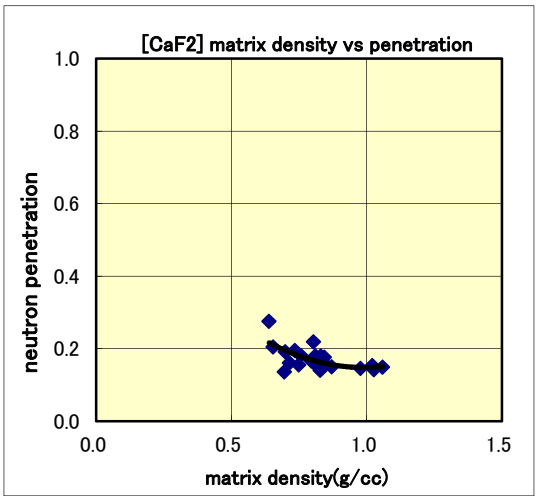
(b) matrix : alumina pellets



(e) matrix : dismantled fragments



(c) matrix : alumina pellets (FM)



(f) matrix : CaF2 precipitates

Figure-23　Correlation between Neutron Penetration against Matrix Density

Table-9 Added-A-Source Analysis

(a) scrap pieces as matrix

No.	Sample Description	BG (cps)	Cf_0 (cps)	T_0 (cps)	T_0+Cf_1	Cf_1 (cps)	Ratio	old eff	new eff
1	scrap	4.530	2798	3.298	1463.41	1460.1	0.522	0.0540	0.0282
2	scrap	4.530	2798	0.140	2073.43	2073.3	0.741	0.0540	0.0400
3	scrap	4.530	2798	0.723	1154.106	1153.4	0.412	0.0540	0.0223
4	scrap	4.530	2798	0.093	1451.756	1451.7	0.519	0.0540	0.0280
5	scrap	4.530	2796	0.177	622.944	622.8	0.223	0.0540	0.0120
6	scrap	4.530	2796	0.278	1412.162	1411.9	0.505	0.0540	0.0273
7	scrap	4.530	2796	-0.044	1171.7	1171.7	0.419	0.0540	0.0226
8	scrap	4.530	2796	0.028	1589.037	1589.0	0.568	0.0540	0.0307
9	scrap	4.530	2796	0.023	605.831	605.8	0.217	0.0540	0.0117
10	scrap	4.530	2794	0.194	1466.224	1466.0	0.525	0.0540	0.0283

(b) dismantled pieces as matrix

No.	Sample Description	BG (cps)	Cf_0 (cps)	T_0 (cps)	T_0+Cf_1	Cf_1 (cps)	Ratio	old eff	new eff
1	dismantled	4.768	2726	4.967	1689.7	1684.8	0.618	0.0552	0.0341
2	dismantled	4.768	2728	4.624	2045.6	2041.0	0.748	0.0552	0.0413
3	dismantled	5.009	2722	5.581	1890.0	1884.4	0.692	0.0552	0.0382
4	dismantled	5.009	2721	0.285	2012.5	2012.2	0.740	0.0552	0.0408
5	dismantled	4.768	2728	6.901	1828.5	1821.6	0.668	0.0552	0.0369
6	dismantled	4.768	2726	0.926	1955.5	1954.6	0.717	0.0552	0.0396
7	dismantled	4.768	2728	0.449	1897.0	1896.6	0.695	0.0552	0.0384
8	dismantled	4.768	2726	0.253	1764.1	1763.8	0.647	0.0552	0.0357
9	dismantled	4.768	2726	5.952	1661.4	1655.4	0.607	0.0552	0.0335
10	dismantled	4.768	2728	0.528	1791.9	1791.3	0.657	0.0552	0.0362

(c) CaF2 precipitates as matrix

No.	Sample Description	BG (cps)	Cf_0 (cps)	T_0 (cps)	T_0+Cf_1	Cf_1 (cps)	Ratio	old eff	new eff
1	CaF2	6.226	2922	53.17	521.68	468.5	0.160	0.0549	0.0088
2	CaF2	6.226	2922	49.10	443.72	394.6	0.135	0.0549	0.0074
3	CaF2	6.226	2922	36.05	443.72	407.7	0.140	0.0549	0.0077
4	CaF2	6.297	2914	13.87	426.00	412.1	0.141	0.0549	0.0078
5	CaF2	6.485	2928	0.19	425.95	425.8	0.145	0.0549	0.0080
6	CaF2	6.226	2924	0.78	437.52	436.7	0.149	0.0549	0.0082
7	CaF2	6.226	2928	2.19	517.32	515.1	0.176	0.0549	0.0097
8	CaF2	6.454	2949	0.37	487.86	487.5	0.165	0.0549	0.0091
9	CaF2	6.226	2926	12.86	459.61	446.8	0.153	0.0549	0.0084
10	CaF2	7.096	2985	55.43	591.86	536.4	0.180	0.0549	0.0099

Table-10 Analyzed Uranium Assay for Actual Wastes Drums

(a) NaF pellets as matrix (technique-A example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	NaF	299	12	3588	519.174	1.024	5.271	0.009	0.98	0.0540	0.201	0.211	45673	2403
2	NaF	299	12	3588	541.148	0.958	5.271	0.009	0.98	0.0540	0.201	0.211	47561	2495
3	NaF	300	12	3600	715.055	1.011	5.271	0.009	0.98	0.0540	0.201	0.211	62906	3285
4	NaF	299	12	3588	544.449	1.144	5.271	0.009	0.98	0.0540	0.201	0.211	47897	2525
5	NaF	299	12	3588	573.122	1.153	5.271	0.009	0.98	0.0540	0.201	0.211	50419	2654
6	NaF	299	12	3588	268.92	0.32	5.271	0.009	0.71	0.0540	0.201	0.157	31831	1658
7	NaF	299	12	3588	191.421	0.284	5.271	0.009	0.71	0.0540	0.201	0.157	22657	1184
8	NaF	298	12	3576	113.183	0.199	5.271	0.009	0.71	0.0540	0.201	0.157	13397	703
9	NaF	300	12	3600	93.424	0.317	5.271	0.009	0.71	0.0540	0.201	0.157	11058	595
10	NaF	300	12	3600	214.708	0.303	5.271	0.009	0.71	0.0540	0.201	0.157	25414	1327

(b) alumina pellets as matrix (technique-A example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	alumina	294	12	3528	10.396	0.073	4.493	0.008	1.1	0.0552	0.138	0.165	1141	65
2	alumina	300	12	3600	20.713	0.099	4.493	0.008	1.1	0.0552	0.138	0.165	2273	125
3	alumina	296	12	3552	6.529	0.063	4.493	0.008	1.1	0.0552	0.138	0.165	717	43
4	alumina	299	12	3588	11.575	0.076	4.493	0.008	1.1	0.0552	0.138	0.165	1270	72
5	alumina	297	12	3564	28.018	0.113	4.493	0.008	1.1	0.0552	0.138	0.165	3075	167
6	alumina	299	12	3588	30.343	0.105	4.493	0.008	1.1	0.0552	0.138	0.165	3333	180
7	alumina	299	12	3588	12.036	0.08	4.493	0.008	1.1	0.0552	0.138	0.165	1322	75
8	alumina	298	12	3576	12.24	0.073	4.499	0.008	1.1	0.0552	0.138	0.165	1345	76
9	alumina	299	12	3588	19.499	0.081	4.499	0.008	1.1	0.0552	0.138	0.165	2142	117
10	alumina	294	12	3528	8.898	0.064	4.499	0.008	1.1	0.0552	0.138	0.165	977	56

(c) dismantled pieces as matrix (technique-B example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	dismantled	299	12	3588	4.967	0.064	4.768	0.008	0.71	0.0552	0.179	0.141	641	40
2	dismantled	296	12	3552	4.624	0.081	4.768	0.008	0.71	0.0552	0.177	0.139	601	41
3	dismantled	299	12	3588	5.581	0.083	5.009	0.009	0.93	0.0552	0.193	0.193	524	34
4	dismantled	297	12	3564	0.285	0.041	5.009	0.009	1.1	0.0552	0.178	0.210	25	5
5	dismantled	296	12	3552	6.901	0.082	4.768	0.008	0.71	0.0552	0.178	0.140	892	55
6	dismantled	295	12	3540	0.926	0.043	4.768	0.008	0.98	0.0552	0.183	0.193	87	8
7	dismantled	297	12	3564	0.449	0.038	4.768	0.008	0.71	0.0552	0.177	0.139	58	8
8	dismantled	297	12	3564	0.253	0.038	4.768	0.008	0.71	0.0552	0.177	0.139	33	7
9	dismantled	298	12	3576	5.952	0.065	4.768	0.008	0.71	0.0552	0.178	0.140	770	47
10	dismantled	299	12	3588	0.528	0.041	4.768	0.008	0.71	0.0552	0.177	0.140	68	9

[note] Singles=ns-nb

Table-10 Analyzed Uranium Assay for Actual Wastes Drums --- continued

(d) scrap pieces as matrix (technique-C example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	scrap	296	12	3552	3.298	0.049	4.53	0.008	0.71	0.028	0.288	0.218	537	35
2	scrap	298	12	3576	0.14	0.035	4.53	0.008	0.71	0.040	0.283	0.215	16	5
3	scrap	290	12	3480	0.723	0.039	4.53	0.008	0.71	0.022	0.283	0.215	151	16
4	scrap	299	12	3588	0.093	0.036	4.53	0.008	0.71	0.028	0.283	0.215	15	7
5	scrap	282	12	3384	0.177	0.037	4.53	0.008	0.71	0.012	0.283	0.215	69	18
6	scrap	298	12	3576	0.278	0.039	4.53	0.008	0.71	0.027	0.283	0.215	47	9
7	scrap	294	12	3528	-0.044	0.038	4.53	0.008	0.71	0.023	0.283	0.215	<12	
8	scrap	284	12	3408	0.028	0.036	4.53	0.008	0.71	0.031	0.283	0.215	<12	
9	scrap	284	12	3408	0.023	0.035	4.53	0.008	0.71	0.012	0.283	0.215	<12	
10	scrap	292	12	3504	0.194	0.05	4.53	0.008	0.71	0.028	0.283	0.215	32	10

(e) dismantled fragments as matrix (technique-C example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	dismantled	299	12	3588	4.967	0.064	4.768	0.008	0.71	0.0341	0.288	0.218	668	42
2	dismantled	296	12	3552	4.624	0.081	4.768	0.008	0.71	0.0413	0.288	0.218	514	35
3	dismantled	299	12	3588	5.581	0.083	5.009	0.009	0.93	0.0382	0.288	0.281	519	34
4	dismantled	297	12	3564	0.285	0.041	5.009	0.009	1.1	0.0408	0.288	0.330	21	4
5	dismantled	296	12	3552	6.901	0.082	4.768	0.008	0.71	0.0369	0.288	0.218	859	53
6	dismantled	295	12	3540	0.926	0.043	4.768	0.008	0.98	0.0396	0.288	0.296	79	8
7	dismantled	297	12	3564	0.449	0.038	4.768	0.008	0.71	0.0384	0.288	0.218	54	7
8	dismantled	297	12	3564	0.253	0.038	4.768	0.008	0.71	0.0357	0.288	0.218	32	7
9	dismantled	298	12	3576	5.952	0.065	4.768	0.008	0.71	0.0335	0.288	0.218	814	50
10	dismantled	299	12	3588	0.528	0.041	4.768	0.008	0.71	0.0362	0.288	0.218	67	9

(f) CaF2 precipitates as matrix (technique-C example)

No.	Sample Description	Number of Cycles	Cycle Count Time	Total Count Time	Singles (cps)	Singles Err	BKG (cps)	BKG Err	Declared Enrich. (%)	counting efficiency	weighing factor	neutron emission (n/s/gU)	Neutron Assay (gU)	gU Err
1	CaF2	300	12	3600	53.17	0.14	6.226	0.010	0.71	0.0088	0.283	0.215	28097	1492
2	CaF2	298	12	3576	49.10	0.14	6.226	0.010	0.71	0.0074	0.283	0.215	30811	1644
3	CaF2	300	12	3600	36.05	0.11	6.226	0.010	0.71	0.0077	0.283	0.215	21893	1167
4	CaF2	297	12	3564	13.87	0.08	6.297	0.010	0.99	0.0078	0.283	0.295	6054	337
5	CaF2	295	12	3540	0.19	0.05	6.226	0.010	0.71	0.0080	0.283	0.215	110	32
6	CaF2	298	12	3576	0.78	0.05	6.226	0.010	0.78	0.0082	0.283	0.234	406	44
7	CaF2	297	12	3564	2.19	0.05	6.226	0.010	0.75	0.0097	0.283	0.226	1002	74
8	CaF2	295	12	3540	0.37	0.04	5.716	0.012	0.71	0.0091	0.283	0.215	188	32
9	CaF2	293	12	3516	12.86	0.08	6.226	0.010	0.87	0.0084	0.283	0.260	5908	333
10	CaF2	300	12	3600	55.04	0.14	7.096	0.010	0.71	0.0099	0.283	0.215	25958	1372

[note] Singles=ns-nb

7.3 Uranium Enrichments

In order to estimate the total uranium mass, the weighing factors "Fw" introduced above, and the uranium enrichments were used. Previously, the each enrichment data was supplied from the past archival record with respect to each actual drum units.

However, such uranium enrichment data was so vague and exhaustive that the precise enrichment value could not obtained.

Therefore we applied supplementary method by gamma spectroscopy data analyzed from 186keV peak of U-235 and 1001keV peak of Pa234m, progeny of U-238 used Ge-SSD. This method provides the analysis of individual identification of the uranium enrichment data. The analytical formula is shown in below.

$$IE = \frac{M(U\ 235)}{M(U\ 235) + M(U\ 238)} \times 100 \qquad \text{---- (Equation-4)}$$

$$M(U\ 235) = \frac{PA(186\ keV)}{t \times \varepsilon(186\ keV) \times \eta(186\ keV) \times SA(U\ 235)}$$

$$M(U\ 238) = \frac{PA(1001\ keV)}{t \times \varepsilon(1001\ keV) \times \eta(1001\ keV) \times SA(U\ 238)}$$

where IE:uranium enrichment(%)
M:uranium mass(gU)
PA:peak count rate(cts)
t:counting time(sec)
ε :counting efficiency(-)
η :gamma ray emission branch(-)
SA:specific activity(Bq/gU)

The trial for individual identification of uranium enrichment used Ge-SSD was performed. It was successfully analyzed the uranium enrichment within 20% error by counting ratio of 186keV and 1001keV peaks of gamma ray spectrometry. The example data analyzed uranium enrichment is shown in **Table-11.** The typical gamma ray spectrums are shown in **Figure-24.**

But unfortunately some data was failed in analyzing because of so much error.

Furthermore, by improving the shielding conditions, it is expected to realize the low background condition.

Table-11　Analyzed Uranium Enrichment (example)

No.	Sample Description	meas. time (sec)	a)186keV (cts)	Err (1sigma)	b)1001keV (cts)	Err (1sigma)	a)186keV (cts/s)	b)1001keV (cts/s)	a)U235 (gU)	b)U238 (gU)	Calcul. Enrich a/a+b	Calcul. Enrich Err
1	CaF2	3600	1.1E+6	1.7E+3	2.6E+5	5.3E+2	2.9E+2	7.1E+1	6.0E+1	8.2E+3	7.2E-3	6.8E-5
2	CaF2	3600	7.1E+5	6.3E+3	2.3E+5	5.1E+2	2.0E+2	6.5E+1	4.0E+1	7.5E+3	5.4E-3	2.1E-4
3	CaF2	3600	1.2E+6	1.7E+3	2.4E+5	6.2E+2	3.3E+2	6.7E+1	6.6E+1	7.7E+3	8.6E-3	8.5E-5
4	CaF2	3600	3.4E+5	8.9E+2	4.9E+4	2.3E+2	9.3E+1	1.3E+1	1.9E+1	1.6E+3	1.2E-2	2.2E-4
5	CaF2	36000	6.3E+3	4.8E+2	1.4E+3	1.1E+2	1.8E-1	3.8E-2	3.6E-2	4.3E+0	8.3E-3	3.3E-3
6	CaF2	3600	1.4E+4	2.2E+2	2.5E+3	7.1E+1	3.8E+0	6.9E-1	7.7E-1	8.0E+1	9.5E-3	1.1E-3
7	CaF2	3600	4.0E+4	2.4E+2	7.7E+3	9.0E+1	1.1E+1	2.1E+0	2.3E+0	2.5E+2	9.2E-3	3.9E-4
8	CaF2	36000	7.1E+3	4.0E+2	1.9E+3	1.9E+2	2.0E-1	5.2E-2	4.0E-2	6.0E+0	6.7E-3	2.6E-3
9	CaF2	3600	2.4E+5	2.0E+3	4.0E+4	2.3E+2	6.7E+1	1.1E+1	1.4E+1	1.3E+3	1.1E-2	4.1E-4
10	CaF2	3600	6.8E+5	6.4E+3	2.1E+5	6.3E+2	1.9E+2	5.8E+1	3.8E+1	6.7E+3	5.7E-3	2.3E-4

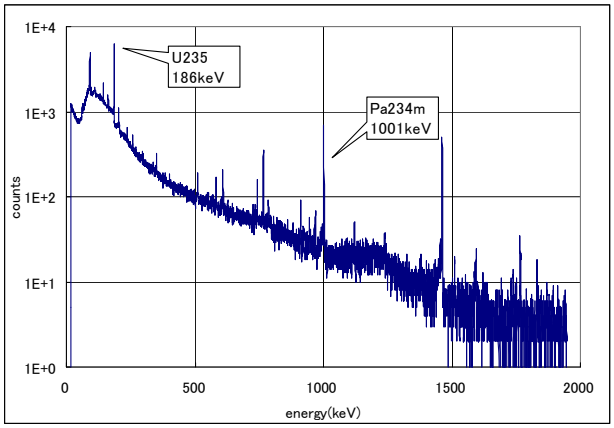


Figure-24　Typical Gamma Ray Spectrums

8. Results and Discussion

8.1 Measurement for the Actual Wastes Drums

In order to respond actively to the needs concerning measurements work of actual uranium wastes drums described above, we have been continuing the measurement for one year. Through those experiences, it was learned the difficulty of NDA measurements, that is to say, to predict the characteristics of unknown wastes drums accurately. The availability of some method was found described below.

i) A methodology using definite weighing factor "Fw" is applicable to the matrix known and averaged bulk density constant (=technique-A)

ii) A methodology using variable weighing factor "Fw" is applicable to the matrix known and averaged bulk density varying (=technique-B)

iii) A methodology using "AAS method" is applicable to the matrix unknown or mixed and averaged bulk density varying (=technique-C)

In particular, the technique-A was used for the wastes drums filled with sodium fluorides pellets or alumina (aluminum oxides) pellets. The technique-B was used for the wastes drums filled with steel fragments and pipes generated from dismantling URCP plants. The technique-C was used for the wastes drums filled with complex scraps (steels, vinyl chloride material and so on) generated from dismantling or calcium fluorides precipitates generated from disposal effluent treatments.

Therefore, the multiple analytical methods are required not exclusively based on the mockup test. In next section, we discuss on the some examples for corresponding the status of actual wastes drums.

If compared between these methodologies, technique-A is the simplest and supreme method than others in the aspect of the measurement accuracy as is index of relative error. The technique-B which is modified technique-A partially is subsequent. The technique-C has the applicability to "unknown matrix wastes drums", but there often appear the accumulated errors owning to some calculation steps.

In conclusion, it is necessary to consider the technique-A,B,C in turn, if needed the choice of analyzing methodology.

8.2 Applicability to the Actual Wastes Drums

Described above the methodology for measuring and analyzing uranium mass are now establishing. We are now convincing the applicability to almost all actual wastes drums in URCP. However we don't mean to say that there are no problems around this methodology.

There is no denying it remains some actual drums which are not applicable to this methodology.

In fact some actual wastes drums contain significant amount of water content (up to

50%), so hydrogen atoms in water would possibly interfere neutron detection. The methodology for accurate measuring such drums is to be purchased surely.

From the beginning, the differences of neutron response between fluorides and oxides are to so much, one order or more, noted by LANL. **[Ref-2]** Contrary to that, experimental neutron response data of oxides found to be 60-80% against that of fluorides approximately. These facts will support the potentiality to measure against uranium oxides wastes.

We do not refer to a decisive basis, however it's an interesting situation to reconsider the neutron emission rate of uranium oxides by (α,n)reaction. That is to say, the neutron emission rate of uranium oxides by (α,n)reaction are comparable to that of fluorides considering the contribution of oxygen-18 whose content is 0.205% with higher cross section of (α,n)reaction than oxygen-16. If so our results, shown in **Figure-13** concerning the uranium mass declared versus neutron emission rate, would be extremely valid.

9. Further Study

9.1 Reducing Background Counting

Through the past tests, it has been recognized that the records of neutron background rate are apt to fluctuate within certain periods. It is assumed that they are caused by cosmic rays, however there may be no way to reduce cosmic rays. Especially Ningyo-toge is located at high altitude area. In order to reduce the neutron background rate another measurement concept is required. Currently, we focus on the time analysis method which are capable to separate (α,n) pulse from the cosmic rays. If this is promising, it is expected to be less neutron background rate conditions.

9.2 Expanding the Measurements Objects

We have been pursued the measurements method and the parameters for the measurement of the wastes drums contained uranium fluorides as source, because the almost all wastes drums in URCP are suggested to be contaminated by uranium fluorides. However, if NWAS would be used in other uranium plants another parameters would be prepared according to uranium compounds such as uranium oxides and so on. We have verified to apply the wastes drums contained uranium fluorides as source, so the further efforts are required to apply the wastes drums contained other uranium compounds as source by the same way.

Furthermore, it is inevitable to be required to achieve the potentiality that the uranium assay tools must be applicable for all kind of uranium wastes, especially “unknown sources and unknown matrices”. In fact, that is the absolute requirements of the inspection tools as is often suggested by IAEA. The AAS method as was described

above, is the one of the promising way.

We should make not only this method but also we think that some other way would be purchase near future.

10. Conclusion

Currently, we are accumulating the precious experiences of the operation NWAS in not only basic tests but also trials for the actual wastes drums. We have received assurance that the NWAS measurement system for neutron passive assay is available to determine uranium mass contained in the uranium wastes drum generated in URCP. Based on the broad basic data obtained hitherto, we will spread the applied field around the actual wastes drums.

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

[Ref-3] JAERI 1324 The data book for neutron yields derived from (α,n) reaction and spontaneous fission, JAERI 1323 (1992)

[Ref-4] LA-UR-01-6761, INCC Software Users Manual (2005)

[Ref-5] private communication from Dr..Beddingfield, Jul/2010

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	$1\ γ=1\ nT=10\text{-}9T$
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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