

STR – 368

STR

International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials

Vienna, November 2010



IAEA

International Atomic Energy Agency

International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials

Mr K. Zhao	IAEA
Mr M. Penkin	IAEA
Ms C. Norman	IAEA
Mr S. Balsley	IAEA
Mr K. Mayer	ESARDA/WGDA
Mr P. Peerani	ESARDA/WGNDA
Mr C. Pietri	ANSI/INMM 5.1
Mr S. Tapodi	ISO TC 85/SC5
Mr Y. Tsutaki	Japanese ITV-2010 Expert Group
Mr M. Boella	EURATOM
Mr G. Renha Jr.	ABACC
Mr E. Kuhn	Consultant

November 2010

“This report is produced under the auspices of the International Atomic Energy Agency. It is based on all information and knowledge available to the author(s) but does not necessarily reflect the policy expressed or implied by the IAEA or its Member States.”

Abstract

This issue of the International Target Values (ITVs) represents the sixth revision, following the first release of such tables issued in 1979 by the ESARDA/WGDA. The ITVs are uncertainties to be considered in judging the reliability of analytical techniques applied to industrial nuclear and fissile material, which are subject to safeguards verification. The tabulated values represent estimates of the 'state of the practice' which should be achievable under routine measurement conditions. The most recent standard conventions in representing uncertainty have been considered, while maintaining a format that allows comparison with the previous releases of the ITVs. The present report explains why target values are needed, how the concept evolved and how they relate to the operator's and inspector's measurement systems. The ITVs-2010 are intended to be used by plant operators and safeguards organizations, as a reference of the quality of measurements achievable in nuclear material accountancy, and for planning purposes. The report suggests that the use of ITVs can be beneficial for statistical inferences regarding the significance of operator-inspector differences whenever valid performance values are not available.

Table of Contents

ABSTRACT.....	1
TABLE OF CONTENTS.....	3
<i>List of Figures</i>	<i>4</i>
<i>List of Tables.....</i>	<i>4</i>
<i>List of Acronyms.....</i>	<i>5</i>
1. INTRODUCTION	7
2. SAFEGUARDS ACCOUNTANCY AND VERIFICATION MEASUREMENTS.....	11
3. EVALUATION OF SAFEGUARDS ACCOUNTANCY VERIFICATION MEASUREMENTS.....	15
4. GUM AND THE USE OF ITVs BY MEASUREMENT LABORATORIES.....	19
5. THE INTERNATIONAL TARGET VALUES 2010	21
6. STRUCTURE AND CONTENT OF THE ITVs -2010.....	23
7. USE OF ITVs	35
8. ORGANIZATIONS INVOLVED.....	41

List of Figures

<i>Figure 1</i>	<i>Accountancy and Verification Measurement Scheme for Item i during Inspection j</i>	13
-----------------	---	----

List of Tables

<i>Table 1</i>	<i>Measurement Method/Instrument Codes</i>	24
<i>Table 2</i>	<i>Bulk and Density Measurements</i>	25
<i>Table 3</i>	<i>Sampling Uncertainties for Element Concentration and ^{235}U Abundance</i>	26
<i>Table 4a</i>	<i>Uranium Element Concentration Measurements (DA)</i>	27
<i>Table 4b</i>	<i>Plutonium Element Concentration Measurements (DA)</i>	28
<i>Table 5a</i>	<i>^{235}U Abundance Measurements (DA)</i>	29
<i>Table 5b</i>	<i>^{235}U Abundance Measurements (NDA)</i>	30
<i>Table 6</i>	<i>Plutonium Isotope Assay of Pu and U/Pu materials</i>	31
<i>Table 7a</i>	<i>Total Mass of ^{235}U (direct NDA)</i>	32
<i>Table 7b</i>	<i>Total Mass of Pu (direct NDA)</i>	33
<i>Table 8</i>	<i>Target Values for Total Pu Mass with Independent Samples and DA</i>	37
<i>Table 9</i>	<i>Target Values for Operator-Inspector Difference on Total Pu Mass, with Common Sample and DA</i>	38
<i>Table 10</i>	<i>Target Values for Operator-Inspector Difference</i>	39
<i>Table 11</i>	<i>Consultants and Observers (CGM March 2010)</i>	41

List of Acronyms

ABACC	Agencia Brasileiro-Argentina de Contabilidade e Controle de Materiais Nucleares
ANSI	American National Standards Institute, USA
BIPM	International Bureau on Weights and Measures
CGM	Consultants' Group Meeting
D	MUF difference estimate
DA	Destructive Analysis
EQRAIN	Programme d'Evaluation de la Qualité des Résultats d'Analyse dans l'Industrie Nucléaire, CETAMA, France
ESARDA	European Safeguards Research and Development Association
ESARDA/WGDA	ESARDA Working Group on Techniques and Standards for Destructive Analysis
ESARDA/WGNDA	ESARDA Working Group on NDA methods
GS	Gamma spectrometry
GUM	Guide to the Expression of Uncertainty in Measurement
HEU	High enriched uranium (^{235}U abundance $\geq 20\%$)
IAEA	International Atomic Energy Agency
IEC	International Electrochemical Commission
IFCC	International Federation of Clinical Chemistry and Laboratory Medicine
INMM	Institute of Nuclear Materials Management, USA
ISO	International Organization for Standardization, Geneva, Switzerland
ISO/TC85/SC5	ISO/TC85 Subcommittee 5 on Nuclear Measurements
ISO/TC85/SC5/WG1	Working Group on Analytical Methodology in the Nuclear Fuel Cycle
ITVs	International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials
IUPAP	International Union of Pure and Applied Physics
JCGM	Joint Committee for Guides in Metrology
LEU	Low enriched uranium ($0.7\% < ^{235}\text{U}$ abundance $< 20\%$)
LSD	Large Size Dry Spike for Isotope Dilution Mass Spectrometry
LWR	Light Water Nuclear Reactor
MOX	Mixed Uranium/Plutonium Oxide Nuclear Fuel Material
MUF	Material Unaccounted For
NDA	Non-Destructive Analysis
NRTA	Near Real Time Accountancy
OIML	International Organization of Legal Metrology
QA	Quality Assurance
QC	Quality Control
SAGSI	IAEA Standing Advisory Group on Safeguards Implementation
SI	International System of Measurement Units
VIM	International Vocabulary of Metrology
XRFA	X-ray fluorescence analysis

1. Introduction

Safeguarding nuclear material involves a quantitative verification of the accountancy of fissile materials by independent measurements. The effectiveness of these verifications depends to a great extent upon the quality of the accountancy measurements achieved by both the facility operator and the safeguards inspectorate. For this reason a typical safeguards agreement based on INFCIRC/153¹ stipulates that:

The Agreement should provide that the system of measurements on which the records used for the preparation of reports are based shall either conform to the latest international standards or be equivalent in quality to such standards.

Although the above requirement is directed to the facility operators, it indeed applies equally well to the safeguards inspectorates.

The International Atomic Energy Agency (IAEA) had defined in the 1970s a set of international standards of nuclear material accountancy², which lists the 'values of measurement uncertainty expected for closing a material balance' for five different types of nuclear facilities. In the absence of relevant international standards of measurements, safeguards evaluators, as well as plant measurement specialists, need references regarding the performance capabilities of measurement methods used for the determination of the volume or mass of a material, for its sampling, and for its elemental and isotopic assays. Such information is needed for the various nuclear materials encountered in the nuclear fuel cycle.

The Working Group on Techniques and Standards for Destructive Analysis (WGDA) of the European Safeguards Research and Development Association (ESARDA) pioneered the way in 1979 by presenting a list of 'Target Values' for the uncertainty components in destructive analytical methods³ to the safeguards authorities of Euratom and of the IAEA. Revised estimates were prepared in collaboration and published as the 1983 Target Values⁴ after four years of extensive discussion and consultation with and within operators' laboratories and safeguards organizations. The international acceptance of the concept grew further with the next review, which involved, besides the ESARDA/WGDA and IAEA, the active participation of the members of two specialized committees of the Institute of Nuclear Materials Management (INMM). The 1987 Target Values, published as a result of this review⁵, defined, as in the previous editions, the values of 'random' and 'systematic' error parameters to be aimed for in elemental and isotopic analyses of the most significant types of materials using common

¹ INTERNATIONAL ATOMIC ENERGY AGENCY, The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons. INFCIRC/153 (corrected), para. 55 Vienna (1972).

² INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safeguards Glossary, 2001 edition, para. 6.35, International Nuclear Verification Series No. 3, Vienna (2002).

³ DE BIEVRE, P., DE REGGE, P., "1979 Target Values for uncertainty components of destructive analysis methods", Minutes of the Meeting of the ESARDA/WGDA in Brussels, April 23-24, 1979, SCK, Mol, Belgium (1979).

⁴ DE BIEVRE, P., et al., 1983 Target Values for uncertainty components in fissile element and isotope assay, ESARDA Bulletin 6 (1983) 1.

⁵ DE BIEVRE, P., et al., "1987 Target Values for uncertainty components in fissile isotope and element assay", (IAEA Proc. Symp. Nucl. Safeguards Technology Vienna, 1986), IAEA, Vienna (1987) 649-662.

destructive analytical methods. The same groups took a new step in the 1988 edition⁶ when they agreed to define the values of the random error parameter to be met in the elemental assays as a result of sampling.

Following a 1988 recommendation of the IAEA Standing Advisory Group on Safeguards Implementation (SAGSI), the IAEA convened a Consultants Group Meeting in June 1991 to provide expert advice on international standards of measurements applicable to safeguards data. A concept of International Target Values (ITVs) was proposed on the model of the 1988 ESARDA Target Values and included estimates of the 'random and systematic error' uncertainties originating from the measurements of volumes or masses of nuclear materials. The scope of ITVs was also extended beyond destructive analysis (DA) methods to include non-destructive assay (NDA) methods, which had won acceptance as accountancy verification tools.

Specialists from four continents took part in the discussion of the proposed concept. The result was the publication of an IAEA Safeguards Technical Report in March 1993, entitled '1993 International Target Values for Uncertainty Components in Fissile Isotope and Element Accountancy for the Effective Safeguarding of Nuclear Materials'⁷. Articles in the ESARDA Bulletin⁸ and in the Journal of the INMM⁹ widely publicized the IAEA technical report. The report itself was translated into Japanese¹⁰.

In 2000, international experts reviewed the experience gained with the use of the 1993 ITVs and the progress made in accountancy and safeguards verification measurements. Subsequently, 'International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials' was published as an IAEA Safeguards Technical Report in April 2001¹¹, in the ESARDA Bulletin¹² and by INMM¹³.

Each ITV bears a date, reflecting a recognition that the quality of measurements may change and that new methods and instruments may be developed and implemented. The ITVs also reflect the current understanding of the structure of the uncertainty components in nuclear material accountancy measurements which may change in the future as this understanding improves or varies.

In preparation for the ITVs-2010 the IAEA conducted 'Verification Measurement Performance

⁶ DE BIEVRE, P., et al., "Random uncertainties in sampling and element assay of nuclear materials; target values 1988", ESARDA Bulletin 13 (1987) 8.

⁷ KUHN, E., et al., "1993 International Target Values for Uncertainty Components in Fissile Isotope and Element Accountancy for the Effective Safeguarding of Nuclear Materials", IAEA STR-294, IAEA, Vienna (1994).

⁸ DERON, S., et al., "1993 International Target Values for Uncertainty Components in Measurements of Nuclear Material for Safeguards Purposes", ESARDA Bulletin 23, JRC, Ispra (1994).

⁹ DERON, S., et al., "1993 International Target Values for Uncertainty Components in Fissile Isotope and Element Accountancy for the Effective Safeguarding of Nuclear Materials", Journal of Nuclear Materials Management, Volume XXII, Number II, January 1997.

¹⁰ "1993 International Target Values for Uncertainty Components in Fissile Isotope and Element Accountancy for the Effective Safeguarding of Nuclear Materials", Japanese Translation, Science and Technology Agency, Japan, (1993).

¹¹ AIGNER, H., et al., "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Material", IAEA, STR-327, IAEA, Vienna (2001).

¹² AIGNER, H., et al., "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Material", ESARDA Bulletin 31, JRC Ispra (2002).

¹³ AIGNER, H., et al., "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Material", Journal of Nuclear Materials Management, Vol. XXX, No. 2 (www.inmm.org/itvs/1698.htm).

Evaluations', using data reported by facility operators and the results of independent measurements performed on the same material by the inspectors¹⁴. These historical operator-inspector paired data, accumulated from over 20 years, represent the most relevant and complete set of information. Based on these performance evaluations and the IAEA's experience from using the ITVs-2000, a set of draft ITVs-2010 tables were prepared, which included some changes in the target values, the deletion and addition of analytical techniques or methods, and changes in the format of the tables.

As in the earlier formulation and revision of ITVs, the IAEA counted on the expertise available in the Working Groups for DA and NDA of ESARDA, the ANSI/INMM 5.1 Analytical Chemistry Laboratory Measurement Control Committee, the Working Group 1 on Analytical Methodology in the Nuclear Fuel Cycle of the ISO TC85/SC5 Subcommittee, the Japanese ITV-2010 Expert Group, and the inspectorates of Euratom and ABACC. The above panels and organizations were asked to review the draft document and provide comments. In addition they were asked to report on measurement quality experience, as derived from QC/QA and inter-laboratory programmes, instrument qualification, or from verification activities. Representatives of the above groups and organizations participated in a Consultants Group Meeting, convened at the IAEA in March 2010. Their comments and recommendations are reflected in this document.

As with the previous lists, the ITVs-2010 should be achievable henceforth under the conditions normally encountered in typical industrial laboratories or during actual safeguards inspections. They do not represent the measurement uncertainties, which would only be achieved under exceptional or ideal laboratory conditions, or with most recently developed methods, which have not yet found wide use for daily and routine measurements. It is expected that the ITVs-2010 will continue to be a motivating goal for beginner laboratories and be used as an independent reference for experienced laboratories and safeguards evaluators. With the growing acceptance of modern quality assurance concepts it is suggested that the ITVs-2010 can also constitute a good reference against which analytical laboratories would validate their measurement systems.

¹⁴ L. Bevaart, W. Fuhr, K. Zhao, and E. Kuhn, 'International Target Values for Measurement Uncertainties in Safeguarding Nuclear Materials: preparing for the 2010 Update', 31st ESARDA Annual Meeting, Vilnius, May 25-28, 2009.

2. Safeguards Accountancy and Verification Measurements

Facility accountancy and safeguards verification measurement data are the major source of information on which the ITVs are based. Conversely, the derived ITVs are primarily used to evaluate the accountancy and verification results in safeguards. Therefore, a description of the safeguards measurement system in connection with the sources of uncertainties at each step of the measurement process is important in order to understand how the derived ITVs should be interpreted.

Figure 1 describes the basic measurement scheme followed in safeguards verification measurements. For each inspection, j , the inspector selects, in accordance with a random sampling plan, the items or batches of nuclear materials to be verified by an independent measurement. The inspector then compares the result of the verification measurement, Y_{ij} , to the result, X_{ij} , which the operator has obtained on the same batch or item, i , and which the operator has declared to the inspectorate. The ability of the inspector to detect whether the difference d_{ij} is significantly different from zero depends upon the overall uncertainties in the results X_{ij} and Y_{ij} . Figure 1 identifies the major steps of the measurement process where uncertainties can arise, although not all steps may be relevant for every method (e.g., several of the steps may be omitted or combined under a single step for NDA methods).

Step 1 corresponds to the measurement of the volume or mass of the item or batch of material. This so-called '*bulk*' measurement, when needed, takes place in the plant area and involves a calibration procedure.

Step 2, the '*sampling*', involves removing, for the purpose of the analytical measurement, a representative portion of the material from the batch or item to be analyzed. This may be a complete item in the case of an NDA measurement.

Step 3 concerns the precautions which must be taken in the way the sample is '*conditioned*' and packaged at the sampling station so that all characteristics to be measured are preserved during its transport to the location or laboratory where the characteristics will be measured. For instance, the '*conditioning*' of powder or solution samples must include a weight measurement to facilitate a correction for weight changes between sampling and analysis.

Step 4, the '*shipment*', is the transport of the sample to the location where it can be measured.

Step 5, the '*treatment*', is intended to bring the sample into the most appropriate geometrical, physical and/or chemical form for the measurement. The treatment of a sample taken for destructive analysis may involve a sequence of individual steps, such as sub-sampling, dissolution, dilution, spiking, chemical treatment or chemical separation, etc.

Step 6 represents the '*measurement*' itself. In general terms, a measurement is based on a calibration from which the parameters linking the observed signal and the measurand are determined. Typical examples are HLNC calibration curves for Pu mass determination, calibrations of gamma spectrometers for ^{235}U abundance determination, or the determination of the mass-discrimination correction factor for a mass-spectrometer. The standardization of a titrant solution is another example of a calibration, although it is frequently not recognized as such. Calibration functions may be as simple as a single calibration factor (actually representing a straight line through the origin), or may be complex and represented by an empirically determined calibration curve. Calibrations based on recognized references, such as certified reference materials or well-known physical constants, establish the traceability chain between

the measurement result and the International System of Units (SI). Calibrations may be valid and used without modifications for a long time, repeated on a daily basis or even performed with each individual measurement. Sometimes, elaborate calibration exercises for determining the fundamental characteristics of the calibration function are combined with more frequently repeated ‘normalization’ measurements to correct for short-term effects or minor deviations from the overall calibration function at the specific working range.

Step 7, the ‘*calculation*’, consists in transforming the results of the physical or chemical measurement obtained in the preceding step into an estimate of the amount of fissile element or isotope in item or batch i . Particularly when the operator and inspector use DA, this involves estimating the total element content, by combining the result of the bulk measurement w_{ij} with the elemental concentration c_{ij} . In the case of Uranium materials, this is combined with the isotope abundances f_{ij} of the fissile isotope (^{235}U or ^{233}U) to yield a measure of the amount of fissile isotope in item or batch i , according to equations (1) and (2), respectively.

$$X_{ij} = w(O)_{ij} \cdot c(O)_{ij} \cdot f(O)_{ij} \quad (1)$$

$$Y_{ij} = w(I)_{ij} \cdot c(I)_{ij} \cdot f(I)_{ij} \quad (2)$$

Every stage of the process, starting with bulk measurements, must be performed under well-controlled conditions. Hence, quality control measures are imperative at every step of the process. Quality control on sampling can be done by taking replicate samples after different mixing times or taking samples from a number of items of the same batch of bulk materials. Quality control materials or samples can be introduced at specific steps to monitor the quality of the whole process or any part of it, including the conditioning and shipment steps. Figure 1 shows an example where control materials are used independently by the operator and the inspector to check the quality of the processes following the sampling. Quality control measures should be performed in the frame of a documented quality system.

The uncertainties in the measurements of element concentrations and isotope abundances in the ITVs refer to the combined effects of the uncertainties in Steps 3 to 6 occurring after the taking of the sample in Step 2.

Step 8, the ‘*reporting*’ of the results, is purely clerical but unfortunately it can be a source of errors. Uncertainties arising from such errors are not considered in the ITVs proposed in this document. Yet it is essential that appropriate quality assurance measures be taken to avoid the occurrence of clerical errors.

When NDA is used, attention is mostly focused on the measurement (Step 6), as the preceding steps have usually less impact or may even be omitted. For example, bulk measurements and sampling are not needed if the NDA method allows direct measurement of the total amount of fissile element or isotope contained in a whole item or batch of nuclear material, as with various neutron counters.

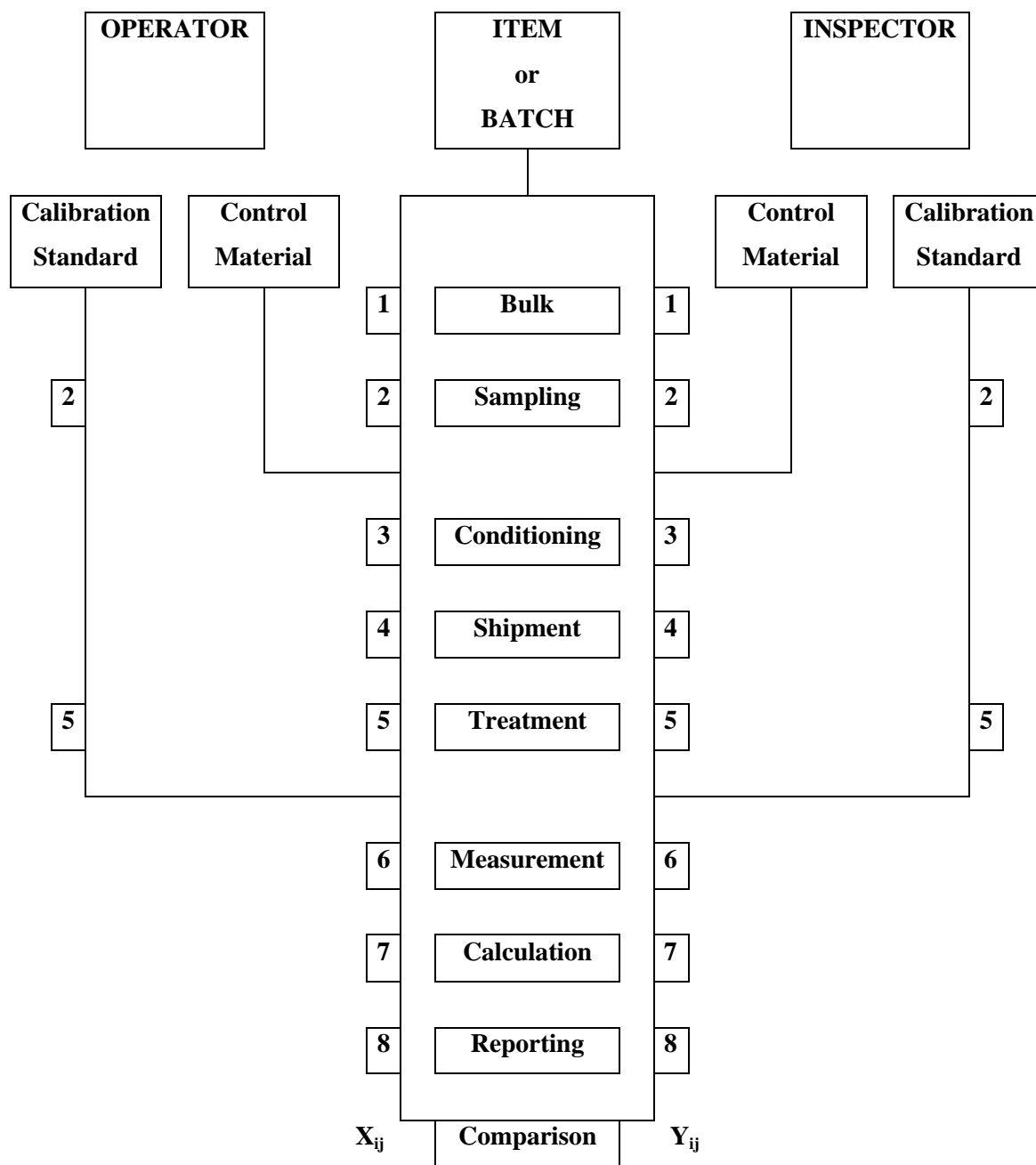


Figure 1. Accountancy and Verification Measurement Scheme for Item i during Inspection j

3. Evaluation of Safeguards Accountancy Verification Measurements

Nuclear material accountancy involves measurement systems for the determination of particular quantities of interest (**measurands**) such as the net weight or volume of an item (bulk measurement), the elemental and/or isotopic concentration for sampled material, and, in the case of NDA, the mass of nuclear material in an item.

Measurement errors are inherent to all the accountancy measurement results for both operators' declarations and inspectors' verification. The **measurement error** of a given result, defined mathematically as the result minus the true value, often represents the combined effect of many sources of errors in the measurement system, which might include statistical sampling error, bulk measurement error, material sampling error, analytical error, and other errors.

With regard to the different behaviours of measurement results on nuclear material accountancy, three broad categories of errors related to safeguards applications can be identified as follows^{15, 16}:

- **random error**, varies in an unpredictable way under **repeatability conditions**, i.e., conditions where independent results are obtained with the same method on identical items using the same equipment by the same operator within short intervals of time. Counting statistics or the repeatability of measurements under constant conditions are typical examples of random errors. The effects of random errors can be reduced by repeated measurements, but it is not possible to correct random errors.
- **bias**, remains constant under **reproducibility conditions**, i.e., conditions where results are obtained using the same method on identical items when using different equipment operated by different operators.
- **short-term systematic error**, remains constant for a short term when measurement conditions or settings, typically expressed as parameters such as calibration curves, normalization parameters, subtracted background, etc., are not altered while varying in an unpredictable way on a long-term perspective due to the random changes of these conditions or settings.

Uncertainty is a statistical parameter, associated with the result of a measurement, to characterize the dispersion of measurement values that could reasonably be attributed to a measurand. This parameter may be a standard deviation, in which case the uncertainty is called standard uncertainty, or the width of a confidence level. In the context of expressing uncertainties in safeguards accountancy measurements, **random uncertainty component, $u(r)$** , and **systematic uncertainty component, $u(s)$** , are simply defined as the standard deviations of the random errors and short-term systematic errors, respectively.

The operator-inspector paired differences are examined to determine whether they are commensurate with the characteristic uncertainties of the operators' and inspectors' measurement systems. For this purpose, the inspectors need to quantify the major uncertainties of the actual data collected during their verification activities.

¹⁵ ISO 3534-1:1993, "Statistics - Vocabulary and Symbols - Part 1: Probability and general statistical terms", ISO Standards Handbook, Statistical Methods for Quality Control, Vol. 1, Fourth Edition, ISO, Geneva, (1995).

¹⁶ BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, International Vocabulary of Basic and General Terms in Metrology, Second Edition, ISO, Geneva, (1993).

A basic assumption for the estimation of the uncertainty components is that $u(r)$ and $u(s)$ are characteristics of the type of material, its chemical and physical form and of the method of measurement. A further assumption is that $u(s)$ is constant for a given inspection period, but that it varies in a random manner from one inspection to another, for both the operator and the inspector.

Consequently, the inspectors group the data pairs, the operator's value X and the inspector's value Y , originating from one inspection period, j , by material balance areas (MBA), by strata of materials of similar characteristics and by measurement methods¹⁷. For a given MBA and stratum, the operator-inspector relative difference, d_{ij} , for item i in inspection j , is given by:

$$d_{ij} = (X_{ij} - Y_{ij}) / X_{ij} \quad (3)$$

where

- $i = 1, 2, \dots, m_j$
- $j = 1, 2, \dots, K$
- K = the number of inspections
- m_j = the number of items verified during inspection j

The assumed error model is given by:

$$d_{ij} = d + \Delta_j + \varepsilon_{ij} \quad (4)$$

where

- d = the mean difference over the K inspections,
- Δ_j = the systematic error of the operator-inspector difference during inspection j , and
- ε_{ij} = the random error of the operator-inspector difference for item i during inspection j .

In addition, the expected values of Δ and ε are assumed to be zero. An analysis of variance of the operator-inspector differences, d_{ij} , according to this model equation, gives the estimates of the variance $s^2(\varepsilon)$ of the random component and of the variance $s^2(\Delta)$ of the systematic component within the given inspection period¹⁸. In performing this analysis of variance, it is generally assumed that Δ_j and ε_{ij} are normally distributed and that the variances of the random error are the same for all inspections. The set of results are therefore screened for outliers prior to performing this evaluation.

Paired comparisons of this type are done separately for bulk measurements, element concentrations and isotope abundances, as well as for the masses of fissile elements and isotopes. Under the assumption that the errors of the operator and of the inspector are independent from each other, one obtains, for each type of measurement, an estimate of the combination of the actual uncertainty components for the operator's and inspector's measurement systems:

$$s^2(\varepsilon) = u^2(r, O) + u^2(r, I) \quad (5)$$

$$s^2(\Delta) = u^2(s, O) + u^2(s, I) \quad (6)$$

where $u(r, O)$ and $u(r, I)$ are the standard random uncertainty components, and $u(s, O)$ and $u(s, I)$ are the standard systematic uncertainty components for the operator and the inspector respectively.

¹⁷ IAEA, "Statistical Concepts and Techniques for IAEA Safeguards", Fifth Edition, IAEA/SG/SCT/5, IAEA, Vienna (1998)

¹⁸ JAECH, J.L., "Statistical analysis of measurement errors", Wiley, New York (1985).

In one simplified situation where the operator's and inspector's uncertainty parameters can be assumed to be equal as a result of using similar measurement methods, $u(r)$ and $u(s)$ can be determined based on $s^2(\varepsilon)/2$ and $s^2(\Delta)/2$, respectively, for both the operator and the inspector. In another simplified situation where the operator's DA results may be compared with much less precise and/or accurate inspector's results obtained for example by some NDA methods, $u(r,I)$ and $u(s,I)$ can be estimated based on $s^2(\varepsilon)$ and $s^2(\Delta)$, respectively, whereas $u(r,O)$ and $u(s,O)$ must be derived from a comparison with inspector's measurements also obtained by DA.

In the IAEA data analysis, various statistical techniques¹⁷ applicable to more general cases are used to derive separate estimates of the operator's and inspector's uncertainty parameters based on the collection of historical operator-inspector differences. The results of these evaluations are 'Performance Values' obtained for each MBA/stratum/measurement method combination. These Performance Values, which are generally updated once a year as more historical data becomes available for DA and NDA, are used in planning inspections¹⁹ and in drawing inferences based on the operator's declared values and the inspector's verification measurement values. There are, however, situations where insufficient historical data is available to derive Performance Values. In these instances ITVs are used until sufficient measurement data are accumulated.

The most recent 'Performance Values' are the basis for updating the two columns of random and systematic uncertainty components, $u(r)$ and $u(s)$, in this ITV-2010 document for each measurement method. New to the ITV-2010 document is a column labelled ITV, which reflects an internationally-adopted standard approach to measurement uncertainty evaluation (*Guide to the Expression of Uncertainty in Measurement* – GUM). This column complements the use of ITVs in the evaluation of operator-inspector data and is provided as a reference for the laboratories.

¹⁹ JAECH, J., Russell, M., Algorithms to Calculate Sample Sizes for Inspection Sampling Plans, STR-261, Rev. 1, IAEA, Vienna (1991).

4. GUM and the use of ITVs by measurement laboratories

The current *Guide to the Expression of Uncertainty in Measurement* (GUM) was published in 2008 by the Joint Committee for Guides in Metrology (JCGM) in the name of the JCGM member organisations (BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML) as JCGM 100:2008²⁰.

The goal of the GUM is to provide measurement laboratories with a standardized, methodical approach to determining a quantitative statement of the measurement uncertainty associated with a measurement result. This standardized approach helps to ensure inter-comparability of results between methods and laboratories, ensures transparency (and traceability) in calculation, and by design adds some additional assurance that laboratories are identifying significant contributors to their measurement's uncertainties. This approach has been adopted by many safeguards laboratories and provides important information to laboratory operators and internal and external evaluators. The GUM is not intended to replace quality control systems or other data verification/validation schemes, but to provide laboratory staff, measurement data users, and regulators with useful, comparable information regarding the performance of particular measurement methods on particular sample types.

The GUM approach consists of modelling the measurement process using mathematical relationships between a measurand and its input quantities, and determining the combined standard uncertainty for a measurement result using the standard procedure of error propagation from the standard uncertainties of the input quantities based on expert knowledge, QC data or other means, and reporting the result with the inclusion of the expanded uncertainty (a coverage factor multiplied by the combined standard uncertainty). In addition, it is recommended that the uncertainty budget or a statement indicating the significant contributors to the uncertainty, and the model equation(s) used be provided.

Typically, a laboratory will establish GUM uncertainties for each of its measurement methods during method validation. Once a GUM evaluation has been completed, the laboratory may choose to monitor the performance of the method and the constraints on those input quantities which affect the uncertainty (e.g. temperature) over a specified period of time or number of measurements and either re-calculate the uncertainty for each measurement using a template, or report a conservative 'stock' uncertainty that is validated by comparing the latest set of results with the previously validated results to ensure the measurement uncertainty remains unchanged. Thus, users do not have to perform a complete GUM uncertainty evaluation every time they perform a routine measurement. Non-routine measurements or significant changes in the sample, calibration standards, or measurement system would require a re-evaluation of measurement uncertainty.

The use of GUM uncertainties in inter-laboratory comparisons is particularly useful for participants and regulators, as it allows all users to immediately compare performance between facilities for the variety of methods and samples in use. The GUM uncertainties in this case may serve as good representations of typical measurement uncertainties achievable by comparable laboratories with real-world samples.

According to GUM, uncertainty is a statistical parameter associated with the result of a measurement to characterize the dispersion of measurement values that could reasonably be

²⁰ JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, Joint Committee for Guides in Metrology.

attributed to a measurand. This ITV-2010 document seeks to link the GUM approach essential for the measurement laboratories with the needs of the evaluators. The GUM does not have the concept of a random and systematic uncertainty component²⁰, as described earlier.

For this reason, new to the ITV-2010 document, the column labelled 'ITV' provides safeguards laboratories with additional useful information, reflecting the combination of the $u(r)$ and $u(s)$ parameter. This is provided as a useful reference for the laboratories, and reflects a state-of-the-practice reasonable expanded uncertainty under routine measurement conditions.

5. The International Target Values 2010

The International Target Values 2010 for Measurement Uncertainties (ITVs-2010) are values for uncertainties associated with a single determination result, e.g., this may be the result reported by one laboratory on one sample (independent of the analytical scheme applied internally in the laboratory), or the result of an NDA measurement performed on a single item. The ITVs-2010 take into account actual practical experiences and should be achievable today under the conditions normally encountered in typical industrial laboratories or during safeguards inspections.

In preparation for the update of the ITVs-2000, the IAEA conducted ‘Verification Measurement Performance Evaluations’, using data reported by facility operators and the results of independent verification measurements¹⁴. The IAEA’s database, consisting of operators’ declared and inspectors’ verified data, most likely represents the largest data set of results obtained for the various types of industrial materials and by the most commonly used measurement techniques. Based on these performance evaluations and the IAEA’s experience in using the ITVs, a set of draft ITVs-2010 tables were prepared and distributed to the Working Groups for DA and NDA of ESARDA, the ANSI/INMM 5.1 Analytical Chemistry Laboratory Measurement Control Committee, the Working Group 1 on Analytical Methodology in the Nuclear Fuel Cycle of the ISO TC85/SC5 Subcommittee, the Japanese ITV-2010 Expert Group, and the inspectorates of Euratom and ABACC for review and discussion.

In addition the above panels and organizations were asked to report on measurement quality experience, as derived from QC/QA and inter-laboratory programmes^{21, 22, 23}, instrument qualification, or from verification activities. Representatives of the above groups and organizations participated in a Consultants’ Group Meeting (CGM), convened at the IAEA in March 2010.

The ITVs-2010 were thus selected by the CGM on the basis of a critical discussion of the inspectorates’ performance evaluations of actual historical data and their comparison with the ITVs-2000. They were also chosen to be consistent with uncertainty assessments available from experimental validation of measurement methods and instrumentation, from inter-laboratory measurement evaluation programmes, or from individual laboratories.

The ITVs-2010 are applicable to the accountancy data collected by the inspectorates. They do not represent the ultimately achievable performance of a measurement system, which would be obtained under exceptional or ideal laboratory conditions. However, they reflect reasonably well the progress observed during the past several years in the routine performance of measurements carried out for the purpose of material accountancy and verification.

The ITVs-2010 also intend to take into account all sources of measurement uncertainties, including sources which may not be apparent in Performance Values resulting from paired comparisons of operators’ and inspectors’ measurements.

²¹ Safeguards Measurement Evaluation Program, SMEP (www.nbl.doe.gov).

²² Regular European Interlaboratory Measurement Evaluation Programme, REIMEP (<http://irmm.jrc.ec.europa.eu>).

²³ Évaluation de la Qualité des Résultats d’Analyses dans l’Industrie Nucléaire, EQRAIN (www-cetama cea.fr).

6. Structure and Content of the ITVs-2010

The presentation of the 2000 ITVs involved seven different tables. Based on the experience in using them, a different format was chosen for the presentation of the ITVs-2010, which now include the following 10 tables:

Table 1	Measurement Method/Instrument Codes
Table 2	Bulk and Density Measurements
Table 3	Sampling Uncertainties for Element Concentration and ^{235}U Abundance
Table 4a	Uranium Element Concentration Measurements (DA)
Table 4b	Plutonium Element Concentration Measurements (DA)
Table 5a	^{235}U Abundance Measurements (DA)
Table 5b	^{235}U Abundance Measurements (NDA)
Table 6	Plutonium Isotope Assay of Pu and U/Pu materials
Table 7a	Total Mass of ^{235}U (direct NDA)
Table 7b	Total Mass of Pu (direct NDA)

- Each of the tables 2 and 4a to 7b identifies separate ITVs according to the type of material and measurement method, as appropriate.
- Table 3 lists the $u(r)$ values for the step of sampling nuclear materials. It has not yet been possible to propose $u(s)$ values applicable to sampling, except for a few cases where this parameter was found to be measurable. It should also be noted that random sampling errors were frequently not assessed on the basis of experimental data and are based on expert opinion and facility experience.
- In the tables the two parameters, $u(r)$ and $u(s)$, characterize the quality, which should be aimed for in a specific measurement of a given material using a specified method at a single laboratory; $u(r)$ and $u(s)$ are specific subsets of the combined standard uncertainty comprising all uncertainties arising from random effects and systematic effects, respectively, according to the description in chapter 3.
- New to the ITV-2010 tables is a column labelled **ITV**, which reflects the combination of the $u(r)$ and $u(s)$ parameters.

$$u_c(ITV) = [u(r)^2 + u(s)^2]^{1/2} \quad (7)$$

- The values in the **ITV** column are provided as a reference for the laboratories to allow them to easily compare their measurement uncertainties, estimated by the GUM approach, against the ITVs-2010. They are expressed as relative combined standard uncertainties.

Table 1
Measurement Method/Instrument Codes

Method/Instrument Code	Technique
ALPH	Alpha Spectrometry
AWCC	Active Well Coincidence Counter
CALO	Calorimetry
CMPU	Combined Product Uranium Concentration and Enrichment Assay (COMPUCEA)
COUL	Coulometry
EBAL	Electronic Balance
ELTM	Electromanometer
ENMC	Epithermal Neutron Multiplicity Counter
FRSC	Fuel Rod Scanner
GBAS	Glove Box Assay System
GRAV	Gravimetry
GSMS	Gas Source Mass Spectrometry
HEPC	High Efficiency Passive Counter
HKED	Hybrid K-Edge/K-XRF Densitometer
HLNC	High Level Neutron Coincidence Counter
HMMS	Hulls Monitor and Measurement System
HRGS	High Resolution Gamma Spectrometry
IDMS	Isotope Dilution Mass Spectrometry
IMCG	Inspector Multichannel Analyzer with Ge detector
IMCN	Inspector Multichannel Analyzer with NaI detector
INVS	Inventory Sample Coincidence Counter
KEDG	K-Edge Densitometer
LCBS	Load-cell Based Weighing System
LMCA	Laboratory Multichannel Analyzer (HRGS)
LMCN	Laboratory Multichannel Analyzer (NaI detector)
MCICP	Multi-Collector Inductively Coupled Plasma Mass Spectrometry
MMCG	Mini-Multichannel Analyzer with Ge Detector
MMCN	Mini-Multichannel Analyzer with NaI Detector
PCAS	Plutonium Canister Assay System
PNCL	Plutonium Neutron Coincidence Collar
POLA	Polarography
PSMC	Plutonium Scrap Multiplicity Counter
PUSP	Pu-VI Spectrophotometry
TIMS	Thermal Ionization Mass Spectrometry
TITR	Titration
UBVS	Uranium Bottle Verification System
UNCL	Uranium Neutron Coincidence Collar
USP	Uranium Spectrophotometry
VTDM	Vibrating Tube Density Meter
WDAS	Waste Drum Assay System
XRF	X-ray Fluorescence

Table 2
Bulk and Density Measurements

Measure- ment	Instrument	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
Mass	LCBS	0.05	0.05	0.07	
	EBAL	0.05	0.05	0.07	
Volume ^{1/}	ELTM (Accountability tanks)	0.05	0.1	0.12	<u>2/</u>
	ELTM (Process tanks; high concentration)	0.2	0.2	0.28	<u>3/</u>
	ELTM (Process tanks; low concentration)	1	1	1.4	<u>4/</u>
	ELTM (Accountability tanks)	0.3	0.2	0.36	<u>5/</u>
Density	ELTM (Accountability tanks)	0.05	0.05	0.07	<u>6/</u>
	ELTM (Process tanks; high concentration)	0.1	0.1	0.14	
	ELTM (Process tanks; low concentration)	0.7	0.7	1	
	VTDM	0.05	0.05	0.07	

1/ Volume determinations are made on the basis of level pressure, density and temperature measurements. The volume measurement uncertainties are highly dependent on the homogeneity of the liquid, the quality of the density measurements and of the calibration equation determined in the calibration process. The volume measurements may also involve an absolute error component which has to be taken into consideration when determining the overall uncertainty of volume measurements.

2/ For accountability tanks in newly built large-throughput facilities, uncertainties of 0.05% for u(r) and 0.1% for u(s) at full volume are achievable if: i.) A carefully designed calibration procedure has been implemented under well-controlled environmental and stable temperature conditions; and ii.) Measurements, using high precision electro-manometers, are performed on a well-characterized and homogenized liquid.

3/ Process tanks for high Pu concentration solutions are generally also equipped with high precision electro-manometers, however, the calibration effort and tank design specifications may be lower.

4/ Equipped with standard electro-manometers, lower calibration effort.

5/ The values apply to older facilities where the tank design was not driven by optimized ELTM volume measurement capabilities.

6/ The same comments as given for the volume measurements apply; one additional important calibration parameter is the determination of the probe (dip tube) separation.

Table 3
Sampling Uncertainties
for Element Concentration and ^{235}U Abundance

Material	Uncertainty Component (% rel.)				Minimum Sample Size ^{1/}
	Concentration		²³⁵ U Abundance		
	u(r)	u(s)	u(r)	u(s)	
DUF ₆	0.1	*	1 ^{2/}	1 ^{2/}	5-10 g
NUF ₆ , LEUF ₆	0.05	*	0.1	*	5-10 g
U-oxide Powder	0.2	*	0.05	*	10-20 g
U-oxide Pellets	0.05	0.05	0.05	0.05	1 pellet
U-oxides (with Gd)	0.2	*	0.05	*	1 pellet
U Scrap (clean) ^{3/}	1	*	1	*	30 g
U Scrap (dirty) ^{4/}	10	*	10	*	2x30 g
Reprocessing Input Solution	0.3	0.2 ^{5/}	0.05	*	2x1 mL
High Active Liquid Waste	5	5	*	*	2x1 mL
U Nitrate Solution	0.1	*	0.05	*	10 mL
Pu, U/Pu Nitrate Solution	0.2	*	0.05	*	10 mL
Pu-oxide	0.1	*			2x1 g
FBR MOX	0.2 (Pu) 0.1 (U)	* *	0.1	*	2x1 pellet, or 2x2 g
LWR MOX	0.7 (Pu) 0.1 (U)	* *	0.1	*	2x1 pellet, or 2x5 g
MOX Scrap (clean)	1	*	1	*	2x5 g
MOX Scrap (dirty)	10	*	10	*	2x10 g
HEU Metal and Alloys	0.2	*	0.05	*	1 - 5 g

* Values have not yet been defined.

^{1/} According to STR-69 (Destructive Analysis and Evaluation Services for Nuclear Material Accountancy Verification, STR-69, Rev. 5, IAEA, Vienna, 2004).

^{2/} Additional sampling uncertainties are expected for DUF₆ when samples are taken from the gas phase of a non-homogenized cylinder.

^{3/} Scrap with low impurity content and suitable for recycling.

^{4/} Sampling uncertainties can vary widely depending on material heterogeneity and sample size.

^{5/} Sampling uncertainties of systematic nature, resulting from airlift effects (evaporation).

Table 4a
Uranium Element Concentration Measurements (DA)

Concentration measurements on powders and solutions require weight change correction because of sample instability.

Method	Material	Uncertainty Component		ITV (%rel.)	Notes
		u(r)	u(s)		
GRAV	U (pure compounds)	0.05	0.05	0.07	<u>1/</u>
	U (with Gd)	0.1	0.1	0.14	
TITR ^{2/}	U (pure compounds)	0.1	0.1	0.14	
	U Alloys	0.2	0.2	0.28	
	Mixed U/Pu	0.1	0.1	0.14	
POLA	U (with Gd)	0.05	0.05	0.07	
IDMS	Hot Cell Conditions	0.2	0.2	0.28	<u>3/ 4/</u>
		0.3	0.3	0.42	<u>3/ 5/</u>
	Glove Box Conditions	0.15	0.1	0.18	<u>3/ 4/</u>
		0.2	0.2	0.28	<u>3/ 5/</u>
KEDG	U and U/Pu Solution	0.2	0.2	0.28	<u>6/</u>
HKED	Spent Fuel Solution	0.2	0.2	0.28	<u>6/</u>
XRF	U Solution (low conc.)	2	2	2.8	<u>7/</u>
CMPU	U Compounds	0.2	0.2	0.28	<u>8/</u>
USP	U Solution (low conc.)	2	2	2.8	<u>7/ 9/</u>

1/ Materials containing non-volatile impurities < 1000 ppm.

2/ Davies & Gray Method.

3/ For all materials typically encountered in the nuclear fuel cycle.

4/ Under conditions of sufficiently different isotopic compositions of spike and sample and near optimum sample to spike ratio, using large size spikes (such as LSD).

5/ Under conditions of sufficiently different isotopic compositions of spike and sample and near optimum sample to spike ratio, using small size spikes.

6/ For samples in solution with > 50 g/L U and measurement time of 3 x 1000 sec.

7/ 1 to 50 g/L U.

8/ 200 g/L U in dissolved samples.

9/ For process analysis under hot cell conditions.

Table 4b
Plutonium Element Concentration Measurements (DA)

Concentration measurements on powders and solutions require weight change correction because of sample instability

Method	Material	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
GRAV	Pu Oxide	0.05	0.05	0.07	<u>1/</u>
TITR	Pu Oxide and Nitrate	0.15	0.15	0.21	<u>2/</u>
	U/Pu Oxide and Nitrate	0.2	0.2	0.28	
COUL	Pu (pure compounds)	0.1	0.1	0.14	<u>3/</u>
IDMS	Hot Cell Conditions	0.2	0.2	0.28	<u>4/ 5/</u>
		0.3	0.3	0.42	<u>4/ 6/</u>
	Glove Box Conditions	0.15	0.1	0.18	<u>4/ 5/</u>
		0.2	0.2	0.28	<u>4/ 6/</u>
KEDG	Pu and U/Pu Solution	0.3	0.3	0.42	<u>7/</u>
HKED	Spent Fuel Solution	0.8	0.5	0.94	<u>8/</u>
XRF	Pu Solution (low conc.)	2	2	2.8	<u>9/</u>
PUSP	Process Solutions	2	2	2.8	<u>10/</u>
ALPH	Waste Solution (low conc.)	7	7	10	
INVS	Pu, U/Pu Oxides	2	1	2.2	<u>11/ 12/</u>
ENMC	U/Pu Oxides	1	1	1.4	<u>12/</u>
CALO	Pu, U/Pu Materials	0.4	0.4	0.56	<u>12/ 13/</u>

1/ Materials containing non-volatile impurities < 1000 ppm.

2/ Techniques such as the MacDonald and Savage and the AgO methods.

3/ For samples containing > 25 µg Fe/g Pu correction or chemical separation is required.

4/ For all materials typically encountered in the nuclear fuel cycle.

5/ Under conditions of sufficiently different isotopic compositions of spike and sample and near optimum sample to spike ratio, using large size spikes (such as LSD).

6/ Under conditions of sufficiently different isotopic compositions of spike and sample and near optimum sample to spike ratio, using small size spikes.

7/ For samples in solution with > 40 g/L Pu and measurement time of 3 x 1000 sec.

8/ Typically 150 to 250 g/L U with a U/Pu ratio of 80 to 150 and measurement time of 3 x 1000 sec.

9/ Pu concentration between 1 and 50 g/L.

10/ >0.1 g/L Pu.

11/ Counting time 600 sec.

12/ Pu isotopic composition determination by mass spectrometry.

13/ Lower uncertainties are achievable for materials containing low burn-up Pu.

Table 5a
²³⁵U Abundance Measurements (DA)

Method	Material	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
GSMS	DUF ₆ & NUF ₆	0.1	0.1	0.14	<u>1/</u>
	LEUF ₆	0.05	0.05	0.07	
TIMS, MCICP	DU (<0.3% ²³⁵ U)	0.5	0.5	0.70	
	U (0.3% < ²³⁵ U <1%)	0.2	0.2	0.28	
	LEU (1% < ²³⁵ U <20%)	0.1	0.1	0.14	
	HEU (>20% ²³⁵ U)	0.05	0.05	0.07	
LMCN	LEU oxides	0.3	0.2	0.36	<u>2/</u>
	HEU oxides	0.2	0.2	0.28	
CMPU	LEU oxides	0.4	0.2	0.45	<u>3/</u>

1/ Sampling uncertainty may be dominating if cylinder contents are not homogenized.

2/ For materials not containing reprocessed uranium.

3/ Measurement time 1000 sec.; adjusted for age of source when necessary.

Table 5b
²³⁵U Abundance Measurements (NDA)

Method	Material	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
IMCN, MMCN ^{1/2/}	DUF ₆	20	8	22	<u>3/4/5</u>
	NUF ₆	10	3	10	
	LEUF ₆	5	3	5.8	
	NU (pure materials) ^{6/}	5	3	5.8	<u>4/5/</u>
	LEU (pure materials) ^{6/}	3	2	3.6	
	NU, LEU Scrap (dirty) ^{7/}	15	5	16	
	LEU Rods	3	1	3.2	
	HEU Metal, Alloys	3	1	3.2	
IMCG, MMCG ^{2/}	DUF ₆	20	8	22	<u>3/4/</u>
	NUF ₆	10	2	10	
	LEUF ₆	5	2	5.4	
	LEU Oxides ^{6/}	3	2	3.6	<u>4/8/</u>
	HEU Metal and Alloys	3	1	3.2	
UBVS	UO ₃ (reprocessed)	5	3	5.8	

1/ For materials not containing reprocessed uranium.

2/ Measurement time 300 sec.

3/ Includes uncertainty associated with ultrasonic thickness gauge measurement of the UF₆ cylinder.

4/ Spectrum analysis: infinite thickness method (enrichment meter principle).

5/ Similar uncertainties should be achievable for peak fitting based spectrum analysis methods.

6/ Includes scrap with low impurity content and suitable for recycling.

7/ Uncertainties for dirty scrap can vary widely due to matrix heterogeneity.

8/ Similar uncertainties are expected for intrinsic calibration based spectrum analysis methods (e.g., MGAU).

Table 6
Plutonium Isotope Assay of Pu and U/Pu Materials

Material Type	Isotope Ratio	Typical Value for Ratio (*100)	Method					
			TIMS, MCICP ^{1/}		IMCG ^{2/}		LMCA ^{3/}	
			u(r)	u(s)	u(r)	u(s)	u(r)	u(s)
High-Burnup Pu	²³⁸ Pu/ ²³⁹ Pu	1.7	1.5	1	1	2	1	1
	²⁴⁰ Pu/ ²³⁹ Pu	43	0.1	0.05	1	1	0.7	0.7
	²⁴¹ Pu/ ²³⁹ Pu	13	0.2	0.2	1	1	0.7	0.7
	²⁴² Pu/ ²³⁹ Pu	8	0.2	0.3				
Low-Burnup Pu	²³⁸ Pu/ ²³⁹ Pu	0.02	10	10	5	10	5	5
	²⁴⁰ Pu/ ²³⁹ Pu	6	0.15	0.1	1.5	2	1.5	1.5
	²⁴¹ Pu/ ²³⁹ Pu	0.2	1	1	1.5	2	1	1
	²⁴² Pu/ ²³⁹ Pu	0.05	2	2				

^{1/} ²³⁸Pu/²³⁹Pu by alpha spectrometry/mass spectrometry combination.

^{2/} Measurement time 1000 sec.

^{3/} Measurement time 3 x 1000 sec.; 0.5 g Pu.

Table 7a
Total Mass of ^{235}U (direct NDA)

Method	Material	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
AWCC	HEU Metal, Alloys	5	3	5.8	<u>1/</u>
	HEU Fuel Elements	3	3	4.2	
FRSC	LEU Fuel Rods	1	1	1.4	
UNCL	LEU Assemblies	4	2	4.5	<u>2/</u>
	HEU Assemblies	1	1	1.4	
HEPC	LEU Items	3	1	3.2	

1/ Measurement time 600 sec.; fast mode operation.

2/ These values are valid for LWR fresh fuel without Gd or with a Gd content, not exceeding the calibration range. In the presence of higher Gd content, u(s) can increase up to 10.

Table 7b
Total Mass of Pu (direct NDA)

Method	Material	Uncertainty Component (%rel.)		ITV (%rel.)	Notes
		u(r)	u(s)		
HLNC	Pu Oxide	1	0.5	1.1	<u>1/2/</u>
	MOX (> 10% Pu) ^{3/}	2	0.5	2.1	
	MOX (< 10% Pu) ^{3/}	4	1.5	4.3	
	MOX (clean scrap) ^{3/4/}	5	2	5.4	
	MOX Rods	2	1	2.2	
	FBR MOX Assemblies	2	1	2.2	
PNCL	LWR MOX Assemblies	1	3	3.2	
PSMC	Pu Oxide	1	0.5	1.1	
	MOX (clean scrap) ^{4/}	4	1	4.1	
	MOX (dirty scrap) ^{4/}	5	1	5.1	
GBAS ^{5/}	Glove Box Inventory	10	5	11	
WDAS ^{6/}	Pu Waste Drums	10	5	11	
HMMS	Hulls Drums	10	10	14	
VCAS	Vitrified Waste Canisters	10	10	14	

1/ Measurement time 300 sec.

2/ Isotopic determination by mass spectrometry and alpha spectrometry.

3/ Including HLNC based canister counters (e.g., PCAS).

4/ Uncertainties for scrap represent average performance observed on historical data; material heterogeneity in the Pu isotopic composition and presence of absorbers or moderators in the matrix can cause much higher uncertainties.

5/ Including other facility-specific measurement systems for Pu inventory in glove boxes.

6/ Including other facility-specific measurement systems for low Pu content solid waste items.

7. Use of ITVs

ITVs are considered to be achievable in routine measurements involved in the determination of the amount of nuclear material for material accountancy and safeguards verification purposes. They are intended to be used as a reference by plant operators, State safeguards systems, and international safeguards organizations. However, they should not be normally used in place of performance uncertainties determined from actual measurement results, when assessing the statistical significance of operator-inspector differences or MUF. Analytical laboratories can find it useful to determine experimentally the actual uncertainties of their measurements, and to compare them with the corresponding values in ITVs-2010.

Safeguards authorities regularly compare the performance values with the current ITVs. In cases where the performance values are significantly higher than the ITVs, and too high to allow the IAEA to meet its detection goals, the safeguards authorities, along with the laboratories, will examine means of improving performance. When reliable performance values are not available, ITVs may be used instead to calculate sampling plans, to set rejection limits, and to calculate estimates of the combined uncertainties of inventories, throughputs, MUF and Ds.

Such applications of the ITVs require having a good insight of the measurement and verification systems. It is in particular important to recognize that, because of practical constraints, some measurement steps may be common to the operator and the inspector. It should also not be forgotten that the operator-inspector differences can carry errors which are not related to measurement uncertainties.

The following three examples illustrate how the tabulated ITVs can be used to calculate ITVs for combined uncertainties applicable to practical situations.

Example 1

Target Values for the Determination of the Total Mass of Fissile Element on Independent Samples

Consider a situation where the operator and the inspector determine fully independently the total amount of plutonium in a batch of LWR MOX pellets. The operator measures the plutonium concentration by titration on ten randomly selected pellets, and the inspector measures by IDMS on an independently selected single pellet.

The Target Values for the combined relative standard uncertainties applicable to the determination of the total mass of plutonium by the operator are derived from the following equations, respectively for the random uncertainty ($u_c(r,O)$), the uncertainty of systematic character ($u_c(s,O)$), and their combination $u_c(O)$:

$$u_c(r,O) = \sqrt{\left[\sum_i u_i^2(r,O) / n_i(O) \right]} \quad (8)$$

$$u_c(s,O) = \sqrt{\left[\sum_i u_i^2(s,O) \right]} \quad (9)$$

$$u_c(O) = \sqrt{u_c^2(r,O) + u_c^2(s,O)} = \sqrt{(0.0555 + 0.0425)} = 0.31\% \quad (10)$$

where i is the index to the i^{th} item in the batch of $n_i(O)$ pellets. The above values would be used in the calculation of Target Values for the relative standard uncertainties to be expected in the inventory, throughput and MUF declared by the operator.

Similar equations are used to calculate the corresponding values applicable to inspector's measurements, $u_c(r,I)$, $u_c(s,I)$ and $u_c(I)$. The Target Value for the combined uncertainties on the total Pu mass measured by the inspector is equal to:

$$u_c(I) = \sqrt{u_c^2(r,I) + u_c^2(s,I)} = \sqrt{(0.5150 + 0.0125)} = 0.73\% \quad (11)$$

Its magnitude is dominated essentially by the random sampling uncertainty component. This is also true for the Target Value applicable to the Operator-Inspector difference:

$$u_d = \sqrt{u_d^2(r) + u_d^2(s)} = \sqrt{(0.5705 + 0.0550)} = 0.79\% \quad (12)$$

Assuming that the values of Target Values (u_c values given in Table 8) are effectively achieved, the 95% confidence intervals of the final results of the operator, of the inspector and of their difference, would be respectively equal to:

$$CL(O) = k u_c(O) = 2 \times 0.31 = 0.62\% \quad (13)$$

$$CL(I) = k u_c(I) = 2 \times 0.73 = 1.46\% \quad (14)$$

$$CL(d) = k u_c(d) = 2 \times 0.79 = 1.58\% \quad (15)$$

where the coverage factor k is 2.

Example 2

Target Values for the Determination of the Total Mass of Fissile Element on a Common Sample

In situations where the inspector analyzes a sub-sample of a homogeneous operator's sample, the sampling errors no longer contribute to the uncertainty of the operator-inspector difference. An example of this situation could be a cooperative effort to identify the existence of biases in the chemical analysis.

Applying these conditions to the first example as shown in Table 9, the Target Value for the operator-inspector difference and its 95% confidence interval will be:

$$u_d = \sqrt{(0.0675 + 0.0550)} = 0.35\% \quad (16)$$

$$CL(d) = k u_d = 2 \times 0.35 = 0.70\% \quad (17)$$

Table 9
Target Values for Operator-Inspector Difference
on Total Pu Mass, with Common Sample and DA (Example 2)

	Step	Method Instr.	n _i	ITV (% rel. Std. Dev.)			Variance Component	
				u _i (r)	u _i (s)	Table	u _i ² (r)/n _i	u _i ² (s)
O P E R A T O R	1- Bulk	EBAL	1	0.05	0.05	2	0.0025	0.0025
	2- Sampling Pu-Conc.		1	0.70	nd	3		
	6- Pu-Conc.	TITR	1	0.20	0.20	4b	0.0400	0.0400
	Sum of variance components						0.0425	0.0425
	Combined Std. Uncertainties, u _c (r,O) and u _c (s,O), (% rel.)						0.21	0.21
I N S P E C T O R	1- Bulk	EBAL	1	0.05	0.05	2	0.0025	0.0025
	2- Sampling Pu-Conc.		1	0.70	nd	3		
	6- Pu-Conc.	IDMS	1	0.15	0.10	4b	0.0225	0.0100
	Sum of variance components						0.0250	0.0125
	Combined Std. Uncertainties, u _c (r,I) and u _c (s,I), (% rel.)						0.16	0.11
D I F F	Variance components of relative difference						0.0675	0.0550
	Standard Uncertainties of Rel. Diff., u _d (r) and u _d (s), (in %)						0.26	0.23

Example 3

Estimation of the Uncertainty of Operator-Inspector Differences for NDA Sampling Plan Calculations

Consider a situation where an inspector must calculate the sample size for verifying the content of LEU UF₆ containers using MMCN. The operator's declarations for the material are based on DA measurements of ²³⁵U abundance and the stoichiometric value for U-concentration in UF₆. No historical inspector measurement data is available. Therefore ITVs need to be used to provide an estimate of the uncertainty which may be associated with the operator-inspector difference.

The variance components calculated from the ITVs-2010 are given in Table 10. The standard combined uncertainty associated with the operator-inspector difference in this example is equal to:

$$u_d = \sqrt{[u_d^2(r) + u_d^2(s)]} = \sqrt{(25.0175 + 9.0075)} = 5.83\% \quad (18)$$

In the absence of an uncertainty estimate based on historical measurement data, the inspector would thus use the above value calculated from the ITVs for performing sample size calculations and establishing rejection limits. In this example, the relatively large uncertainty associated with the NDA measurement almost entirely dominates the overall uncertainty of the operator-inspector difference.

Table 10
Target Values for Operator-Inspector Difference (Example 3)

	Step	Method/Instr.	ITV (% rel. Std. Dev.)			Variance Component	
			u _i (r)	u _i (s)	Table	u _i ² (r)	u _i ² (s)
O P E R A T O R	1- Bulk	EBAL	0.05	0.05	2	0.0025	0.0025
	2- Sampling ²³⁵ U wt. %		0.1		3	0.0100	
	6- U-Conc.	Stoichiom. Val.					
	6- ²³⁵ U wt. %	GSMS	0.05	0.05	5a	0.0025	0.0025
	Sum of variance components					0.0150	0.0050
	Combined Std. Uncertainties, u _c (r,O) and u _c (s,O), (% rel.)					0.12	0.07
I N S P E C T O R	1- Bulk	EBAL	0.05	0.05	2	0.0025	0.0025
	6- U-Conc.	Stoichiom. Val.					
	6- ²³⁵ U wt. %	MMCN	5	3	5b	25.0000	9.0000
	Sum of variance components					25.0025	9.0025
	Combined Std. Uncertainties, u _c (r,I) and u _c (s,I), (% rel.)					5.00	3.00
D I F F	Variance components of relative difference					25.0175	9.0075
	Standard Uncertainties of Rel. Diff., u _d (r) and u _d (s), (in %)					5.00	3.00

8. Organizations Involved

The following groups of experts and organizations participated in the review of the draft ITVs-2010 tables and nominated their representatives to participate in a Consultants Group Meeting (CGM) at the IAEA. In addition to these consultants several observers attended the discussions which led to the definition of the ITVs-2010.

Table 11
Consultants and Observers (CGM March 2010)

Organization	Consultants' Group Meeting	
	Consultant	Observer
ESARDA Working Group on DA	K. Mayer	J. Tushingham
ESARDA Working Group on NDA	P. Peerani	
ANSI/INMM 5.1 Analytical Chemistry Laboratory Measurement Control Committee	C. Pietri	P. Mason
ISO TC 85/SC5 Subcommittee on Analytical Methodology in the Nuclear Fuel Cycle	S. Tapodi	T. Morris
Japanese ITV-2010 Expert Group	Y. Tsutaki	S. Hara
EURATOM Safeguards Directorate	M. Boella	O. Alique
Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC)	G. Renha Jr.	F. Cordeiro Dias

The following internal experts from the IAEA also participated in the review process and/or the CGM:

- Division of Analytical Services (S. Balsley, S. Buerger, G. Duhamel, A. Fajgelj, F. Tadjer)
- Division of Information Management (J. Baute, C. Norman, K. Zhao)
- Divisions of Operations (R. Binner)