DETECTING NUCLEAR MATERIAL DIVERSION AT THE STATE-LEVEL: CHALLENGES AND OPPORTUNITIES

C. NORMAN, J. BAUTE
International Atomic Energy Agency (IAEA)
Vienna, Austria
c.norman@iaea.org

ABSTRACT

INFCIRC/153 (Corrected) [4] designates nuclear material accountancy as *a safeguards measure of fundamental* importance (Part II-Article 29) in detecting the diversion of nuclear material and describes the *technical conclusion of the Agency's related verification activities* (Part II-Article 30) in terms of the conclusions of material balance evaluation (MBE), i.e., the periodic evaluation for each material balance area (MBA) of the declared *material unaccounted for (*MUF). However, the basic undertaking (Part I-Article 1) stipulates that the State should *accept safeguards, in accordance with the terms of the Agreement, on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices.*

MBE procedures which were developed several decades ago to support safeguards implementation under a comprehensive safeguards agreement (CSA) are rooted in a facility-based structure with conclusions drawn for each material category (i.e., plutonium, enriched uranium, natural and depleted uranium, etc.), each MBA, and each material balance period (MBP). The evolution of safeguards concepts to the State level posed the question of how to draw a meaningful conclusion on the absence of diversion of nuclear material for the State as a whole. Since attempts to tackle methodological challenges associated, *inter alia*, with non-synchronized MBP proved ineffective, a more promising approach was explored, based on a holistic analysis of nuclear material flow and inventories in the framework of the State's declared nuclear fuel cycle and against the results of its acquisition path analysis. The purpose of this paper is to discuss the initial experience gained from applying this method and to present prospective developments.

INTRODUCTION

One of the missions of the International Atomic Energy Agency (IAEA) in promoting the peaceful use of nuclear energy is to implement safeguards measures to detect and deter the misuse of nuclear material and technology in States under safeguards agreements. The first generic safeguards objective of safeguards implementation at the State Level [1], [2] is *the detection of diversion of declared nuclear material at declared facilities or locations outside facilities (LOFs).* After the entry into force of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) [3] in 1970, it has also been the core technical objective of safeguards implementation under a comprehensive safeguards agreement (CSA). As stated in Article 28 of INFCIRC/153 (Corrected), Part II [4]: *The agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.*

As is further described in Article 29, the objective of diversion detection is pursued by applying nuclear material accountancy (NMA) to all declared *nuclear material*, i.e. any fissionable or source material as defined in Article XX of the IAEA Statute [5]. The principle of

NMA and its keystone, material balance evaluation (MBE), is to detect and deter diversion by evaluating the nuclear material balances established through the State's systems of accounting for and control of nuclear material (SSAC) against the corresponding uncertainties.

In order to provide a structured background to the following parts of the paper, the principles of diversion detection are recalled in Section 1. Section 2 summarises the fundamentals of the State-level concept and how the diversion detection objective is addressed in its framework. The approach currently being developed by the Nuclear Fuel Cycle Information Analysis Section within the Department of Safeguards, Division of Information Management (SGIM-IFC), to support a State-level safeguards conclusion on diversion detection is described in Section 3.

1. DETECTION OF NUCLEAR MATERIAL DIVERSION: FOUNDATIONS

Nuclear material inventories in declared nuclear fuel cycle (NFC) facilities and LOFs and nuclear material movements between them are reported to the IAEA by the State through formalized State reports for all material balance areas (MBA) within facilities and LOFs and for periods called material balance periods (MBP). The credibility of the IAEA's conclusions regarding non-diversion is warranted by the verifications of the State's accounting declarations by the IAEA's inspectors through independent observations and quantitative measurements, complemented by containment and surveillance measures ([4] Article 29).

The rate at which nuclear material could be diverted is considered by the IAEA in establishing safeguards verification goals. If one significant quantity (SQ) of nuclear material ([6] § 3.14) is diverted in a time shorter than a MBP, this strategy, called ***abrupt diversion***, is countered by performing inspections to verify nuclear material inventories at a frequency depending on the conversion time of the material considered, i.e., the time required to convert it to the metallic components of a nuclear explosive device. These activities constitute the *timeliness component* of the verification goal. The strategy which consists in diverting one SQ of nuclear material gradually over a MBP or more, is referred to as *protracted diversion*. The verification measures implemented to detect this diversion strategy support the *quantity component* of the verification goal. These measures come under the scope of MBE and their general principle is described in [4] Article 30: *The Agreement should provide that the technical conclusion of the Agency's verification activities shall be a statement, in respect of each material balance area, of the amount of* ***material unaccounted for*** *over a specific period, giving the* ***limits of accuracy*** *of the amounts stated.*

In other words, the main objective of material balance evaluation is to evaluate the imbalance or *material unaccounted for* (MUF) declared by NFC operators for each MBA and each MBP against the associated uncertainty to determine if it can be explained by the measurement errors associated to the facility processes. This objective is referred to as detection of *diversion into MUF*, since it is intended to counter a strategy which consists of disguising nuclear material diversion into an overstated MUF uncertainty. This measure is associated with another important provision of CSAs (Ref. [4] Article 55): *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.* The history and evolution of such international standards is discussed in [8].

As stated above, the nuclear material inventory and transfer declarations which result in the MUF declared by facility operators are subject to verifications by inspectors. These verifications are based on random sampling plans designed to achieve a desired *detection probability* using an optimum combination of verification methods over the range of possible *defect*[1] sizes to maximize detection probability while minimizing cost and disruption to the NFC facility production activities. Some verification methods are used to *qualitatively* confirm the presence of nuclear material in items, i.e. for the detection of *gross defects.*[2] Other, more precise verification methods return *quantitative* results, making it possible to detect *partial*[3] *and bias*[4] *defects* and to establish *operator-inspector differences*[5]. Such methods are based on non-destructive (NDA) assay techniques or involve the taking of samples for destructive analysis (DA) by the IAEA safeguards analytical laboratory (SAL), combined with a measurement of the net weight or volume of nuclear material present in the verified item. Individual operator-inspector differences greater than prescribed rejection limits are reported by IAEA inspectors and the reason is investigated. Moreover, one of the objectives of material balance evaluation is to assess all operator-inspector differences observed during an MBP by testing an aggregate statistic called the D Statistic against its estimated uncertainty, to preclude falsification of the declared amounts, i.e. a diversion strategy which is termed *diversion into D*.

In a large number of MBA, the nuclear material transits through the facility in the form of discrete, identifiable items whose physical form remains identical and which are not subject to measurements. Such MBA, e.g. nuclear power plants, nuclear material stores are called *item MBA*. The balance in these facilities is expected to come out right and the MUF should be zero. A non-zero MUF may be explained by a variety of circumstances such as clerical errors, i.e. the records are incorrect and/or incomplete; hidden inventories, i.e. the operator has lost track of some items in the plant; undeclared accidental losses or gains; and, of course, diversion. This situation requires follow-up and resolution by safeguards inspectors.

In contrast, at bulk handling facilities (BHF), where one or several MBA hold material processed in loose forms (gases, liquids, powders), complex measurement systems are needed to establish the flows and inventories of material and the conclusions regarding material balances rest on statistical analyses based on the propagation of measurement uncertainties into overall uncertainties associated to balance statistics. For each MBP and each material balance MBA, the MUF[6] declared by a BHF operator is statistically tested on the basis of its estimated standard deviation σ_{MUF} to ascertain whether it could plausibly be explained by legitimate measurement uncertainties or whether some other explanation such as diversion is more likely. The D Statistic is also evaluated and the result of the statistical analysis includes estimates of the detection probabilities of diversion into MUF and into D. A team of specialised IAEA statistical analysts are in charge of MBE for more than 80 MBA in BHF. This work requires an in-depth understanding and experience of NFC nuclear materials and processes combined with advanced expertise in the measurement systems used by operators and inspectors and the associated uncertainties. It currently supports a dual process corresponding to two cycles of conclusions: the safeguards implementation report (SIR), i.e., the Report by the Director General on Safeguards Implementation for a given year, which reports safeguards conclusions at both NFC facility and

---

[1] The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons.

[1] A difference between the declared amount of nuclear material and the material actually present. [6] §10.7

[2] Gross defect refers to an item or a batch that has been falsified to the maximum extent possible so that all or most of the declared material is missing. [6] §10.7

[3] Partial defect refers to an item or a batch that has been falsified to such an extent that some fraction of the declared amount of material is actually present. [6] §10.7

[4] Bias defect refers to an item or a batch that has been slightly falsified so that only a small fraction of the declared amount of material is missing. [6] §10.7

[5] The difference between the facility operator's declared value and the IAEA inspector's measured value for the quantity of nuclear material in an item. [6] §10.3

[6] The shipper-receiver difference (SRD) which is a component of the MUF is also subject to an independent statistical test against its standard deviation σ_{SRD} which is computed from the shipper's and operator's measurement uncertainties for the material type and measurement method involved.

State level and the internal safeguards evaluation reports (SERs) which support the State-level concept (SLC) cycle described in Section 2 with a different schedule for each individual State.

2. DETECTION OF NUCLEAR MATERIAL DIVERSION AND THE STATE-LEVEL CONCEPT

The statistical methods supporting MBE were developed more than 25 years ago, and were implemented using robust computer algorithms that are still used by statistical data analysts today. However, several major reasons call for their review, upgrade and evolution. The main motivation is the evolution of safeguards concepts in the last decades, from a facility-level framework based on the attainment of a set of criteria and centered on nuclear material to the present SLC based on the cycle described in Fig.1: the collection of all safeguards relevant information supports an acquisition path analysis (APA) which leads to the identification of specific technical objectives (TO). These TO are addressed through a State-level approach (SLA) that determines in-field and headquarter-based annual implementation plans (AIP) whose results are evaluated to draw safeguards conclusions, themselves feeding into the next analytical cycle. In this context, a number of State-level safeguards approaches make an increasing use of random verification schemes to optimize efficiency and effectiveness in attaining TO. The analysis of verification data resulting from this variety of probabilistic schemes poses new statistical problems that need to be addressed in order to warrant the validity of the related conclusions.

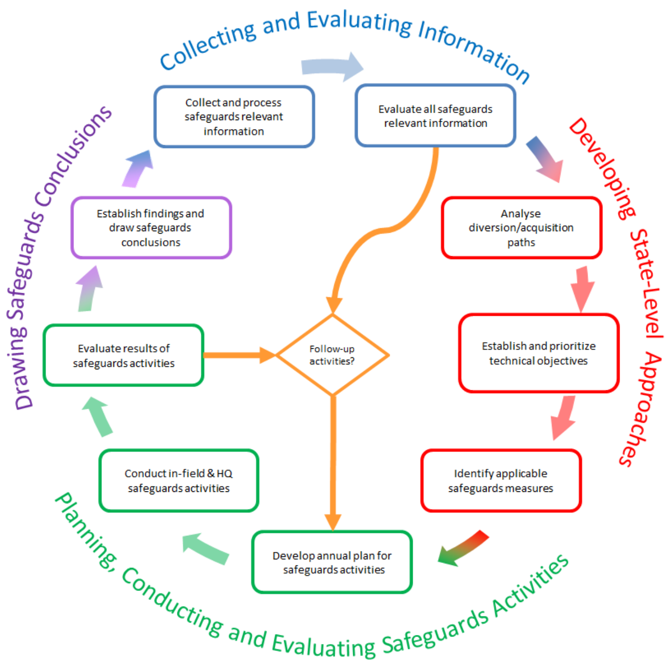

Fig.1: SLC processes to support safeguards implementation for all States with safeguards agreements [2]

In the last decade, extensive efforts have been made to address these methodological challenges, including the creation of a biennial International Technical Meeting (TM) on Statistical Methodologies for Safeguards to establish an overview of the methodological landscape in this field, gather worldwide expertise in addressing current gaps and questions, draft recommendations and build a network of specialists to remedy the lack of internal development resources by identifying potential Member State Support Programme (MSSP) support tasks. Four TMs were held in Vienna to date in 2013, 2015, 2017 and 2020. Three interconnected areas for methodological development were identified along the high-level structure represented in Fig.2.

Extensive progress has been made in the field of uncertainty quantification (UQ) and random verification schemes with the crucial assistance of the US and German support programmes who provide continued support and expertise in the form of cost-free experts (CFE) and specific development tasks. These achievements are described in general in [9] and in a large number of publications addressing specific topics, e.g. references [10, 11, 12,13, 14,15 ,16,17,18,19 ,20] to only mention a few. Of particular note is the re-engineering and integration of legacy statistical analysis IT tools into a consolidated Statistical Evaluation Platform for Safeguards (STEPS) including a new enhanced UQ software (OPTANOVA) and an in-built knowledge management feature, called *data tagging*, which makes it possible to associate declaration and verification data with information relevant to its evaluation, like container type, poison, e.g. Gd, content etc… through the capture extended metadata. Another important achievement is the progress made in reconciling bottom-up UQ methodologies based on the Guide to the Expression of Uncertainty in Measurement (GUM) [8, 22] used by safeguards laboratories with the statistical error model-based approached used by safeguards evaluators, which opened effective communication channels between these professional communities and created opportunities for mutual learning and synergies.

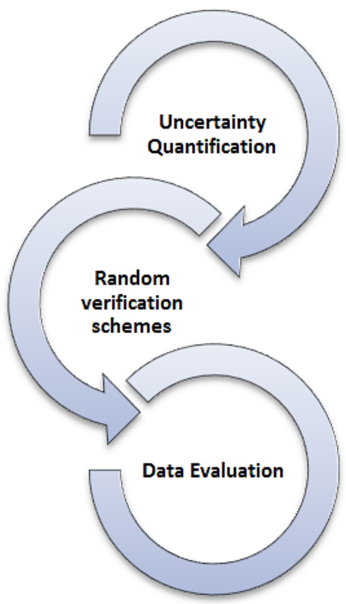

Fig.2: Three high-level interconnected methodological development areas were identified during the 1st TM on Statistical Methodologies for Safeguards (Vienna, October 2013).

The area of data evaluation is the keystone which needs to integrate the quantification of the uncertainty associated to the data collected, the associated metadata and the data collection approach determined by the applied random verification schemes to support a conclusion on the absence of diversion of nuclear material. While progress has been and is still being made in specific methodological areas, like the improvement of D Statistic uncertainty algorithms, the harmonization and consolidation of Near Real Time Accountancy (NRTA) methodologies (UK support programme) and the exploration of Bayesian data evaluation methods, the present paper focusses on the global challenge which consists in evolving of material balance evaluation concepts from the MBA level to support conclusions on the absence of diversion at the level of a State.

The evolution needed is twofold: on the one hand, a *method* is needed to combine or project facility-based material balance evaluation results to the whole State, including the assessment of its detection effectiveness in terms of detection probabilities of diversion of nuclear material into MUF (uncertainty of the balance) and D (falsification of reports); on the other hand, the dual SIR and State Evaluation (SE) *processes* based on different time frames must be coordinated and harmonised to effectively support the Safeguards Department's safeguards conclusions while optimizing their efficiency to be adjusted to the limited specialized manpower and resources available. These two aspects are developed in Section 3.

3. DIVERSION DETECTION AT STATE-LEVEL: CONCEPTS AND PROCESSES

3.1 Drawing State-level conclusions on nuclear material diversion detection

Several methods, based on numerical combinations have been explored in the early 2000s to design a concept of material balance evaluation at the State level. However, they were either limited in effectiveness and/or meaningfulness or faced methodological obstacles and intricacies such as the need to combine balances for MBA with unsynchronized MBP or to combine statistical uncertainties related to different MBA considering correlations when appropriate.

From 2011, an entirely different approach was developed, proposing a concept which makes it possible to evade the statistical complexity of MBE at State level while *optimizing its effectiveness* at detecting diversion at *key points* of the State nuclear fuel cycle and *prioritizing verification efforts by making full use of the SLC principles* [23,24]. This approach rests on a visualisation of a State's nuclear fuel cycle based on the IAEA Physical Model [25,26] with successive overlays leading to a map type representation of detection effectiveness – in terms of detection probability for the TOs related to nuclear material diversion along the State's APA, making it possible to review the priority of MBE activities and/or to flag the need to intensify the focus on other TOs along the same path.

The *first visual layer* of this visualisation system represents the State's declared flows, inventories and material balance data using the Physical Model as a general backdrop. Facilities are organized according to their function in the State nuclear fuel cycle. The flows and inventories of nuclear material between the facilities showing the material type and the magnitude of the flow are represented visually, which make it possible to identify functional links between NFC facilities that can influence specific MBE statistics and their trends. After an initial feasibility test based on a State with a complex NFC [24], the method proved to be effective but resource-intensive. The first layer was then significantly enhanced by the automated application of Sankey flow diagrams (see: Wikipedia Sankey diagram https://en.wikipedia.org/wiki/Sankey_diagram) into what is now called the SNAKEY tool [24] in reference to the sinuous shapes of the flow arrows, and to the fact that the Python language was used to develop the prototype. The SNAKEY tool applied to the fictional State *Middle Earth* based on J.R.R Tolkien's *Lord of the Rings* saga is illustrated in Fig.3 below.

In the *second overlay*, the APA conducted by the State Evaluation Group (SEG) is superposed to the State's nuclear material flows and inventories to identify the TOs which involve the detection of diversion and the associated performance targets. Flows and inventories are identified where MBE *should focus* versus areas where it may be *ineffective* or where *other safeguards measures,* e.g. containment and surveillance, applied under the State level approach (SLA), render it redundant. Operating links between facilities that can influence specific MBE statistics and their trends are considered in the evaluation and prioritisation process of MBE activities. The development of the second overlay is currently kept pending, awaiting the final results of the SLA improvement project (SLAIP) which was initiated in 2019 to refine and standardize the SLA principles and procedures, including the TO prioritization, verification levels and performance targets.

The final and *third overlay* is planned to represent the results of *verification activities* to support conclusions relative to the diversion detection TOs addressed by these activities at the MBAs involved, the main intended outcome being an assessment of the achieved effectiveness of the verification efforts implemented in terms of detection probability, in order to compare it with the prescribed targets. This representation is expected to assist the safeguards effectiveness evaluation process irrespective of the approach chosen regarding a potential combination of quantitative and qualitative detection performance parameters related to all TO types at the level of an acquisition path. Its objective is to provide the SEG and evaluators with a visual chart of achieved versus planned performance for diversion detection TOs and, hence, to feed back into the prioritization process in the next cycle, i.e., the next AIP. When applicable, the third overlay should also include an assessment of the quality of the operator's measurement and accounting system at each facility to support potential recommendations for improvements and inform design information verification (DIV) planning and activities.

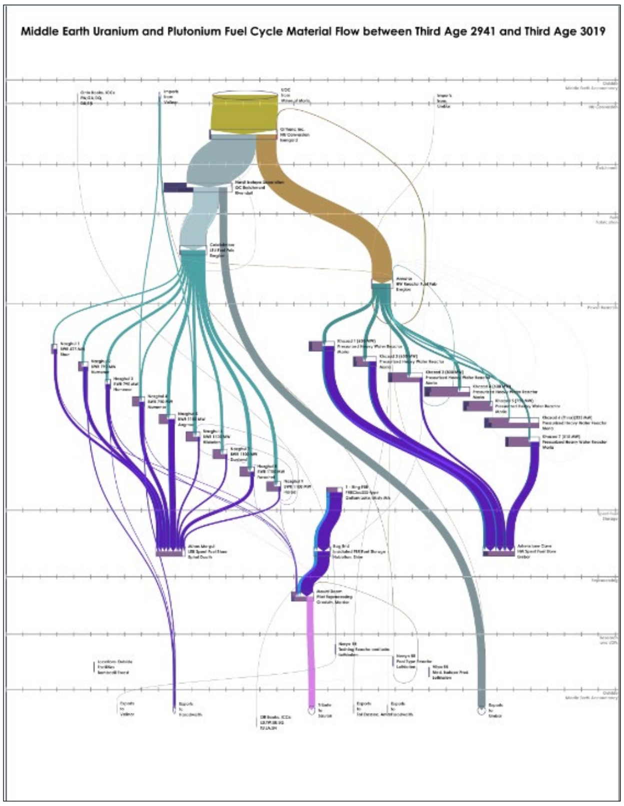

Fig.3: Snapshot of a nuclear material flow "SNAKEY" diagram for a the Middle Earth hypothetical State

3.2 <u>Coordinating and harmonising safeguards processes in support of nuclear material diversion detection</u>

Although this topic is of less general interest, since it essentially pertains to the Department of Safeguards' internal organisation, it may be useful to provide an overview of the progress and status of evolution efforts in this area for the benefit of interested parties and stakeholders. The approach taken to streamline, coordinate and harmonise MBE efforts in support of the SIR and SER processes while meeting their respective timelines is explained in the diagram of Fig.4.

The main constraint associated to the SIR process is the need to provide MBE conclusions to IAEA safeguards inspectors for all material categories (>200) for MBA in BHF holding more than one SQ of nuclear material within the very limited time between the availability of all necessary data, including DA sample results, and the strict deadline imposed by the SIR schedule. In order to provide efficient support to the SIR process, conventional MBE reports have been simplified to optimize efficiency in allowing operation inspectors to complete their facility-level reports on time. As is illustrated on the left-hand side of Fig. 4, the MBE results in the form of a structured summary of observations and recommendations (Mod. 18.2) is uploaded into the computerised inspection report system (SAFIRE) after reviewing it on the basis the supporting information (MBE tables, trend diagrams) in liaison with the Operation Division's facility officer (FO) who may bring additional information. The final consolidated results are documented in a short facility-based report called the Summary Statistical Evaluation Report (SSER).

The State Evaluation Report (SER), which supports the conclusions of the SLC cycle illustrated in Fig. 1 is the collective work of the SEG under the lead of the Operation Division's country officer (CO) and is the result of an in-depth examination of all safeguards relevant information related to the State, including a thorough consistency analysis. The MBE contribution to the SER must therefore be consolidated from facility-based results to provide a conclusion on the absence of diversion at State-level. In order to effectively support the integrated information evaluation process and inform follow-up actions to be planned in the next AIP, it has to include a detailed investigation of MBE observations, formulate potential solutions and, when applicable, convey clear and actionable recommendations. Unlike the facility-based reports which support the SIR cycle, SER contributions lend themselves to a prioritisation process – they are issued or updated as a function of the significance in the broader safeguards picture of the results observed. MBE contributions to the SER are based on the principles and structure described in Section 3.1 and issued after review in liaison with the CO under the title: Detailed Statistical Evaluation Report (DSER). Facility-based DSER components are currently being drafted as a first stage of the detailed analytical work. Their consolidation to the State-level is intended to take place in the upcoming cycles as a second phase of the MBE process evolution undertaken to support the SER cycle (see Fig. 4 – right-hand side).

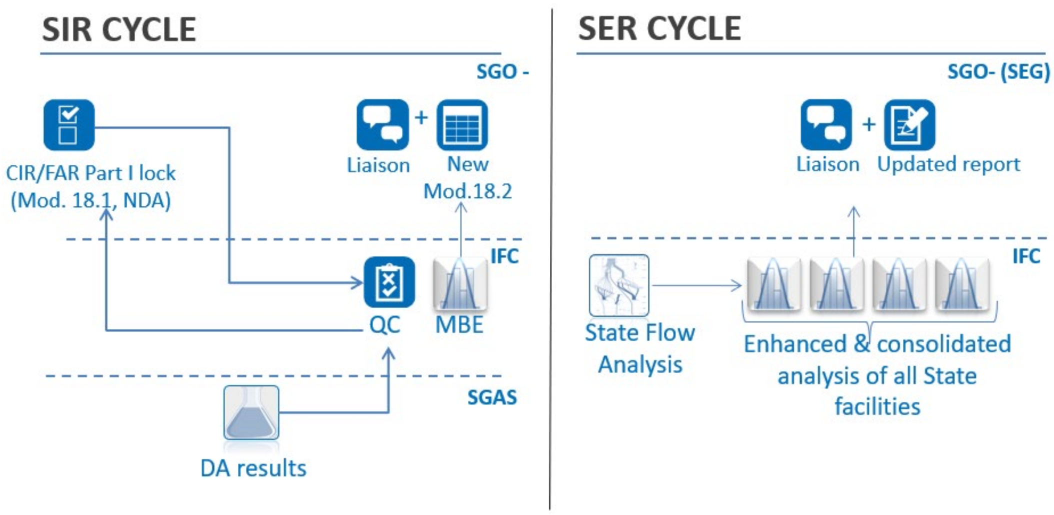

Fig.4 The dual SIR and SER material balance evaluation process supporting the detection of diversion of nuclear material

CONCLUSION

The principles and methodologies which support the detection of nuclear material diversion were developed at an early stage of safeguards' history and were rooted in the criteria-driven, facility-based approach which has long underpinned the IAEA's safeguards conclusions. While they remain generally valid in the framework of a State-level evaluation, their scope, previously restricted to material balance areas (MBA) within facilities, needs to be expanded to include the analysis of nuclear material flows, inventories and balances and the related conclusions for a whole State, considering the increasing use of random inspection schemes in State-level approaches (SLA) and the implications for the statistical analysis of data collected according to these patterns. New material balance evaluation concepts, methods and processes have been and are still being developed by the Nuclear Fuel Cycle Information Analysis Section within the Department of Safeguards, Division of Information Management (SGIM-IFC) to meet these challenges. Extensive efforts were made in the last decade to consolidate increasingly large and diversified data flows, to empower their interpretation through the use of modern visualisation tools, to bring their analysis in line with the State-level TOs identified through the APA performed by the SEGs and to develop probabilistic methods for the comparison of the targeted versus achieved attainment of these TOs. Considerable progress was also made in the field of information technology (IT): the deployment of the Statistical Evaluation Platform for Safeguards (STEPS) made it possible to integrate upgraded UQ methodologies and in-built knowledge management features into a new integrated software environment. Work on the evolution of diversion detection to the State-level is well on the way and efforts will be continued to build a fit for purpose and effective process while streamlining the data evaluation procedures and optimizing the distribution of limited expert statistical analysis resources.

REFERENCES

[1] The Conceptualization and Development of Safeguards Implementation at the State Level, GOV/2013/38, IAEA, Vienna (2013).
[2] Supplementary Document to the Report on The Conceptualization and Development of Safeguards Implementation at the State Level (GOV/2013/38), GOV/2014/41, IAEA, Vienna (2014).
[3] Treaty on the Non-Proliferation of Nuclear Weapons (NPT), INFCIRC/140, IAEA, 22 April 1970.
[4] The Structure and Contents of Agreements between the Agency and States in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/ 153 (Corrected), IAEA, Vienna (1972).
[5] IAEA Statute, IAEA, Vienna (amended in 1989).
[6] IAEA Safeguards Glossary, IAEA, Vienna (2001).
[7] IAEA, International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials, STR-368, IAEA, Vienna (2010).
[8] NORMAN,C., BINNER R., BALSLEY S., International Target Values (ITV) 2020: The Role of Stakeholders, Institute of Nuclear Materials Management (INMM) 60th International Meeting, Palm Desert, USA, 14-18 July 2019.
[9] NORMAN,C., BINNER R., BURR,T. , PETER, N. ,WALCZAK-TYPKE, A.,WÜSTER, J., KRIEGER, T., MARTIN, K., Evolving Statistical Methodologies for Safeguards, 13th Symposium on International Safeguards: Building Future Safeguards Capabilities, Vienna, 5-8 November 2018.
[10] NORMAN,C., KRIEGER,T.,BINNER,R., BONNER,E., PETER,N., PORTAIX,C., RICHET,S., WALCZAK-TYPKE,A., WÜSTER,J., ZHAO,K., Outcome and Perspectives from the first

IAEA International Technical Meeting on Statistical Methodologies for Safeguards; Proceedings of the IAEA International Safeguards Symposium, Vienna, (2014).
[11] BAUTE,J., NORMAN,C., BINNER,R., NIKKINEN,M., WÜSTER,J., WALCZAK-TYPKE,A., KRZYSZTOSZEK,K., RICHET,S., NG,J., MAISTRENKO,O., STEPS for the modernization of safeguards information analysis tools.
[12] BURR, T., KRIEGER, T., NORMAN, C., Approximate Bayesian Computation applied to Metrology for Nuclear Safeguards Journal of Physics: Conference Series, 2018.
[13] BONNER, E., BURR, T., KRIEGER, T., MARTIN, K., NORMAN, C., Comprehensive Uncertainty Quantification in Nuclear Safeguards, Science and Technology of Nuclear Installations, 1-16, 10.1155/2017/2679243, 2017.
[14] BURR, T., CROFT, S., JARMAN. K., NICHOLSON, A., NORMAN, C., WALSH, S., Improved Uncertainty Quantification in NonDestructive Assay for Non-proliferation, Chemometrics, 159, 164-173, 2016.
[15] BURR, T., CROFT, S., FAVALLI, A., KRIEGER, T., WEAVER, B., Bottom up and Top down Uncertainty Quantification for Measurements, in *Chemometrics and Intelligent Laboratory Systems,* 2021.
[16] K. MARTIN, Estimation of Variances of Random and Short-Term Systematic Measurement Errors based on Data from Two and Three Independent Measurement Methods – An introduction to the evaluation of measurement uncertainties; software package OPTANOVA- (2018).
[17] IAEA, Statistical Methods for Verification Sampling Plans (STR 381), Vienna: IAEA, 2017.
[18] KRIEGER,T.,BURR,T.,NORMAN,C., Consequences of non-zero item variability on the IAEA's inspection sampling plans, in *Proceedings of the INMM 58th Annual Meeting*, Indian Wells, California USA, July 16-20, 2017.
[19] AVENHAUS,R.,KRIEGER,T., Inspection Games over Time: Fundamental Models and Approaches, to be published 2018.
[20] NORMAN,C., BAUTE,J., BINNER,R., NIKKINEN,M.,WALCZAK-TYPKE,A.,Evolution of Verification Data Evaluation under the State-Level Concept, ESARDA Symposium 2017, 39th Annual meeting,15-18 May 2017, Jülich / Düsseldorf, Germany.
[21] Evaluation of measurement data – Guide to the expression of uncertainty in measurement. JCGM 100:2008.
[22] ALIQUE, O., AREGBE, Y., BENCARDINO, R., BINNER, R., BURR, T., CHAPMAN, J.A., CROFT, S., FELLERMAN, A., KRIEGER, T., MARTIN, K., MASON, P., NORMAN, C., PROHASKA,T., TRIVEDI, D., WALSH, S., WEGRZYNEK, D., WRIGHT, B., WÜSTER, J., Statistical error model-based and GUM-based analysis of measurement uncertainties in nuclear safeguards – a reconciliation, *draft submitted to Metrologia, 2021.*
[23] NORMAN,C., ZHAO, K., BAUTE,J., Nuclear fuel cycle verification data and the State evaluation process challenges and opportunities, INMM 54th Annual meeting, Palm Springs, July 2013.
[24] BAUTE, J., NORMAN, C., BINNER, R., WALCZAK-TYPKE, A., CAILLOU, F., ZHAO, K., BONNER, E., Dynamic Exploratory Visualization of Nuclear Fuel Cycle Verification Data in Support of the State Evaluation Process, INMM 56th Annual meeting, Palm Springs, July 2015
[25] IAEA, Physical Model (Volumes 1-12), STR-314, IAEA, Vienna (1998-2008).
[26] BOYER, B.D., DISSER, J., RICHET, S., GAGNE, D., POIRIER,S., WHITLOCK, J., WALCZAK-TYPKE,A., NORMAN, C., The IAEA's Physical Model: Fine Tuning Nuclear Fuel Cycle Understanding for Robust State-level Safeguards, in Journal of the Institute of Nuclear Materials Management (JNMM), January 2018.