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Evolution of Verification Data Evaluation under the State-Level Concept

Claude Norman, Jacques Baute, Robert Binner, Mika Nikkinen, Agatha Walczak-Typke

International Atomic Energy Agency (IAEA)
Wagramer Strasse 5, A-1400 Vienna, Austria

Abstract:

Every year, thousands of days are spent by IAEA inspectors in nuclear fuel cycle (NFC) facilities and other sites around the world. A large portion of this time is used for carrying out in-field measurements by various non-destructive assay (NDA) techniques and for taking environmental samples (ES) and/or destructive analysis (DA) samples. Comparably intensive resources are needed to maintain continuity of knowledge (CoK) on the verification data collected through these activities by means of a range of sophisticated containment and surveillance (C/S) systems. The IAEA collects, authenticates, quality controls, maintains and evaluates a large body of verification data and compares them with State declarations to support two of the main objectives of safeguards under the State-level concept (SLC), that is: the detection of diversion of nuclear material and of undeclared production or processing of nuclear material at declared facilities and locations outside facilities (LOFs).

In recent years, the NFC Information Analysis Section of the Safeguards Department Division of Information Management (SGIM-IFC), which is in charge of the evaluation of verification data, has been faced with a number of challenges: the first and most demanding is the need to evolve facility-based evaluation concepts to innovative, consolidated concepts that can integrate different types of information and support credible State-level safeguards conclusions, the second is the increasing volume and diversification of verification data to be evaluated given static resources, and the third is the need to keep abreast of modern methodologies and technologies with a view to ensure optimal effectiveness and efficiency.

This paper reviews the conceptual and methodological issues associated with these challenges and the approach that was applied to address them while taking advantage of the corresponding development opportunities. It presents the overall strategy adopted as well as the supporting project plan and the progress made to date in the related project components, with a special emphasis on the implementation of data visualization tools.

Keywords: evaluation; State-level Concept; methodology; diversion detection; visualization.

1. Introduction

The main mission of the IAEA Department of Safeguards is to provide credible assurances that States are abiding by their safeguards obligations. Since the safeguards system was strengthened after the discovery of a clandestine nuclear weapon programme in Iraq in the early 1990s and its legal authority was subsequently reinforced by the additional protocol (AP) in 1997, the nature and sources of information collected and evaluated by safeguards experts have extensively diversified and the volume of material to be researched has considerably increased. The Division of Information Management provides the Department of Safeguards with services of data processing, secure information distribution, information analysis and knowledge generation and consists of teams of professionals specialized in the analysis of different types of information plus a team in charge of information integration. These specialists play a critical role in the work of the Division of Operations' State evaluation groups (SEGs) in identifying, analysing and consolidating safeguards-relevant information from all sources to draw independent, non-discriminatory and soundly based conclusions for all States having concluded a safeguards agreement (Fig. 1) [1,2,4].

All-source safeguards-relevant information falls in three broad categories:

- Information declared by States, which consists in nuclear material accountancy (NMA) reports and reports submitted to the IAEA pursuant to the AP to the States' safeguards agreements.
- Information resulting from verification activities, e.g. results of NDA measurements, DA samples and ES samples, seals verification, surveillance review and other verification activities.
- Other relevant information, e.g. from open sources (OS) or provided by third parties, such as, for example, media, scientific publications, IAEA and public databases, trade import/export information and commercial satellite imagery.

The organizational structure of the Division of Information Management reflects these categories, which correspond to different analytical competencies. Besides the Integration and Coordination Team, it comprises four specialized

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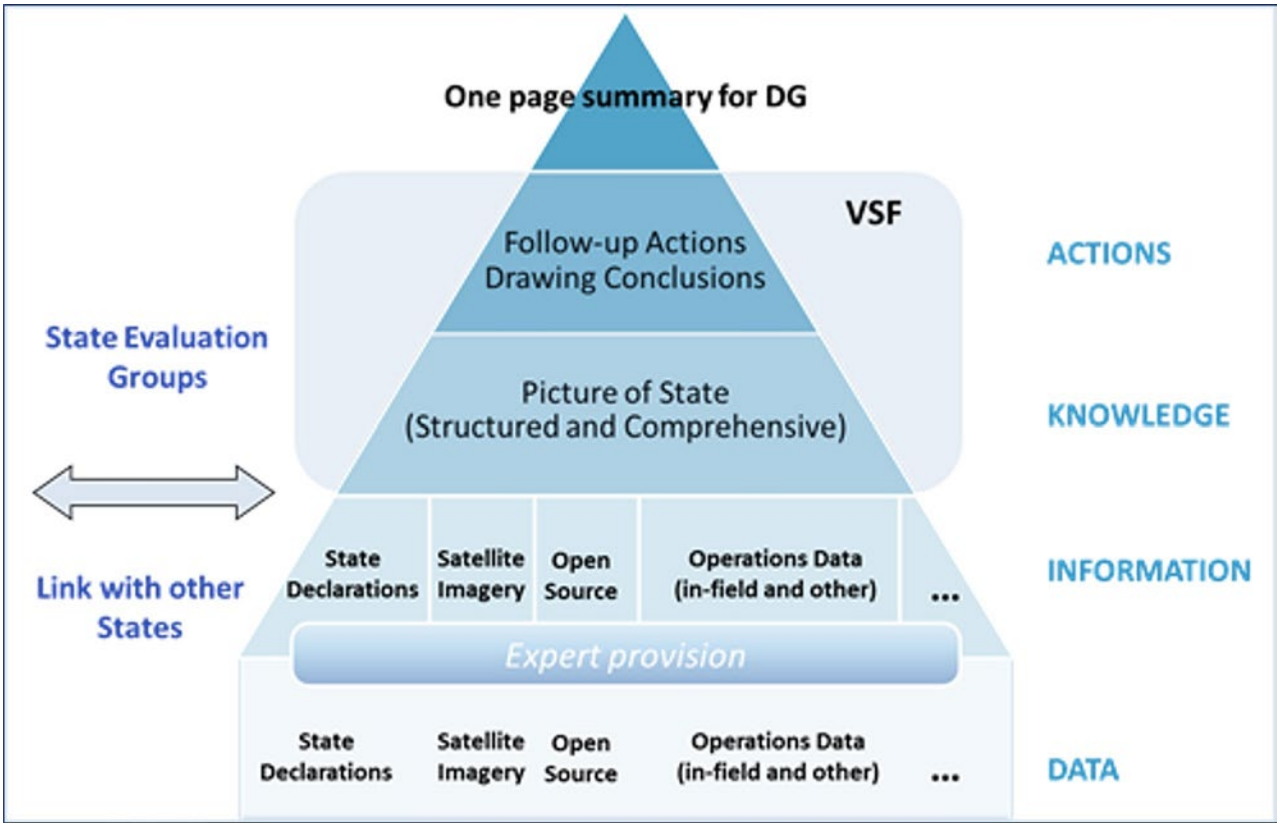


Fig.1: All Source safeguards-relevant information analysis – from data to actions [3]

Sections: the Declared Information Analysis Section whose role is self-explanatory, the State Factor Information Analysis Section in charge of general OS information analysis, the State Infrastructure Analysis Section specialized in geospatial information and satellite imagery analysis and the Nuclear Fuel Cycle (NFC) Information Analysis Section which collects, performs quality control of, stores, and evaluates results from in-field NDA measurements and from ES and DA samples to compare them with State declarations.

This paper will focus on the activities of the NFC Information Analysis Section. Its objective is to describe the challenges and opportunities encountered in this area from the evolution of the safeguards landscape and concepts [5], from the need for enhanced efficiency to cope with an ever increasing volume of data under static and sometimes reduced resource conditions, as well as from the progress made in information technology (IT) and data processing and evaluation methodologies. Section 2 below describes the strategy that was developed to address these challenges in a consistent, integrated and synergic manner, while utilizing state-of-the art IT tools and innovative data analysis and presentation. For each component of this strategy, it will review the progress accomplished to date as well as future development plans.

2. Verification data evaluation and its evolution under the State Level Concept

Every year, thousands of days are spent by IAEA safeguards inspectors in NFC facilities and other sites around the world. A large portion of this time is used for carrying out in-field measurements by various NDA techniques and for taking ES and/or DA samples. Comparably intensive resources are needed to maintain CoK on the verification data collected through these activities by means of a range of sophisticated C/S systems. The IAEA collects, authenticates, quality controls, maintains and evaluates a large body of verification data. In this context, the specific mission of the NFC Information Analysis Section, as illustrated in Fig. 2 below is defined as follows: *to contribute to the Department's provision of credible safeguards conclusions through the evaluation of verification data from samples (ES, DA) and in-field measurements (NDA) and their comparison with State declared information in order to detect and deter diversion and undeclared activities at declared facilities and sites.*

2.1 ES data evaluation – detection of undeclared nuclear material and activities

Fig. 2 shows that the role of ES data evaluation [12,13] is different from that of NDA and DA data evaluation and that

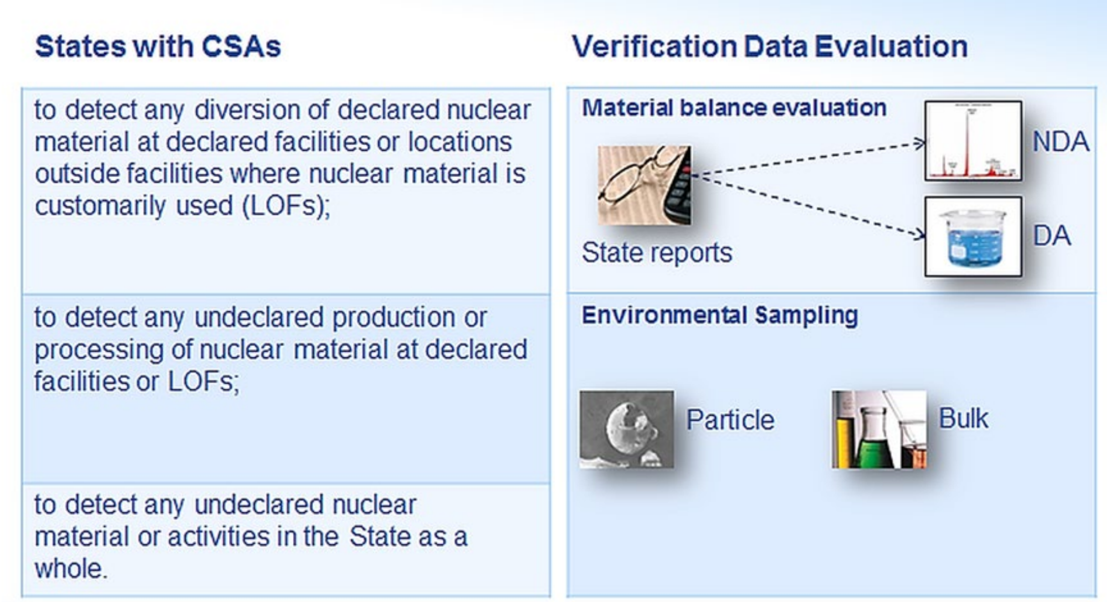


Fig.2: Role of verification data evaluation in supporting safeguards objectives under the State-level concept (example: States with a comprehensive safeguards agreement (CSA)).

it requires different expertise profiles. Its purpose is to confirm that NFC facilities are operated as declared, that there are no undeclared nuclear materials or activities in these facilities and, within the limits of its implementation modalities, that there are no undeclared nuclear materials or activities in the State as a whole. The principle of ES rests on the premise that nuclear processes release traces of nuclear and other material that constitute a signature of these processes and that can be transferred to samples collected at appropriate places. The characteristics of materials found on swipe samples (e.g. isotopic ratios, association with radionuclides or other elements) are compared with those predicted by specialized process-modelling tools. Particle analysis methods rely on the detection and measurement of individual nuclear material bearing particles on the sample. Bulk analysis methods involve the analysis of an entire swipe sample - in this case, the analytical results represent average values associated with the nuclear material contained within the sample [7].

ES was implemented in the context of strengthening the effectiveness of the safeguards system following the discovery of Iraq's clandestine nuclear weapons programme in the aftermath of the 1991 Gulf War. Its feasibility and detective power were established through a series of field trials in the context of the *Programme 93+2* with the support of Member States. Analytical laboratories that would later form the basis of the present international network of analytical laboratories (NWAL) demonstrated their capability to perform the extremely low-level radiochemical and isotopic measurements needed for the analysis of environmental samples. The field trials also showed that swipe sampling is the preferred method and it is now the standard, although other types of samples may be collected according to the technical objective pursued. For example, small quantities of ore or other compounds are regularly collected for material characterization as described below.

Since 1995, ES samples have been taken at locations where IAEA inspectors have access during inspections and design information verifications (DIV) and, following the approval of the Additional Protocol by the IAEA Board of Governors in 1997, ES can be taken at a broader range of locations in States where an AP is in force. ES has expanded over the years to include all NFC facility types and the number of ES collected increased steadily to reach the current number of up to ~400 samples per year. Sub-samples are distributed to the NWAL, which presently includes 21 laboratories in 8 States in addition to two European Commission Joint Research Centers and the IAEA safeguards analytical laboratory (SAL) in Seibersdorf, Austria.

ES continues to evolve through scientific and technical developments supported by Member States' laboratories in close collaboration with the IAEA. Technical Meetings are held every year, alternatively focusing on bulk or particle analysis, to review technological advances, among other objectives, and to discuss potential developments with representatives of the NWAL. For example, age dating [14,15,16] makes it possible to establish the chronology of certain processes based on the isotopic composition of plutonium bearing particles. Age dating of uranium bearing particles based on thorium in-growth would require an improvement of the sensitivity of laboratory analyses but is also of high interest for potential future applications. Another promising development field is nuclear material characterization (aka impurity analysis) [17, 18], which associates samples of ore and other uranium compounds with signatures in terms of the trace elements they contain (for example lanthanides). These signatures, compared with global databases currently being populated, can be used to determine the origin of these materials by applying specialized statistical algorithms. Trace element fingerprints can also provide information about processes the material may have undergone. More generally, stable chemical elements in nuclear material bearing particles could reveal chemical signatures associated to processes such as reprocessing or enrichment. The feasibility and technical requirements of such evaluation methods are currently being investigated. An existing routine application of impurity analysis is to determine if the purity of the material sampled is suitable for fuel fabrication or isotopic enrichment and hence, if it should be subject to nuclear material accountancy measures under article 34 (c) of INFCIRC/153 (Corr.).

Since they have been developed in the wake of the strengthened safeguards system and in synergy with the evolution of safeguards concepts in the last decades, ES evaluation processes and deliverables are well integrated in the present SLC system. ES evaluation reports are delivered to Operation Divisions at both sample and State level according to increasingly performant time targets. Weekly performance indicators are regularly issued to monitor the timeliness of the process and the number of ES samples evaluated in different categories. The ES evaluation processes are effectively and efficiently supported by a state-of-the art ES database, automated report generation tools and regularly upgraded expert NFC modelling tools. This advanced IT environment makes it possible to compare the characteristics of isotopic species found in samples with those predicted by theoretical models and with isotopic species observed at other facilities worldwide. However, the unique expertise necessary for ES evaluation is very rare and its application to safeguards requires a long on-the-job training period. Therefore, a well-thought-out long-term recruitment and training plan is needed to maintain an adequate level of professional capacity and capability in the ES evaluation area.

2.2 DA and NDA data evaluation – detection of nuclear material diversion

For their part, the NDA and DA data resulting from inspectors' verification sampling plans and combined with bulk measurements, i.e. weight and volume measurements, are compared with the State's NMA reports to detect diversion through the material balance evaluation (MBE) process. MBE is a complex analytical activity which assesses and combines all quantitative declared information and verification results. In particular, at bulk handling facilities (BHF) where material is processed in loose forms (gases, liquids, powders), complex measurement systems are needed to establish the flows and inventories of material. The conclusions regarding material balances rest on resource-intensive statistical and metrological analyses based on the estimation and propagation of measurement uncertainties into uncertainties associated to balance statistics. The objective of these analyses is to determine if the BHF operators' imbalances and the differences between nuclear material amounts declared by operators and measured by inspectors can plausibly be explained by legitimate measurement errors and, hence, to draw conclusions on the absence of diversion from these facilities.

In contrast with ES data evaluation, MBE was developed at a much earlier stage of the safeguards' history and is rooted in the criteria-driven, facility-based approach which has long underpinned the IAEA's conclusions. While MBE principles and methodologies 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 the analysis of the nuclear material flows, inventories and balances of the whole State, taking into account 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. In addition to this undertaking, which poses a number of methodological challenges, new approaches are needed to address increasingly large and diversified data flows, to optimize the distribution of limited MBE resources and to align them with the State-level technical objectives (TO) identified through the acquisition path analysis (APA) performed by the SEGs. In addition, MBE results need to be consolidated and compared with information from other sources. Last but not least, considerable progress was made in the field of IT and statistical methodologies since MBE was first developed several decades ago. The current migration of the safeguards Departmental IT platform under the Modernization of Safeguards Information technology (MoSaIc) project provides a unique opportunity to adapt and evolve methodologies and to integrate them into new software tools.

An additional and stringent practical challenge is to effectively address these development needs under a static budget with a small group of statistical analysis professionals whose primary mission is to deliver timely input to safeguards approaches, evaluations and conclusions for all States with extended NFCs. Priority mandates also include a substantial support to the IAEA verification activities under the Joint Comprehensive Plan of Action (JCPOA) in Iran. Furthermore, evolving evaluation approaches and processes make it necessary to regularly communicate and collaborate with stakeholders within and outside the Safeguards Department through the organization of training and liaison actions. A fruitful project to evolve safeguards verification data evaluation must therefore rest on a well-structured and synergic strategy, based on a clear long-term development plan and taking into account manpower limitations while making the best use of available extra-budgetary support, e.g. in the form of Member State Support Program (MSSP) human resources and expertise. The strategy implemented by the NFC information analysis Section since its creation in July 2011 and illustrated schematically in Fig. 3 is articulated around a set of components whose common objective is to promote and provide new types of evaluation reports designed to effectively support the work of SEGs in drawing sound safeguards conclusions:

Fig.3: Organization and components of the NFC Information Analysis Section strategy to evolve verification data evaluation under the State-level concept

Quite evidently, the starting point of any strategy, as represented at the top of the diagram is to ensure sufficient human resources (HR) both in terms of manpower and expertise. The first implementation phase of the project therefore consisted in rebuilding a team of competent statistical data evaluators after the Safeguards Department capability and capacity in this field had virtually vanished following retirements and rotation of long-standing specialized staff. This was achieved through an extensive recruitment and training campaign completed in 2013 and 2014. However, maintaining adequate staffing, based on a regularly reviewed succession plan, remains a continuous effort, given the current shortage of adequate expertise on the world market.

In order to address the methodological component of the project and to foster new ideas, a biennial Technical Meeting (TM) on Statistical Methodologies for Safeguards was initiated to establish an overview of the methodological landscape in this field, gather worldwide expertise in addressing current gaps and questions, draft recommendations around the high-level structure represented in Fig.4 below and build a network of specialists to remedy the lack of internal resources by identifying potential MSSP support tasks. The first TM was held in Vienna in October 2013.

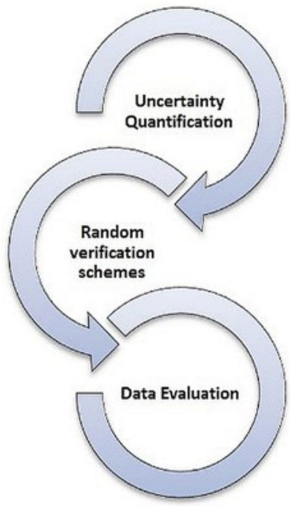
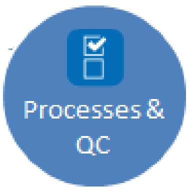
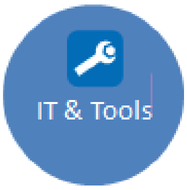


Fig.4: Three high-level interconnected methodological development areas as identified during the 1st TM on Statistical Methodologies for Safeguards (Vienna, October 2013).

Considerable progress, described in numerous publications [10], was made to date in the first two areas (uncertainty quantification and random verification schemes) and led to the preparation of several new safeguards technical reports (STRs), thanks to extensive MSSP support in the form of cost free experts (CFEs) and individual support tasks. The next phases planned include the harmonization of uncertainty quantification terminology between safeguards partners (evaluators, facility operators, laboratories) in preparation of the periodic review of international target values (ITV -2020) as well as a methodological consolidation of random inspections schemes. These topics will be the focus of the 3rd TM in October 2017. On completion of the prerequisite methodological work on uncertainty quantification and random verification schemes, the final phase will consist in reviewing and upgrading data evaluation methodologies which constitute the cornerstone of the overall project.



In parallel to the methodological review, evaluation processes and procedures are being adapted to the Departmental organisation which supports the work of the SEGs under the State-level concept. Process improvements were implemented in coordination with Operation Divisions in order to optimize both timeliness and quality based on available resources. Direct collaboration with inspectors in the framework of State-level approaches have significantly increased as well as in-field integration of evaluator expertise through their participation in inspections and design information verification (DIV) activities. This has greatly improved communication and collaboration between inspectors and evaluators and, in some cases, has allowed the resolution of long-standing issues. Quality control (QC) continues to be an essential component of the data evaluation activities and is now implemented at the level of the source data, of the evaluation process and of the resulting conclusions, by systematic peer-review, and by an additional review by inspectors in charge of facilities and States to ensure that all in-field and operational information has been taken into account.



In the context of the re-engineering and integration of safeguards databases and software under the MoSaIc project and their migration into the secure integrated safeguards environment (ISE), all legacy software that was developed over the last decades to support statistical analysis, e.g. sampling plans, verification performance evaluation, analysis of DA sample results, and MBE, are also being re-engineered and integrated under the Statistical Testing, Evaluation and Planning for Safeguards (STEPS) project. The STEPS project is designed to take into account both methodological and best practise developments and is expected to substantially increase the efficiency of the evaluation processes through the automation of calculations, QC checks and report generation.

In the framework of the State-level concept, operations inspectors and safeguards analysts need to understand and consolidate conclusions from many different sources of information. A structured programme of seminars is organised by the NFC Information Analysis Section to ensure effective communication with safeguards analysts from different areas and with Operation inspectors. These seminars address the mathematical rationales underlying safeguards verification strategies as well as the statistical treatment of the quantitative data declared by NFC facility operators and collected by operations inspectors. Their objective is to present the mathematical and statistical methodologies applied in safeguards in a clear and progressive way, using a minimum of formalism and with special emphasis on practical examples taken from everyday safeguards experience.

In addition to training and regular liaison with IAEA partners, a valuable measure in monitoring the quality of NMA and verification data is a trilateral liaison framework [11] with the SRA[10] and facility operators to discuss MBE results for the elapsed material balance period, review trends in material balance statistics, investigate their causes and agree upon recommendations and possible remedial actions. When available, DA sample results from three laboratories (IAEA, RSAC/SSAC[11], facility operator) are also examined to identify biases and compare analytical uncertainties. Using not only IAEA's and operators' measurement results but also the SRA's results can help to investigate the source of significant pairwise differences of DA sample results. The cooperation of SRAs and facility operators with the IAEA in the framework of trilateral liaison meetings provides a useful mechanism to remedy any issue related to the quality of the operator's measurement systems before it becomes a safeguards concerns, thereby promoting a proactive rather than reactive approach. This considerably enhances safeguards effectiveness and efficiency since the root cause of NMA issues may be difficult to establish at a later point, when their effects on the material balance have reached a safeguards significant threshold. In several instances, yearly trilateral liaison meetings organized between the IAEA, the SRA and plant operators have noticeably improved the operators' accounting procedures and/or measurement performance. In addition, trilateral meetings considerably increase the quality of communications between safeguards partners by fostering direct contacts between IAEA, SRA experts and facility staff specialized in NMA and by making it possible to maintain continuity of knowledge on complex technical files in case of rotation of responsible staff on all sides. Given their in-depth knowledge of industrial processes, operational conditions and accounting systems, nuclear fuel cycle facility operators are often the most knowledgeable when it comes to identifying the source of procedural or measurement issues. A regular dialogue with them is an important confidence building measure that improves their understanding of safeguards objectives and practices and engages them to willingly cooperate in ensuring the performance of the facility's accounting and measurement system.

As was commented above, the bases for evolving DA, NDA and MBE data evaluation reports and designing new report types were laid by the NFC Information Analysis Section as a keystone and convergence point since the strategy described in this paper was first implemented. However, the deployment of new reports is progressive and depends on the development stage of the project components described above. The central challenge is to design a concept addressing the complexity of MBE at State level while *optimizing its effectiveness* at detecting diversion and/or misuse at *key points* of the State nuclear fuel cycle. This paragraph describes some of the main guiding principles, i.e. a) evolution from a facility oriented approach to a State-level approach b) integration of

[10] State or regional authority responsible for safeguards implementation.

[11] State/regional Systems of Accounting and Control.

the *Physical Model* [8], as a backbone of the method, to support flow analysis and information consolidation; c) use of modern *visualization tools* to extract significant facts and patterns and identify potential inconsistencies in growing volumes of data [6].

The table in Fig. 5 compares the main features of the new data evaluation reports with the former facility-oriented concept:

BEFORE	NOW
• Facility based evaluation	• Facility and State evaluation.
• For BHF holding more than 1 SQ	• For any facility if relevant.
• Fixed criteria (e.g. detection of 1 SQ)	• Focus on technical objectives.
	• Enhanced analytical content.
• Not fully developed in SER	• Supports SIR and SER.
• SIR "crunch" – 60 facilities (~210 MBE) in 2.5 months. Needs:	• Integrated in SE cycle:
✓ All BHF CIR Part I completed.	✓ effort spread over the year.
✓ All NDA reported and QC.	✓ improved quality.
✓ All DA reported and QC.	✓ More sustainable under reduced resources.
✓ Uncertainties (RSD) actualized.	• Combined with enhanced liaison.

Fig.5: Evolution from a facility oriented approach to a State-level approach

In addition to providing a solution to resource limitations related to internal processes and timetables, the highlight of this new evaluation approach is that it is in line with one of the main tenets of the SLC, i.e. it addresses specific technical objectives (TO) resulting from the SEGs' APA and makes it possible to focus analytical resources on these TO as opposed to systematically checking a certain number of predetermined criteria. For example, while MBE evaluation was performed in the past for BHF holding more than one significant quantity (SQ) only, it can now be performed for any facility in agreement with the SEG if this is considered relevant to an identified acquisition path. Conversely, although it is important to mention that all large BHF will continue to be subject to MBE, the thoroughness of the evaluation may be adapted to prioritize analytical resources in case diversion during a given material balance period was covered by effective and conclusive measures (e.g. C/S), making MBE redundant, or in case the effectiveness of MBE is insufficient (e.g. low detection probabilities due to very large material flows/inventories).

The key principle of the method consists in visually representing nuclear material flows on a backdrop structure based on the Physical Model (PM) as shown in Fig 6. It can be outlined as follows:

- Facilities are represented by boxes grouped according to their function in the State nuclear fuel cycle (stages of the PM).
- For a period that can be customized by the user, nuclear material flows between facilities are visualized by solid curves whose colour represents material types and whose width is proportional to their magnitude (normalized in SQ), which can be read from the tick marks on the PM separation lines.
- Beginning and ending inventories are represented according to the same scale convention.
- Flows into and out of the States are symbolized by ellipses.

The APAs developed by SEGs identify paths, steps and the corresponding TOs which involve diversion or misuse of nuclear material at declared facilities. This makes it possible, as described above, to align data evaluation efforts with the results of the APA, taking into account the other safeguards measures foreseen by the SLA. In addition, operational links between facilities that can influence specific MBE statistics and their trends are emphasized and integrated in the data evaluation. Initial EXCEL-based prototypes (2011) and later automated trials (2013) performed in collaboration with SEGs demonstrated that the interest of the nuclear material flow diagrams underlying this method –referred to as Sankey diagrams[12] or "Snakeys" in reference to their sinuous appearance (Fig.6 below) - go beyond data evaluation and can usefully support the general work of SEGs, *inter alia*, the APA itself. The method has now evolved from the key elements described above to include a number of interactive features which support the current Departmental evolution from paper to electronic deliverables. In addition, the original concept is designed to integrate other types of relevant information (e.g. APA, SLA as well as ES, NDA and DA verification results). It is envisioned that, in future, it could serve as a possible portal to safeguards information in a State seen from a nuclear material perspective.

3. Conclusion

A structured, comprehensive and synergic long-term strategy is implemented by the Department of Safeguards' Division of Information Management NFC Information Analysis Section to evolve the evaluation of verification data in order to ensure the integration of its concepts, methods and processes into the SLC framework while optimizing its effectiveness in detecting undeclared nuclear material and activities and diversion of nuclear material at declared facilities. The present paper presents the complementary and mutually supporting components of this strategy, which converge towards the promotion and provision of new types of data evaluation reports designed to better support the work of SEGs.

An essential and innovative feature of this new generation of safeguards data evaluation reports is that it utilizes the power of modern IT, which allows interactivity, supports the Department's evolution to secure electronic deliverables and takes advantage of data visualization to complement the limited capacity of the human brain to extract useful and relevant information from large volumes of data.

[12] Sankey diagrams are named after Irish Captain Matthew Henry Phineas Riall Sankey, who used this type of diagram in 1898 in a classic figure (see panel on right) showing the energy efficiency of a steam engine (from Wikipedia)

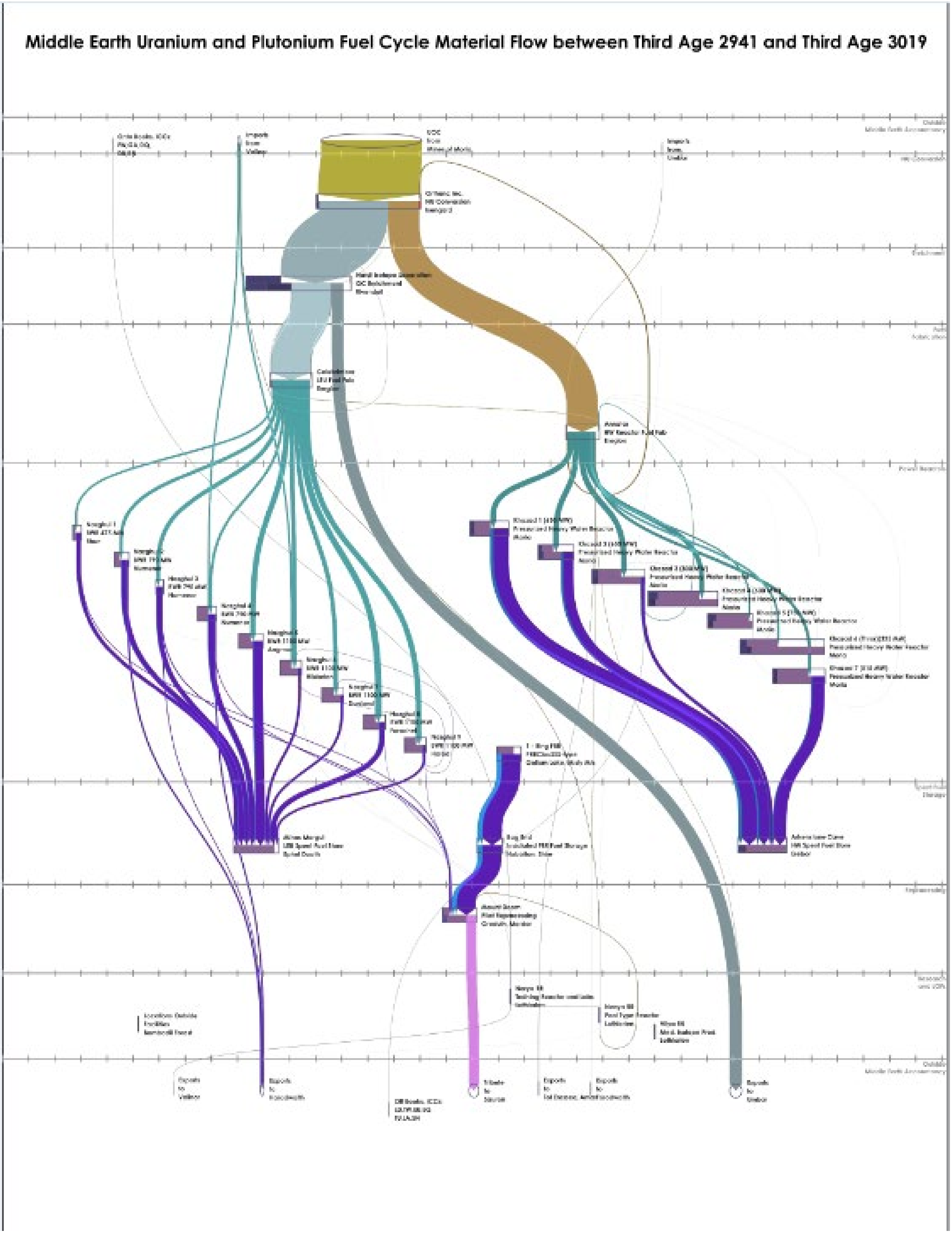


Fig.6: Snapshot of a nuclear material flow “Snakey” diagram for a hypothetical State

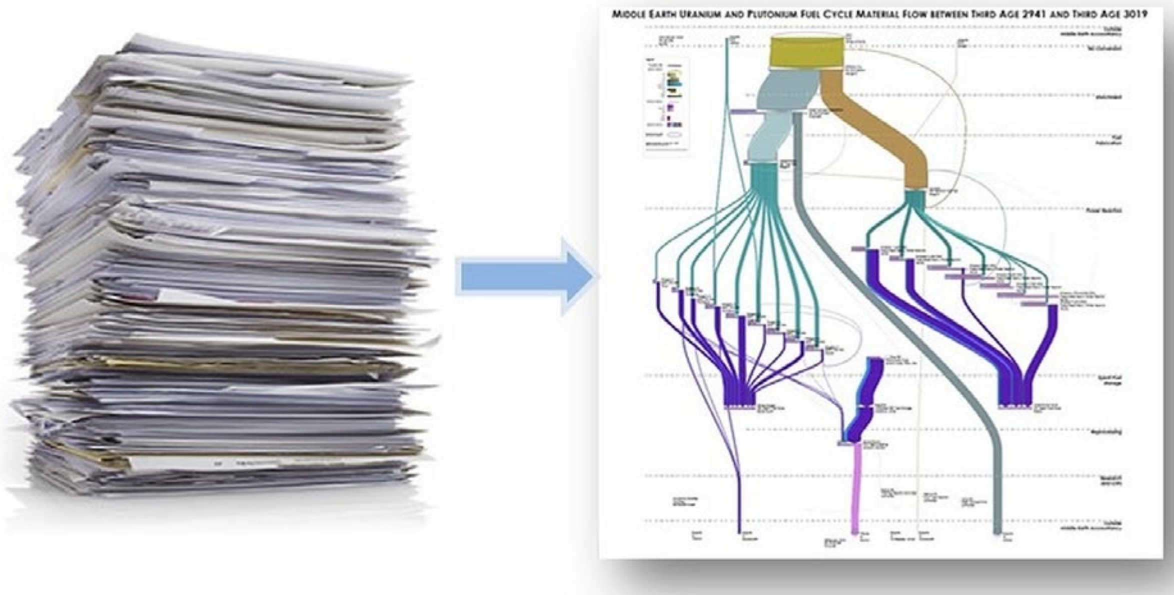


Fig.7: Data visualization can help analyze and understand large volumes of data

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