Development of a National Nuclear Forensics Library: A System for the Identification of Nuclear or Other Radioactive Material out of Regulatory Control

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DEVELOPMENT OF A NATIONAL NUCLEAR FORENSICS LIBRARY: A SYSTEM FOR THE IDENTIFICATION OF NUCLEAR OR OTHER RADIOACTIVE MATERIAL OUT OF REGULATORY CONTROL

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DEVELOPMENT OF A NATIONAL NUCLEAR FORENSICS LIBRARY: A SYSTEM FOR THE IDENTIFICATION OF NUCLEAR OR OTHER RADIOACTIVE MATERIAL OUT OF REGULATORY CONTROL

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FOREWORD

Nuclear forensics supports measures to prevent and respond to a nuclear security event by providing information on the origin and history of nuclear and other radioactive materials out of regulatory control in the context of international legal instruments and national laws related to nuclear security. An important element of a nuclear forensics examination is the ability of a State to determine whether nuclear and other radioactive material in that State is consistent with domestic holdings. A national nuclear forensics library can facilitate interpretation of findings and assist States in this making this determination.

There is growing recognition of the importance of nuclear forensics in enhancing a State's nuclear security infrastructure. IAEA General Conference resolutions on nuclear security regularly endorse work in the field of nuclear forensics, including the establishment of national nuclear material databases and libraries. A key finding of the 2014 IAEA International Conference on Advances in Nuclear Forensics: Countering the Evolving Threat of Nuclear and Other Radioactive Material out of Regulatory Control was the role of a national nuclear forensics library in aiding data interpretation and furthering nuclear security investigations. This publication follows IAEA Nuclear Security Series No. 15, Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control, which encourages States to assess their nuclear forensics capabilities, including consideration of a national nuclear forensics library.

The preparation of this publication involved extensive consultations with Member States, beginning in 2010 and continuing through the drafting process. The IAEA is grateful to these Member States for their many valuable comments and other contributions to this publication.

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1. INTRODUCTION

1.1. BACKGROUND

To address the threat posed by nuclear and other radioactive material out of regulatory control, the International Atomic Energy Agency (IAEA) is assisting States in the use of nuclear forensic science to investigate incidents involving such material.

"Nuclear forensic science or nuclear forensics is a discipline of forensic science involving the examination of nuclear and other radioactive material, or of other evidence that is contaminated with radionuclides, in the context of legal proceedings" (see Ref. [1]). A nuclear forensic examination consists of a measurement of the characteristics of nuclear or other radioactive material found out of regulatory control, a comparison of its measured characteristics with reference information, and an interpretation by a subject matter expert to formulate nuclear forensic findings that answer investigative questions in accordance with national laws and procedures. [1] [2] This comparison step can be facilitated by using a National Nuclear Forensics Library. The comparison step is often an important part of an investigation of nuclear or other radioactive material found out of regulatory control, and may assist in determining the origin and history of the material out of regulatory control.

A 'National Nuclear Forensics Library' (hereafter, Library), is a national system for the identification of nuclear and other radioactive materials found out of regulatory control. It comprises reference information and subject matter expertise on nuclear and other radioactive materials produced, used, or stored within a State that may be used to identify the materials out of regulatory control. A Library enables comparisons to information on known materials and data obtained from analytical measurements of nuclear or other radioactive materials found out of regulatory control. In combination, the resources contained in the Library support the examination of nuclear or other radioactive material found out of regulatory control to evaluate information and formulate nuclear forensic findings, i.e. make determinations on material origin and history [1, 2].

Use of the information contained in this publication is voluntary. Both the establishment of a Library and the principles of organizing a Library remain the prerogative of a State.

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[1] Reference information refers to data that is collected nationally to meet legal, regulatory, or quality assurance requirements, i.e. nuclear material accountancy records, import-export certificates, and material specification certificates that, *inter alia,* include the physical, chemical, elemental and isotopic properties of nuclear and other radioactive materials that may have been collected for purposes not related to nuclear forensics. Reference information may be found in, for example, nuclear research laboratories, academic institutions, regulatory bodies, and material production, nuclear, medical, industrial, or other facilities.

[2] A subject matter expert is an individual who specialize in the nuclear fuel cycle or production of radioactive sources, and could assist in making determinations on nuclear or other radioactive material found out of regulatory control. Depending on the judicial system in place nationally, a subject matter expert may be an official person or institute/organization that has satisfied specific requirements defined by national laws.

1.2. OBJECTIVES

The objectives of this publication are:

- To provide policy makers, competent authorities, law enforcement officials, and technical personnel with information about the role and benefit of establishing and using a Library as part of a nuclear security investigation;
- To impart context for the use of a Library to identify the origin and history of nuclear or other radioactive material found out of regulatory control.

This publication seeks to assist States that choose to develop a Library tailored to their individual circumstances, national legal requirements, and security needs.

1.3. SCOPE

This publication provides the rationale for the development of a Library and addresses how a State may use a Library in investigations of nuclear and other radioactive material out of regulatory control. Additionally, it provides information helpful to understand and organize information on nuclear and other radioactive material within the State, relevant to nuclear forensics, based on nuclear processing steps, radioisotope source types, and radioisotope source applications.

This publication does not include detailed information on the establishment of a Library; the establishment of a material sample archive; legal, policy, and financial aspects regarding the establishment or use of a Library; what, if any, information can be shared with other States; or advice on how to conduct nuclear forensic examinations. Guidance on conducting nuclear forensic examinations is provided in (see Ref. [1]), *Nuclear Forensics in Support of Investigations (Nuclear Security Series No. 2-G)*.

1.4. STRUCTURE

The remainder of this publication is organized as follows: Section 2 describes the rationale and practical considerations for development and maintenance of a Library. Section 3 presents data resources that may support a Library. Section 4 illustrates the application of a Library for identification of nuclear or other radioactive material encountered out of regulatory control. Section 5 provides a context how a Library can facilitate international cooperation to identify nuclear and other radioactive material out of regulatory control. Annex I provides information on various categories of nuclear and other radioactive material and material signatures from stages of the nuclear fuel cycle and radioactive source production that may be associated with a State's Library. Annex II provides an example of a data structure from a hypothetical Library. Finally, Annex III lists preferred reporting units for Library data.

2. DESCRIPTION OF A NATIONAL NUCLEAR FORENSICS LIBRARY

A National Nuclear Forensics Library is a national system for the identification of nuclear and other radioactive materials found out of regulatory control. A Library is composed of subject matter expertise and reference information on nuclear and other radioactive materials produced, used, or stored within a State that may be used to identify these materials.

Reference information on the characteristics of nuclear or other radioactive material produced, used, or stored within a State contributes to the State's ability to assess whether nuclear or other radioactive material found out of regulatory control originated within the State or outside the State. Information that contributes to a Library may already exist in a State, having been collected at other times and for other purposes, e.g. a national registry of radioactive sources. The timely availability of nuclear forensics reference information may strengthen the ability of subject matter experts to formulate nuclear forensic findings and assist investigations.

Subject matter experts use a Library to interpret results from analysis of nuclear or other radioactive materials found out of regulatory control and formulate nuclear forensic findings in response to queries from investigators regarding the nature of the material. Subject matter expert judgement is essential for comparisons and formulation of high confidence nuclear forensic findings.

The physical properties, chemical and elemental composition, isotopic ratios, and other signatures of the material may provide information on the material's provenance, manufacture, and processing and serve as important indicators of the materials' origin, history, and intended use (see Ref. [2]).[3] The interpretation of these signatures allows nuclear forensics to both assist investigations and serve as a preventive measure to deter the diversion of nuclear and other radioactive materials (see Ref. [1]).

A State may choose the most effective way to establish its Library. As such, a State may decide to establish a Library as a consolidated set of subject matter expertise and databases or as a distributed model relying on subject matter expertise and databases from a variety of locations and agencies involved in nuclear and radioactive production, use, or storage.

2.1. RATIONALE FOR THE DEVELOPMENT OF A NATIONAL NUCLEAR FORENSICS LIBRARY

Illicit trafficking of nuclear and other radioactive material is of national and transnational concern. When nuclear and other radioactive material is detected out of regulatory control, States should be prepared to respond appropriately, including applying nuclear forensics in support of investigations.

[3] For the purposes of this publication, a signature is a characteristic or a set of characteristics that enables that nuclear or other radioactive material found out of regulatory control to be compared with reference materials to make determinations on origin and history.

The use of a Library may assist investigators in answering various questions regarding nuclear and other radioactive materials found out of regulatory control. These questions can include assessments to identify intended material uses, possible origins, connections between different cases involving illicit trafficking, and pathway or trafficking route analysis. Consideration of the types of questions investigators may ask during the response to a nuclear security event, can inform a State in determining how to best develop a Library. Examples of such questions may include the following:

- Is the material consistent with the State's holdings?
- What is the material and what threat does it pose?
- What is the intended use of the material?
- From which nuclear fuel cycle process does the material originate?
- Is there more material missing?
- Which facilities are associated with the manufacture, use, or storage of the material?
- Does the material share a common origin with a material from another case?
- Is environmental or biological evidence contaminated with radionuclides connected to a bulk material source?

The combination of reference information and subject matter expertise that contribute to a State's Library can enhance confidence in assessments of possible material origin or history, and whether material is consistent with a State's holdings. Furthermore, a Library can ensure availability of information and subject matter expertise necessary to facilitate credible and timely decisions, and coordination between investigators, forensic scientists, and other relevant entities.

It is the prerogative of the State to decide how a Library may be developed and support a nuclear forensics examination, and when and if it is appropriate to request external assistance.

2.2. SCOPE OF A LIBRARY

A Library is commensurate with the nuclear fuel cycle within the State, or by parties within the State, and the size and complexity of its nuclear and other radioactive material holdings. The development and maintenance of an effective Library involves a coordinated national effort to collect and use reference information and subject matter experts within the State (see Fig. 1).

Nuclear forensic conclusions are often drawn using information inherent to nuclear and other radioactive material, such as physical properties, chemical and elemental composition, and isotopic ratios arising from geological or manufacturing processes. These indicators, often referred to as signatures, form the basis for nuclear forensic comparisons and are the information at the core of a Library. However, for States with smaller inventories of nuclear and other radioactive material, non-technical indicators such as serial numbers and labels for radioactive sources may be sufficient to identify whether material is consistent with State holdings.

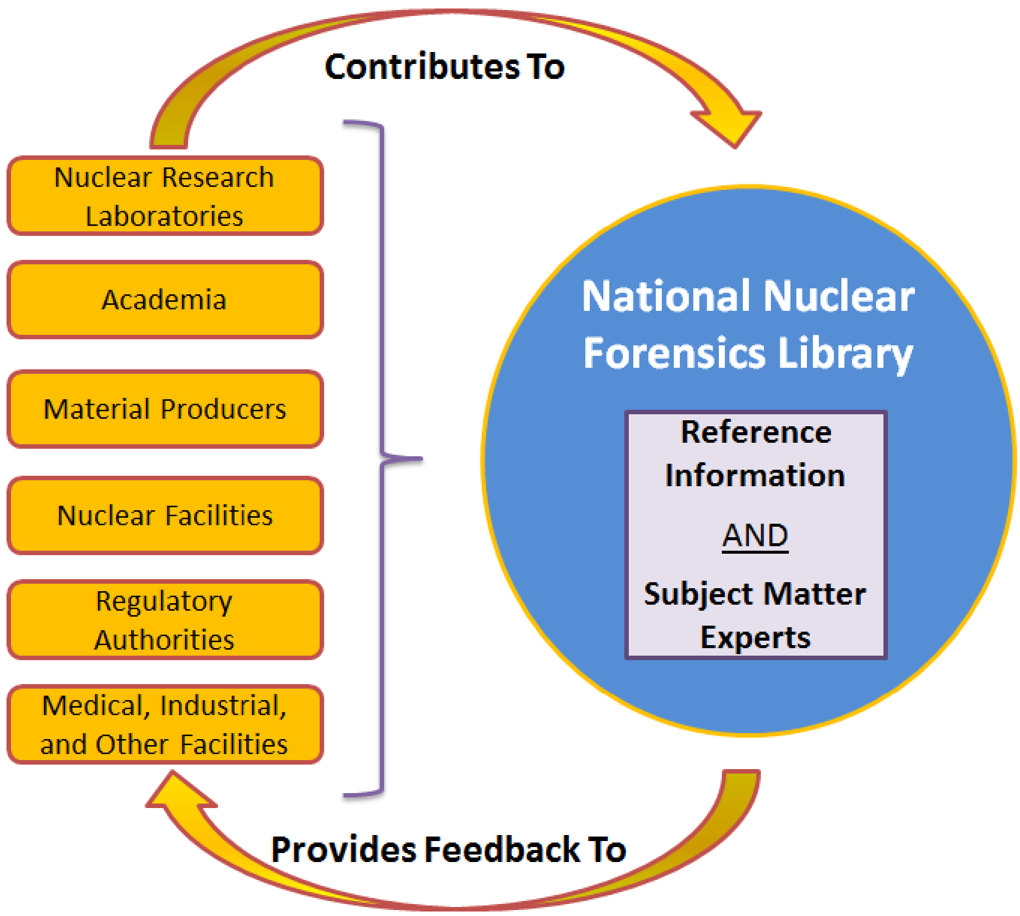

FIG. 1. Association between a States' existing reference information, subject matter expertise, and a Library.

2.3. DEVELOPMENT PROCESS

The development of a Library involves, at a minimum, the identification of responsible organizations, personnel, as well as data and information resources. This includes identifying and organizing existing reference information related to nuclear and other radioactive material in the State, as appropriate, including information related to the production and use of radioactive sources. The subject matter expertise within the State can be used to determine reference information relevant for inclusion in a Library.

A single batch of nuclear or other radioactive material is assumed to incorporate unique signatures. For each batch, the general information, such as the name and address of the material custodian, supplier address, and batch identification with specific isotopic, chemical, and physical data, can assist investigators in identifying the material. The Library may also include information pertaining to material from intermediate production processes, for example, process samples.

The development and maintenance of a Library is a continual process of surveying, collecting, organizing, and interpreting information about nuclear and other radioactive material produced, used, and stored in the State and maintaining the subject matter expertise necessary for interpretation of analytical results. In particular, to develop and maintain a Library, it may be necessary for a State to sustain subject matter expertise in nuclear and other radioactive material characterization, laboratory techniques and the infrastructure necessary for a nuclear forensic analysis, and comparative methods for material identification.

States may need to consider whether additional resources or policy endorsements would be necessary to ensure their Library effort is successful and sustainable. Depending on a State's interests and needs, it may also involve the allocation of resources and personnel to verify and harmonize data, to analyse nuclear or other radioactive material found out of regulatory control, and possibly to develop and apply new nuclear forensics techniques. It is also important to consider the possibility of receiving assistance from partner nations to support a State's ability to identify material, and how this assistance might be integrated into the State's nuclear security infrastructure. Consideration may include whether existing law enforcement or diplomatic information sharing mechanisms are sufficient to facilitate needed regional or international dialogue regarding nuclear forensic examination.

2.3.1. Human resources

Subject matter experts from various technical disciplines such as nuclear engineers, radiochemists, geochemists, nuclear fuel-cycle specialists, reactor physicists, and statisticians, may contribute to nuclear forensic interpretations. However, more training of subject matter experts may be needed to ensure an understanding of investigative requirements, for example, in maintaining the chain of custody (see Ref. [1]).

States that do not produce nuclear or radioactive materials nor have indigenous subject matter expertise on the material they use and store may not have subject matter experts that are suitably experienced to interpret information on nuclear or other radioactive material found out of regulatory control. Such States may choose to seek training and development opportunities through bilateral exchanges or through offerings from IAEA and the Nuclear Forensics International Technical Working Group.

2.3.2. Use of existing information

Available reference information regarding known nuclear and other radioactive material holdings may be considered for inclusion in a Library. For example, a State may consider incorporating information related to nuclear and other radioactive material available in nuclear material databases, material analysis reports, documentation and expertise from manufacturers, historic document archives, and information from past investigations. A significant portion of this reference information may have been collected for purposes other than nuclear forensics and may be found in, for example, nuclear research laboratories; academic institutions; regulatory bodies; and material production, nuclear, medical, or industrial facilities. Such information might include nuclear material accountancy records, import-export certificates, and material specification certificates.

Other aspects may need to be considered when including information in a Library. When preparing for an examination as part of an investigation, subject matter experts should consider the quality, validity, and limitations of data used, as these aspects may impact the defensibility of nuclear forensic findings during an investigation and subsequent prosecution. The comparability of data may also require consideration during an investigation, for example, data from different sources may need to be converted to a standard format, e.g. International System of Units (SI), before performing comparative analysis. Because the development of the Library involves a continual process, reference information can be included later.

2.3.3. Understanding of signatures in materials

Signatures derived from nuclear forensics analysis of nuclear or other radioactive material found out of regulatory control are compared to signatures of known material to help determine whether the material out of regulatory control is consistent or inconsistent with material produced, used or stored within the State.[4]

A comprehensive understanding of a State's materials helps subject matter experts to identify unique signatures and allows for subsequent interpretation of analytical results. This understanding will enhance a State's ability to analyse nuclear or other radioactive material found out of regulatory control, or its traces, with known materials. It may also help to recognize information gaps that need to be filled.

It may be useful for a State to develop a methodology for the discriminating material signatures, for example, by identifying the major and minor isotopes, age of the material, and its physical dimensions. As samples of nuclear and other radioactive material may possess many signatures, subject matter experts within a State may consider determining which of those signatures may assist nuclear forensic examiners in determining if materials encountered out of regulatory control are or are not consistent with a State's material holdings.

2.3.4. Nuclear or other radioactive material sample archive

Nuclear forensic findings can be effectively formulated by comparing the characteristics of materials found out of regulatory control (including traces, if necessary) with nuclear or other radioactive material samples existing within the State with known manufacturing parameters and characteristics. States may find it useful to support their Library with a collection of relevant nuclear and other

[4] For the purposes of this publication, known material refers to materials under domestic regulatory control and with documented characteristics.

radioactive materials, for example, material samples from nuclear fuel cycle operations within the State, as feasible.

In States where nuclear and other radioactive materials are produced, samples are often stored at the production sites. In these circumstances, a distributed archive model may be more practical than a centralised archive structure.

Archive samples can be studied in detail to identify unique material characteristics and signatures, for validating analytical procedures and training personnel in nuclear forensic analytical and investigative methods.

2.3.5. Library sustainability

Once a Library has been developed, the bureaucratic, legal, and financial mechanisms for sustaining it need to be considered. Such mechanisms can take various forms, and would benefit from the inclusion of all competent authorities and interested parties involved in a nuclear forensics examination.

As part of sustaining its Library, a State might consider mechanisms for continuously updating the reference information considered to be part of the Library. As information is collected by institutions such as nuclear research laboratories, academic institutions, regulatory bodies, and material production facilities for various purposes, a State may consider developing mechanisms to better catalogue the types of reference information available for comparison with nuclear and other radioactive materials encountered out of regulatory control.

A State may consider provisions to maintain subject matter expertise associated with this information through knowledge transfer to subsequent generations of subject matter experts. This can be augmented through training programmes for specialties in nuclear science, for example, technologists and analysts specializing in nuclear material, environmental sampling, and nuclear fuel-cycle activities.

A State may also consider exercising a Library capability regularly to ensure Library resources are available and subject matter experts are capable of responding to queries from investigators. Such exercises, which can be carried out nationally or internationally, may represent real-world scenarios of actual investigations of nuclear and other radioactive material found out of regulatory control.[5] During such exercises, subject matter experts—analysts and technologists—will gain an understanding of how their results and assessments inform the investigative process. The outputs from these exercises will allow subject matter experts to refine the nuclear forensic analytical process and to ensure nuclear forensic findings will be able to meet investigative requirements.

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[5] Nuclear Forensics International Technical Working Group Galaxy Serpent Exercises.

3. DATA RESOURCES TO SUPPORT A NATIONAL NUCLEAR FORENSICS LIBRARY

Characteristic data of materials are an important component of a Library. It is used by subject matter experts to help formulate nuclear forensics findings on whether nuclear or other radioactive material found outside of regulatory control is consistent with materials used in the State.

When deciding which data resources are potentially valuable to include in a Library, a State might first assess what nuclear or radioactive material exists within the State (please see Table 1 for examples of nuclear and other radioactive material processes and applications and related materials). Reflecting economic, technical, or personnel constrains, a State may choose to prioritize its Library efforts by initially focusing on understanding information associated with nuclear or other radioactive material deemed of highest concern, for example, nuclear-weapons-usable nuclear material or highly radioactive sources. The size and complexity of a State's Library scales with a State's nuclear or other radioactive material holdings, for example, a State with small inventories of radioactive material holdings might find it adequate to keep track of sealed sources using a list of serial numbers, labels, and other parameters rather than a full catalogue of data characteristics.

TABLE 1. Nuclear and Other Radioactive Material Processes and Applications and Related Materials Relevant to Nuclear Forensics.

Nuclear and Other Radioactive Material Processes and Applications	Related Materials
Uranium mining, milling, and extraction	Ore, Ore concentrate, e.g. U_3O_8 (yellow cake)
Uranium conversion	UF_6, UF_4, UO_2, UO_3, U_3O_8, uranyl nitrate, uranium metal and alloys
Uranium enrichment and uranium and mixed-oxide (MOX) fuel fabrication	UF_6, UF_4, UCl_4, UO_2, U_3O_8, ThO_2, MOX powder, uranium metal, pellets, rods, plates, elements, scrap, fuel assemblies, scrap
Irradiated (spent) nuclear fuel	Spent fuel
Reprocessing	Plutonium nitrate, uranyl nitrate, plutonium oxide, uranium oxide, mixed oxide, other actinides
Radioactive waste processing, handling, and storage	Radioactive waste forms
Radiography, well logging sources, sterilizers, and therapeutic medicine	Sealed radioactive sources
Tracer studies, research and development, diagnostic or therapeutic medicine, and irradiated targets	Unsealed radioactive sources

Consideration of the sources of reference information and relevant subject matter expertise is necessary to support a Library. Subject matter experts can also help analyse information for patterns or trends that enhance a State's ability to determine distinguishing characteristics for the identification of its own materials. A detailed description of data characteristics potentially useful for material identification can be found in Annex I and in Ref. [2].

4. USE OF A NATIONAL NUCLEAR FORENSIC LIBRARY TO SUPPORT THE IDENTIFACTION OF NUCLEAR AND OTHER RADIOACTIVE MATERIAL OUT OF REGULATORY CONTROL

If a nuclear security event occurs in a State, a Library can provide valuable support to the investigation. The Library can support investigators during several phases of a nuclear forensic examination, including the following:

- Initial material characterization;
- Development of a data-informed nuclear forensic analytical plan;
- Comparative analysis to identify possible material origins and process history.

The use of a Library can help investigators answer questions in relation to various evidence sample types, including the following:

- Bulk nuclear or other radioactive material;
- Items contaminated with radionuclides;
- Biological samples, i.e. urine, blood, hair, and tissue contaminated with radionuclides;
- Environmental or geological samples associated with the nuclear or other radioactive material [1].

For all these examples, data from a nuclear forensic analysis may be compared to data in a State's Library in conjunction with subject matter expert assessment to help provide insight into material provenance, production history, or to assist investigators to understand where nuclear or other radioactive material was diverted out of regulatory control.

As data is returned from a nuclear forensics examination, for example when data is obtained in the field, a Library can be used to evaluate material characteristics to provide investigative leads. If a nuclear forensic analysis is conducted, subject matter experts may provide valuable input into the development of a nuclear forensic analytical plan to ensure the characteristics necessary for evaluating production history, provenance, or any other forensic questions are included in the plan. As additional data becomes available during analysis, further consultations with subject matter experts may identify archived samples appropriate for comparative analysis. Once an analysis is complete, answers to queries from investigators in concert with a description of any additional work needed, can contribute to high confidence nuclear forensic findings. Each of these three aspects is discussed in more detail in the following sections.

When conducting nuclear forensics analysis and interpreting resultant data, it is important to note that limitations exist concerning the use of a Library, and care should be taken when communicating findings to investigators. Data characteristics of nuclear or other radioactive material may or may not be consistent, with a given uncertainty, with data contained in a Library. If the characteristics of nuclear or other radioactive material found out of regulatory control material are assessed to be consistent with a State's holdings, it is not necessarily an indication of origin of the nuclear or other radioactive material. Often, a nuclear forensics examination may not definitively identify the origin of nuclear and other radioactive materials, but its ability to exclude possible sources can contribute to the goals of an investigation.

4.1. INITIAL MATERIAL CHARACTERIZATION

The initial characterization of nuclear and other radioactive material or its traces found out of regulatory control in the field can produce valuable information that can be used to formulate nuclear forensics findings. This information can include, for example, results from non-destructive analysis of nuclear and other radioactive material, or its traces, associated with evidence (see Ref. [1]).

Based on the initial and subsequent laboratory characterization, it is possible to identify material characteristics (isotopic compositions, elemental compositions, physical form). Subject matter experts may use these characteristics to query databases and compare with other information sources and material archives to further guide nuclear forensic analysis.

4.2. DEVELOPMENT OF A DATA-INFORMED NUCLEAR FORENSICS ANALYTICAL PLAN

Considering the nature and amount of the nuclear or other radioactive material found out of regulatory control, the results of its initial and subsequent characterizations, as well as, the availability of relevant archive samples and information from databases, nuclear forensics examiners might seek guidance from the Library when developing a data-informed analytical plan for material identification. As an analytical plan is iterative and deductive, it can be adjusted as the results from the comparative analyses are obtained (see Ref. [1]).

Close collaboration between all stakeholders, i.e. investigators, nuclear forensics examiners, and subject matter experts, is necessary to ensure timely and effective exchange of information to support an investigation. This collaboration ensures laboratory analyses are prioritized and that the only analyses performed are those necessary to answer investigative questions and provide opportunity to advise the technical scope of the investigation.

4.3. COMPARATIVE ANALYSES TO IDENTIFY POSSIBLE MATERIAL ORIGINS AND PROCESS HISTORY

A key feature of a State's Library is the ability to compare data from a nuclear or other radioactive material found out of regulatory control to other sources of existing data, such as reference information, to help answer investigative questions. In some cases, following characterization, a Library might be used to compare a nuclear or other radioactive material found out of regulatory control with either a material from an archive, or with a technical specification for a material from a known source. In other cases, questions regarding possible origin or process history can be answered through comparison to modelled data or populations of data from databases.

Examples of how comparative analysis performed by a State's Library might support a nuclear security investigation include the following:

- Linking multiple cases involving the same material or materials;
- Connecting evidence contaminated with trace or micro-particles of material to a bulk material;
- Determining whether a nuclear material is consistent with the technical specifications for a material produced in a particular facility;
- Determining whether a radioactive source is consistent with the specifications for a source produced by a particular supplier.

Subject matter experts may use three types of comparative analyses for determining associations between a nuclear or other radioactive material found out of regulatory control and characteristics of actual or modelled materials. These three comparison types include the following:

- Point-to-point comparisons, where characteristics from a nuclear or other radioactive material found out of regulatory control are compared directly to characteristics from a known material; for example, characteristics of an archive comparator sample or the technical specifications for a particular material;
- Point-to-model comparisons, where characteristics from a nuclear or other radioactive material found out of regulatory control are compared to modelled data; for example, comparing measured isotopic composition to data predicted from the consumption of nuclear fuel in a reactor (i.e. burn-up);
- Point-to-population comparisons, where characteristics from a nuclear or other radioactive material found out of regulatory control are compared to populations of data for similar materials; for example, comparing trace element concentrations in a uranium ore concentrate to databases of trace element concentrations measured in uranium ore concentrates produced at various plants.

Various outcomes are possible from the comparative analysis of a nuclear or other radioactive material found out of regulatory control with archive materials, based on the degree of similarity in the characteristics of the materials. These outcomes include:

- All measurable characteristics within the limits of uncertainty are the same, indicating the characteristics of the nuclear or other radioactive material found out of regulatory control are consistent with known materials;

- Some measurable characteristics are the same, indicating the nuclear or other radioactive material found out of regulatory control may be related and potentially share a common origin or process history with known materials;
- No measurable characteristics are the same, indicating the nuclear or other radioactive material found out of regulatory control are unlikely to be related with known materials;
- Measurements are inconclusive and an assessment of a relationship between a nuclear or other radioactive material found out of regulatory control in question and archive samples is not possible with known materials.

These possible outcomes of a comparative analysis, combined with subject matter expert evaluation, are used to formulate nuclear forensic findings of the history of the material. Subject matter expert judgement is important in reaching a finding when comparing data from different sample types; for example, archive samples, trace radionuclide evidence, or samples with large differences in the magnitude of measurement uncertainty. Subject matter experts often use their judgement to evaluate the likelihood or confidence in a nuclear forensic comparison assessment.

When the comparative analysis indicates that the parameters and characteristics of the nuclear or other radioactive material found out of regulatory control coincide with one of the materials from the archive, a preliminary nuclear forensic finding is possible. However, in cases where only certain characteristics of the nuclear or other radioactive material found out of regulatory control coincide with materials from the material archives, a preliminary nuclear forensic finding may not be possible. Such a situation may occur, for example, when the quantity of a bulk sample is very small. In this case, certain essential characteristics of the materials may be determined with uncertainties exceeding the difference in the characteristics of different materials. In such cases, based on the comparison, the subject matter expert may make a determination that regulatory control might have been lost over any of the materials whose characteristics, within the measurement accuracy, coincide with characteristics of material found out of regulatory control.

4.3.1. Point-to-point comparisons

Point-to-point comparisons are instances where characteristics from a nuclear or other radioactive material found out of regulatory control are compared directly to characteristics from a known material; for example, characteristics of an archive comparator sample, or the technical specifications for a particular material.

The comparative analysis of nuclear and other radioactive materials found out of regulatory control (or their traces) with samples from a material archive is a reliable identification mechanism. In an ideal situation, an analysis of nuclear or other radioactive material found out of regulatory control and archived materials would be performed in the same laboratory, by the same subject matter experts, using the same methods (see Fig. 2). However, performing a wide variety of analyses using a single laboratory is rarely possible. Analysis of samples using similar methods but in different laboratories is also an acceptable practice, and it is a common practice to compare data from analyses completed by different laboratories. Moreover, the coincidence of results based on the analyses of different laboratories using the same methods strengthens the assessment confidence. If the results are inconsistent, additional study may be required. In this case, it is important to understand data quality and any issues that may limit comparability.

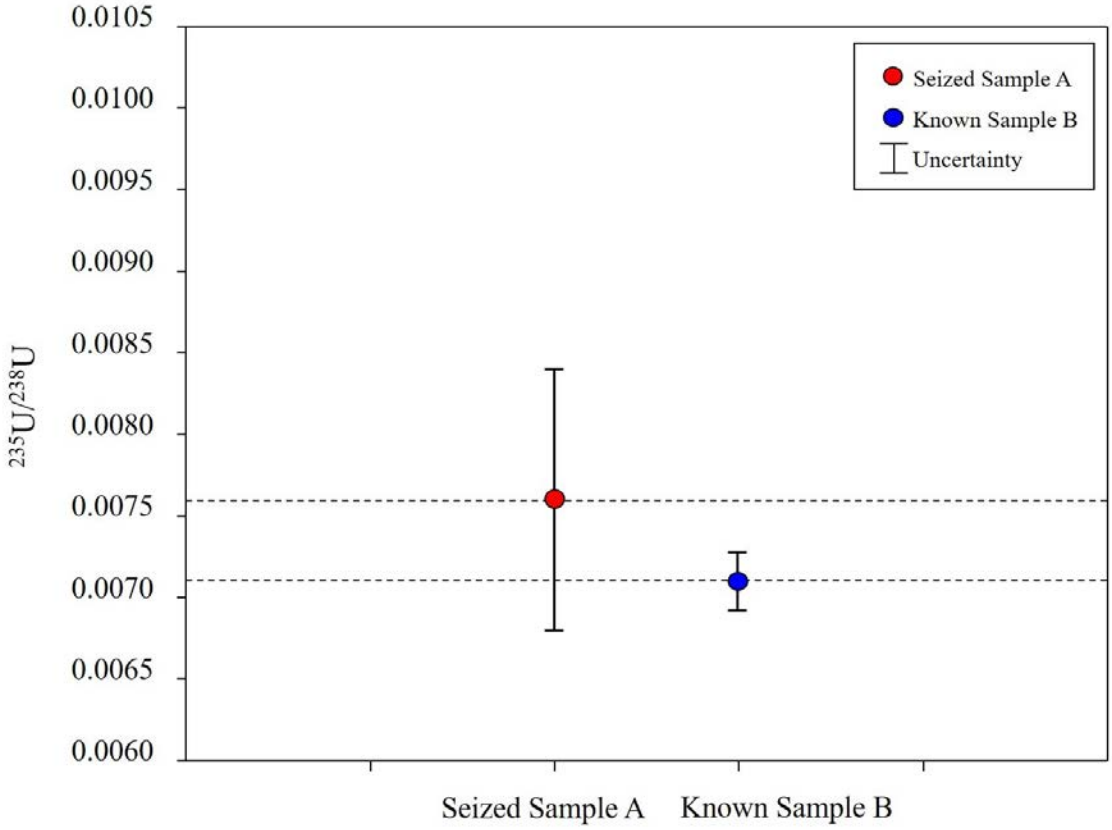


FIG. 2. Comparison of uranium isotopic ratios with analytical uncertainty for a hypothetical nuclear or other radioactive material found out of regulatory control sample with a known sample within the analytical uncertainty.

4.3.2. Point-to-model comparisons

Point-to-model comparisons are instances where characteristics from a nuclear or other radioactive material found out of regulatory control are compared to modelled data; for example, comparing measured isotopic composition to modelled reactor burn-up data.

Cases may arise where archive samples or data from the characterization of samples similar to a nuclear forensic sample are not available for comparative analysis. In this event, Library subject matter experts may employ modelling techniques (i.e. reactor modelling,) to evaluate the material characteristics.

Therefore, it is important to consider how subject matter expertise in modelling characteristics of nuclear or other radioactive materials is to be included as part of a State's Library. Often, expertise in predictive modelling of material characteristics is associated with subject matter expertise in nuclear fuel-cycle or radioactive source production operations. Common examples include modelling of reactor fuel burn-up, uranium enrichment, and process chemistry. Fig. 3 shows a hypothetical comparison of a nuclear or other radioactive material found out of regulatory control with modelled reactor burn-up data. Fig. 3 illustrates how the material is likely consistent with one type of fuel, but unlikely consistent with another type of fuel.

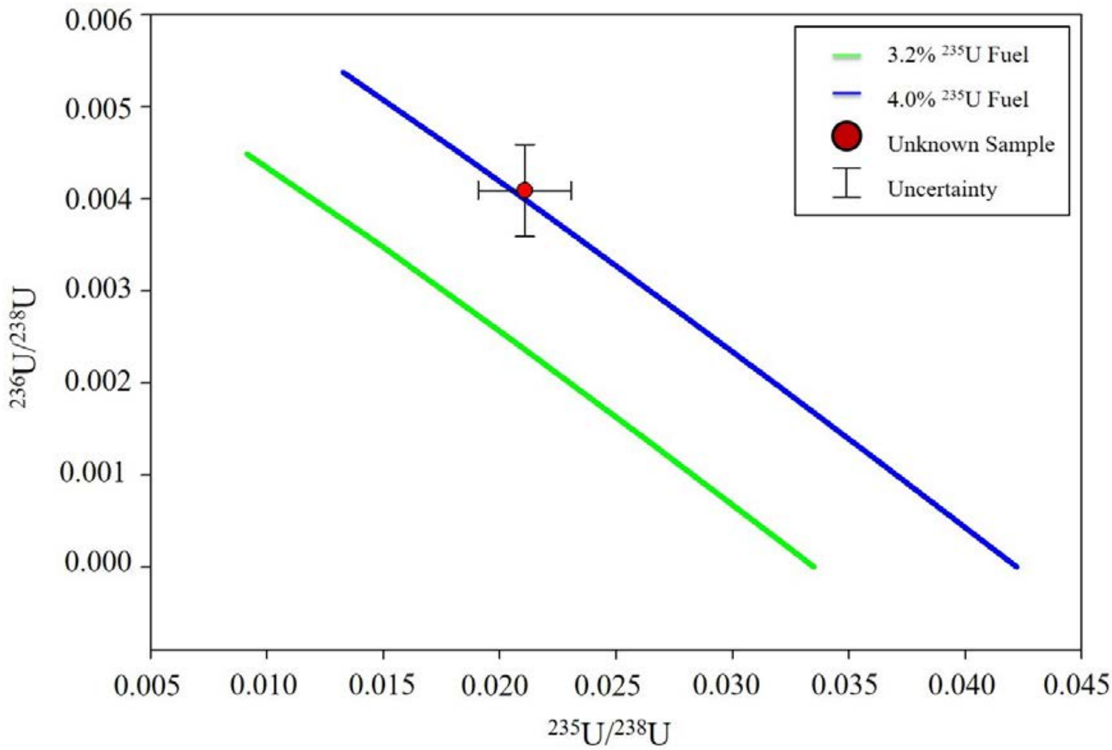


Fig. 3. Comparison of uranium isotopic ratios for a hypothetical unknown uranium material found out of regulatory control to modelled pressurized water reactor (PWR) burn up data.

As with any comparative analysis, subject matter experts may assess and communicate any limitations associated with the nuclear forensic findings regarding the consistency between a nuclear or other radioactive material found out of regulatory control and modelled characteristics.

4.3.3. Point-to-population comparisons

Point-to-population comparisons are instances where characteristics from a nuclear or other radioactive material found out of regulatory control are compared to populations of data for similar materials; for example, comparing trace element concentrations in a uranium ore concentrate to databases of trace element concentrations measured in uranium ore concentrates produced at various fabrication facilities.

Nuclear forensics point-to-point matching, as described in Section 4.3.1, is often not possible. In this case, point-to-population comparisons may be able to be used to associate the nuclear or other radioactive material found out of regulatory control with classes of material characterized by combinations of known quantifiable features (e.g. isotope ratios, chemical composition, impurities, and physical characteristics).

To facilitate such comparisons, a Library may contain information that enables data comparisons to be performed that compare data from nuclear or other radioactive material found out of regulatory control with data from populations of known materials, with the goal of excluding or including material produced, used, or stored within the State (see Fig. 4). Taken together, these data comparisons aim to determine the appropriate signature combinations that identify a material as consistent or inconsistent with a State's holdings. Sometimes, advanced statistical analysis techniques, including multivariate comparisons, may be required to identify consistency of the nuclear or other radioactive material found out of regulatory control with populations of known materials.

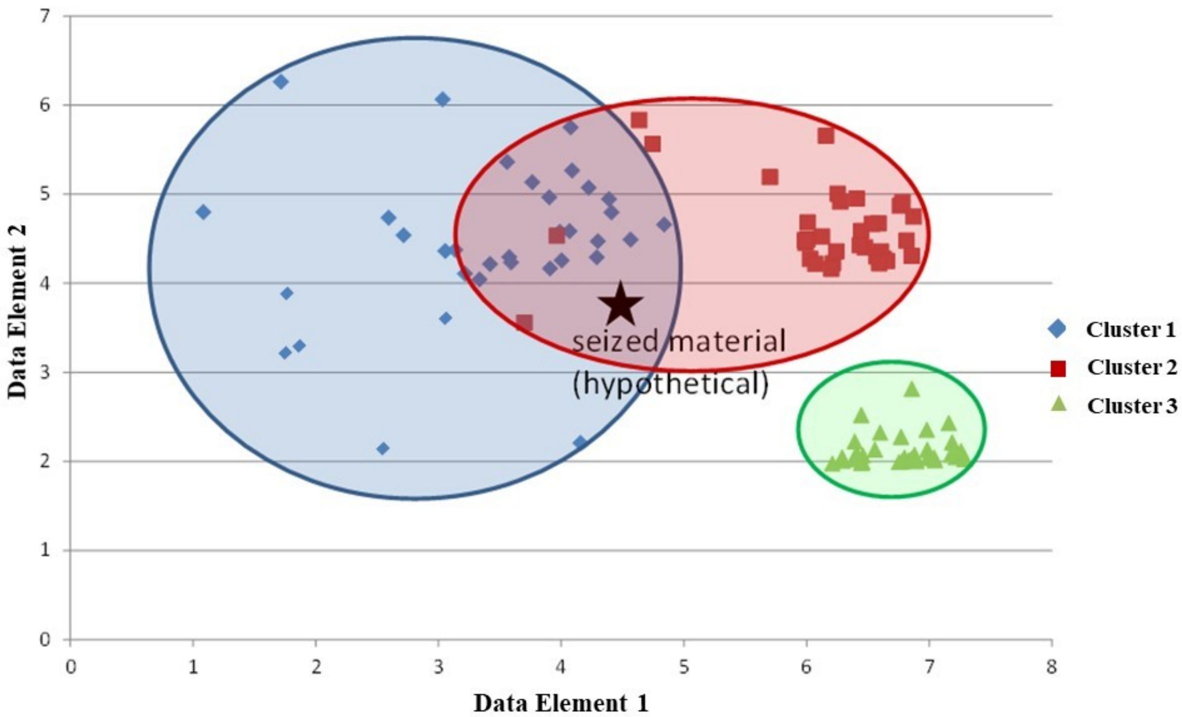


Fig. 4. Use of pattern classification to associate a hypothetical nuclear or other radioactive material found out of regulatory control with existing data element (signature) fields.

A hypothetical example of this association is illustrated in Fig. 4. In this example, statistical techniques are used to associate the discriminating features of the hypothetical nuclear or other radioactive material found out of regulatory control with three known classes designated by the blue, red, and green fields. In the case shown in Fig. 4, features of the nuclear or other radioactive material found out of regulatory control may be consistent with characteristics represented by the blue and red clusters, but it is unlikely that the nuclear or other radioactive material found out of regulatory control is consistent with the green cluster. Thus, class information represented by the green cluster may be excluded from further consideration, and as a result, the investigative leads can be narrowed.

5. INTERNATIONAL COOPERATION TO ASSIST IN THE IDENTIFICATION OF NUCLEAR AND OTHER RADIOACTIVE MATERIAL OUT OF REGULATORY CONTROL

International cooperation can facilitate investigations of nuclear or other radioactive materials found out of regulatory control, including through information exchange, investigative assistance, and provision of assistance for nuclear or other radioactive material analysis (see Ref. [1]). Sharing of information and assistance occurs at the discretion of the State, and States are in no way obligated to share sensitive or proprietary information.

The international exchange of experience and good practices can increase a State’s ability to identify and assess the origin or process history of nuclear or other radioactive material found out of regulatory control. In addition, potential Library information exchange between States, either bilateral or undertaken in association with an international organization, may assist a State in answering a variety of questions to support the investigation of a nuclear security event. This information exchange can include, but is not limited to the following:

- Whether characteristics of nuclear or other radioactive material encountered out of regulatory control are consistent with material used, produced, stored, or transported in another State;
- Whether comparative analysis of nuclear or other radioactive material encountered out of regulatory control can be carried out using samples of materials located within another State;
- Whether a State can request to use another State’s capabilities, to include subject matter experts, to assist with the nuclear forensic examination. Such assistance may be relevant for States lacking the capability to perform comprehensive nuclear forensic analysis.

Cooperation, including the exchange of information relating to the nuclear forensic examination, can be undertaken between States using several types of mechanisms, including existing and informal arrangements.

Information exchange can be carried out through official channels, consistent with national law and international obligations, including international police organizations or at the direction of national investigative authorities. To facilitate information exchange, States may consider establishing national arrangements for supporting requests for information or assistance from the Library.

The exchange of information and experiences and best practices among subject matter experts is also important for enhancement of national systems for identifying and assessing the origin and history of materials. Exchanges of experience and best practices between subject matter experts and investigative authorities can help to identify possibilities for collaboration between States, to develop capabilities, or to obtain practical investigation assistance. Such exchanges can take place during international scientific conferences, technical meetings, and exercises. Approval from national authorities may be required for participation in like exchanges or clearance of information presented or published.

REFERENCES

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Forensics in Support of Investigations, IAEA Nuclear Security Series No. 2-G (Rev.1), IAEA, Vienna (2015).
2. INTERNATIONAL ATOMIC ENERGY AGENCY, Identification of High Confidence Nuclear Forensics Signatures: Results of a Coordinated Research Project and Related Research, IAEA TecDoc 1820, IAEA, Vienna (2017).
3. INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Security Recommendations on Nuclear and Other Radioactive Material out of Regulatory Control, IAEA Nuclear Security Series No. 15, IAEA, Vienna (2011).

ANNEX I

SUMMARY OF PROCESSES INVOLVING NUCLEAR MATERIAL OR APPLICATIONS OF RADIOACTIVE MATERIAL RELEVANT TO NUCLEAR FORENSICS

The organizational scheme for linking nuclear fuel-cycle processes and radioactive source applications, and corresponding data categories is presented in Tables I1–10. Each table represents a process step in the nuclear fuel cycle or the type of radioactive source and includes the key material characteristics corresponding to each process step. For each process step, the associated material characteristics are assigned a data discriminator of high, medium, or low denoting the significance of the key material characteristic's contribution to a nuclear forensic signature; for example, its ability to be a distinguishing feature.

I-1. GENERAL INFORMATION

In addition to the material data and information contained in Tables I-1 – I-10, general information for inclusion in Library may include the following:

- Data record date (date of inclusion into a Library);
- Name and address of the custodian of the nuclear and other radioactive material (e.g. production or storage facility or installation);
- Name and address of the analytical laboratory and laboratory identification number with the date of analysis of the nuclear and other radioactive material, if applicable;
- Country of origin of the nuclear and other radioactive material;
- Name and address of the producer and/or supplier (i.e. originator) of the nuclear and other radioactive material;
- Nuclear and other radioactive material batch identification and process date from supplier (to the extent possible, such information may already be available within a State, and such existing information is helpful for a Library);
- Shipper (or carrier) and receiver information, including dates;
- Data evaluation information (e.g. determination of data quality, pedigree and completeness);
- Variation in the range of a data characteristic (e.g. technical specifications); for example, fresh low-enriched uranium used in commercial light-water reactors typically ranges in isotopic enrichment between 3 to 5% ^{235}U;
- Information acquisition date, including stating if archived information was used.

General information topics associated with materials information in a Library will depend on a State's requirements. Thus, States will include topics of general information they deem appropriate for their needs, and these topics may differ from the suggested topics listed above.

I-2. SPECIFIC INFORMATION: NUCLEAR FUEL-CYCLE PROCESSES AND RADIOACTIVE SOURCE APPLICATIONS

Analytical measurement data included in a Library can use consistent units to help facilitate timely and meaningful comparisons. SI units can be used; isotopic compositions may be reported as atom ratios, with all isotopes of uranium reported relative to ^{238}U, e.g., $^{235}U/^{238}U$, and to ^{239}Pu, e.g. Pu^{240}/Pu^{239}, for plutonium. Sometimes, due to existing data streams or other circumstances, it may be easier to capture data in the Library using non-SI units. For this reason, careful attention is needed to ensure unit agreement between data from disparate sources.

Radionuclide or isotope ratio measurement results can be reported with a reference date to facilitate quality comparative analysis. This is especially true for measurements that include shorter-lived radionuclides, e.g. ^{241}Pu (fourteen years). Inclusion of measurement reference dates or production dates may also help facilitate the application of radiochronometry measurements to help identify whether a nuclear or other radioactive material found out of regulatory control is consistent with materials found in the Library. For example, if the $^{230}Th/^{234}U$ ratio measured in uranium fuel indicates it is 30 years old, and the only plant in a State producing material began operations 10 years ago, then based on age alone the nuclear or other radioactive material found out of regulatory control is not consistent with material produced in the State. Radiochronometers are generally only applicable to relatively pure materials, typically found in the later stages of the fuel cycle, and it is important to understand limitations of radiochronometry measurements if they are to be effectively used as nuclear forensic signatures.

It is also important to include available analytical uncertainties for each measurement result included in a Library. Ideally, analytical uncertainties would be estimated using internationally accepted practices; for example, those practices found in the *Guide for the Estimation of Uncertainty in Measurement* (GUM).[6] Acknowledging that data included in the Library may have been generated for other purposes, e.g. for process quality control, uncertainties may not always be available. In these cases, data may still be valuable, but a thorough understanding of any limitations concerning data accuracy or poor precision is important before including data in a Library or using data for a comparative analysis.

In summary, when beginning to develop a Library, the first step is for the State to identify responsible organizations, personnel, and data and information resources. The second step is to refer to Tables I1–10, as they pertain to the State's fuel-cycle activities, type of radioactive sources, and material

[6] *Joint Committee for Guides in Metrology, Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, JCGM 100-2008 (2008).

holdings, as a general guide to organizing existing data and associated expertise in the context of material production processes and use of material.

I-3. TABLES OF MATERIAL AND INFORMATION CATEGORIES

The scheme to organize a Library builds upon sequential steps. Initially, the applicable nuclear fuel-cycle processes are determined by the State based on its experience and nuclear security requirements. Then, for each nuclear fuel-cycle process step selected, key discriminating material characteristics, e.g. isotope abundance and trace element concentration, are identified. Finally, a data discriminator (high, medium, or low) is assigned to each material characteristic to indicate the characteristic's impact as a parameter for comparing materials with different production histories.

Tables of information categories and material characteristics may be helpful to include in a State's Library (see Annex III). These tables are not intended to be data input templates (i.e. fill-in tables). States may adopt or modify this structure as they deem appropriate to meet their needs for a Library.

The tables specifically include characteristics and processes associated with uranium and plutonium, because these are the most common. Further, the tables are applicable to other fuel cycles, such as thorium. Depending on the needs of a State, the tables could be adapted where applicable to other fuel cycles and the characteristics that would be included in a Library would be similar. For example, for a thorium fuel cycle, Table I3 on conversion would be the same but with thorium replacing uranium in the table.

TABLE I-1. GEOLOGICAL DEPOSITION (ORE AND ORE DEPOSITS)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Geology	• Mine location • Geological formation • Deposit types • Mining technique • Colour	High	Relevant description of the geology of the material (ore) deposit and body (e.g. vein, sedimentary deposit, etc.)
Mineralogy	• Minerals present • Chemical composition of minerals • Volume percentages of minerals	Low	Mineral identified as part of exploration and mining processes
Uranium concentration	• Uranium concentration • Uranium concentration uncertainty	Low	Typically expressed in g/tonne
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	Low	$^{235}U/^{238}U$ and $^{234}U/^{238}U$
Stable isotopes	• Isotope name • Use standard units for particular isotope system • Uncertainty	High	Add isotope ratios similar to Pb Per mil (‰) for C, O, N, S $^{87}Sr/^{86}Sr$ ratio for Sr ε_{Nd} for Nd Isotope ratios for Pb ($^{204}Pb/^{208}Pb$, $^{207}Pb/^{208}Pb$, $^{206}Pb/^{208}Pb$)
Trace elements	• Trace element concentration • Trace element concentration uncertainty	High	Typically expressed in µg/g sample

TABLE I-2. URANIUM MINING, MILLING, AND EXTRACTION (ORE CONCENTRATE, YELLOWCAKE)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Chemical form	• Compound name • Stoichiometry deviation	High	e.g. U_3O_8, $((NH_4)_2U_2O_7)$
Physical characteristics	• Density	Low	Density expressed in g/cm^3
Morphology/ crystallography	• Lattice structure • Aspect ratio • Porosity • Colour • Particle size (and distribution) • Shape • Surface features (e.g. striations)	Low	Descriptive shape of individual grains (e.g. round, oval, square, smooth, rough)
Uranium concentration	• Uranium concentration • Uranium concentration uncertainty	Low	Expressed in g/g
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	Low	^{235}U/ ^{238}U and ^{234}U/ ^{238}U
Uranium decay series radionuclides	• Isotope name • Activity concentration • Activity concentration uncertainty	High	Radioactive disequilibrium indicates chemically processed materials
Stable isotopes	• Isotope name • Use standard units for particular isotope system • Uncertainty	High	Per mil (‰) for C, O, N, S ^{87}Sr/^{86}Sr ratio for Sr ε_{Nd} for Nd Isotope ratios for Pb (^{204}Pb/^{208}Pb, ^{207}Pb/^{208}Pb, ^{206}Pb/^{208}Pb)
Trace elements	• Trace element concentration • Trace element concentration uncertainty	High	Typically expressed in µg/g sample
Process information (in context of how it affects material)	• Mining and milling process • Location of processing site • Dates when production occurred (range)	High	Process facility description, location of plant and dates of production

TABLE I-3. URANIUM CONVERSION, ENRICHMENT AND FUEL PRODUCTION (INCLUDING UF_6, UF_4, UO_2, UO_3, U_3O_8, URANYL NITRATE, DEPLETED URANIUM, LOW ENRICHED URANIUM AND HIGHLY ENRICHED URANIUM, PELLETS, RODS/PLASTES, SCRAP AND WASTE)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Physical characteristics	• Density • Solid, liquid, gas • Mechanical properties (e.g., tensile strength, hardness, ductility, etc.) • Description of fuel (pellet) and dimensions (rods, plates) • Cladding information • Serial numbers (as applicable)	High	Density expressed in g/cm^3 Plans, technical drawings or photographs of pellets, rods and plates (as available)
Morphology/ crystallography	• Lattice structure • Aspect ratio • Porosity • Colour • Particle size (and distribution) • Shape • Surface features (e.g. striations)	Medium	Descriptive shape of individual grains (e.g. round, oval, square, smooth, rough)
Chemical form	• Compound name	High	
Elemental concentration (to include burnable poisons in pellets)	• Uranium concentration • Uranium concentration uncertainty • Burnable poisons (e.g. Gd or B)	Medium	Expressed in g/g
Trace elements	• Trace element concentration • Trace element concentration uncertainty	Medium	Typically expressed in µg/g sample
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	High	$^{235}U/^{238}U$, $^{234}U/^{238}U$, $^{236}U/^{238}U$, $^{233}U/^{238}U$, $^{232}U/^{238}U$
Process information (In context of how it affects material)	• Process type • Date range for production • Location of processing site	Medium	Process description (e.g. fluorination), location of plant and dates of production
Container	• Container type • Volume • Dimensions	High	Primarily for UF_6

TABLE I-4. MIXED OXIDE FUEL (MOX) FUEL FABRICATION: POWDER, PELLETS, RODS, SCRAP AND WASTE

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Physical characteristics	• Description for fuel (pellet, pebble, etc.) and dimensions (for rods, plates, etc.) • Density • Solid, liquid, gas • Mechanical properties (e.g. tensile strength, hardness, ductility, etc.) • Cladding information (type) • Fuel coating information	High	Density expressed in g/cm^3 Plans, technical drawings or photographs of rods, plates and pellets
Serial number	• Serial number	High	Could be individual serial numbers or ranges of serial numbers associated with a particular design
Morphology/ crystallography (for fuel and cladding material)	• Lattice structure • Aspect ratio • Porosity • Colour • Particle size (and distribution) • Shape • Surface features (e.g. striations) • Plutonium homogeneity (i.e. distribution within the matrix)	Medium	
Chemical form	• Compound name (for U and Pu components)	High	
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample To include U and Pu burnable poisons (e.g. Gd or B)
Trace elements	• Trace element concentration • Trace element concentration uncertainty	Medium	Typically expressed in µg/g sample
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	High	$^{235}U/^{238}U$, $^{234}U/^{238}U$, $^{236}U/^{238}U$, $^{233}U/^{238}U$, $^{232}U/^{238}U$
Plutonium isotopes	• Isotope ratios (^{239}Pu in the denominator) • Isotope ratio uncertainty	High	$^{238}Pu/^{239}Pu$, $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$
Process information (In context of how it affects material)	• Process type • Date range for production • Location of processing site	High	Process description, location of plant and dates of production

TABLE I-5. FRESH NUCLEAR FUEL (ASSEMBLIES, ELEMENTS FOR POWER OR RESEARCH REACTORS; ISOTOPE PRODUCTION CAPSULES)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Physical characteristics	• Description for fuel assembly and dimensions (for rods, plates, etc.) • Cladding information (type) • Assembly structure	High	Plans, technical drawings or photographs of nuclear fuel assemblies
Serial number	• Serial number	High	Could be individual serial numbers or ranges of serial numbers associated with a particular design
Chemical form	• Compound name	High	
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample To include U and Pu burnable poisons (e.g. Gd or B)
Trace elements	• Trace element concentration • Trace element concentration uncertainty	Low	Typically expressed in μg/g sample
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	High	$^{235}U/^{238}U$, $^{234}U/^{238}U$, $^{236}U/^{238}U$, $^{233}U/^{238}U$, $^{232}U/^{238}U$
Plutonium isotopes	• Isotope ratios (^{239}Pu in the denominator) • Isotope ratio uncertainty	High	$^{238}Pu/^{239}Pu$, $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$
Process information (In context of how it affects material)	• Process type • Date range for production • Location of processing site	High	Process description, location of plant and dates of production

TABLE I-6. IRRADIATED (SPENT) NUCLEAR FUEL

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Physical characteristics	• Description for fuel assembly and dimensions (for rods, plates, etc.) • Cladding information (type) • Assembly structure • Surface oxide thickness	High	Plans, technical drawings or photographs of nuclear fuel assemblies
Serial number	• Serial number	High	Could be individual serial numbers or ranges of serial numbers associated with a particular design
Chemical form	• Compound name	High	
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample To include U and Pu burnable poisons (e.g. Gd or B)
Trace elements	• Trace element concentration • Trace element concentration uncertainty	Low	Typically expressed in µg/g sample
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	High	$^{235}U/^{238}U$, $^{234}U/^{238}U$, $^{236}U/^{238}U$, $^{233}U/^{238}U$, $^{232}U/^{238}U$
Plutonium isotopes	• Isotope ratios (^{239}Pu in the denominator) • Isotope ratio uncertainty	High	$^{238}Pu/^{239}Pu$, $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$
Irradiation history	• Reactor type • Burn-up (to include, actinides and fission products) • Assembly power history • Operating records • Load and discharge dates • Radiation level	High	

TABLE I-7. REPROCESSING (PLUTONIUM NITRATE, URANYL NITRATE, PLUTONIUM OXIDE, URANIUM OXIDE, MIXED OXIDE, OTHER ACTINIDES)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Physical characteristics	• Description for fuel (pellet, pebble, etc.) and dimensions (for rods, plates, etc.) • Density • Solid, liquid, gas • Mechanical properties (e.g. tensile strength, hardness, ductility, etc.) • Cladding information (type) • Fuel coating information	Low	Density expressed in g/cm^3
Chemical form	• Compound name	High	
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample
Trace elements	• Trace element concentration • Trace element concentration uncertainty	High	Typically expressed in µg/g sample
Uranium isotopes	• Isotope ratios (^{238}U in the denominator) • Isotope ratio uncertainty	High	$^{235}U/^{238}U$, $^{234}U/^{238}U$, $^{236}U/^{238}U$, $^{233}U/^{238}U$, $^{232}U/^{238}U$
Plutonium isotopes	• Isotope ratios (^{239}Pu in the denominator) • Isotope ratio uncertainty	High	$^{238}Pu/^{239}Pu$, $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$
Process information (In context of how it affects material)	• Process type • Date range for production • Location of processing site	High	Process description, location of plant and dates of production

TABLE I-8. RADIOACTIVE WASTE PROCESSING, HANDLING, AND STORAGE (HIGH LEVEL RADIOACTIVE WASTE)

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Serial number	• Serial number (e.g. container or cask)	High	Could be individual serial numbers or ranges of serial numbers associated with a particular design
Physical characteristics	• Activity • Density • Solid, liquid, gas (general description of matrix) • Mass • Dimensions	High	Density expressed in g/cm^3 Total activity or dose rate
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample
Major isotopes	• Isotope name • Isotope activity • Isotope activity uncertainty	High	Expressed as activities in Bq, include reference date
Process information (In context of how it affects material)	• Process type • Date range for production • Location of processing site	High	Process description, location of plant and dates of production
Container	• Container type • Volume • Dimensions	High	

TABLE I-9. TYPES OF RADIOACTIVE SOURCES: SEALED

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Description of the source or package	• Source type (emission type, intended use) • Quantity • Description and dimensions • Encapsulation or cladding • Serial number • Radiograph or photograph • Shipping and receiving history	High	Identifying information from the supplier
Source activity information	• Activity • Reference date of the activity • Neutron intensity or flux	High	Activities in Bq, [neutron/sec] with a radioactive decay reference date
Chemical form	• Compound name	High	
Elemental concentrations (in matrix)	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample
Major and minor isotopes	• Isotope name • Isotope activity • Isotope activity uncertainty	High	Expressed as activities in Bq, include reference date

TABLE I-10. TYPES OF RADIOACTIVE SOURCES: UNSEALED

Characteristic	Characteristics – Data Elements	Data Discriminator	Notes
Description of the source or package	• Source type (emission type, use type) • Quantity • Description and dimensions • Radiograph or photograph • Shipping and receiving history	High	Identifying information from the supplier
Source activity information	• Activity • Reference date of the activity	High	Activities in Bq, with a radioactive decay reference date
Chemical form	• Compound name	High	
Elemental concentrations	• Element concentration • Element concentration uncertainty	High	Expressed in g/g sample
Major and minor isotopes	• Isotope name • Isotope activity • Isotope activity uncertainty	High	Expressed as activities in Bq, include reference date

ANNEX II

REPRESENTATIONS OF HYPOTHETICAL LIBRARY DATA FOR THREE DISTINCT MATERIALS

The three Library data representations below serve only as a hypothetical guide of what a Library entry might contain. These representations are not prescriptive templates for the design of a Library or the corresponding data entries.

The fields encompass reference information. Entries in a Library will likely include fields appropriate to all categories of nuclear and other radioactive material.

TABLE II-1. HYPOTHETICAL LIBRARY DATA SUMMARY FOR Sr-90 SEALED SOURCE

MATERIAL: Sr-90 Sealed Source	**DATA RECORD DATE**: 18 October 2012
CUSTODIAN/OWNER: **Medical Research Institute** **4371 Waterfall Drive** **Capital City, Westland**	**ANALYTICAL LABORATORY**: Not Applicable; Vendor Data
COUNTRY OF ORIGIN: **Northland**	**SUPPLIER**: RADTECH, Inc. 3001 Main Street South Village, Northland, 60032
SHIPPER/CARRIER: **PDP, Ltd.; Waybill No. 40512432**	**DATA VETTING**: Vendor Data: Model XZAP90-SR
DATE INFORMATION ACQUIRED: **28 June 2012**	**FINAL DISPOSITION** (if known): RAD Surplus, Ltd

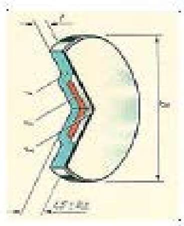
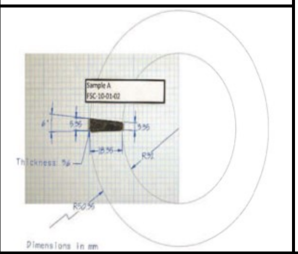
CHARACTERISTIC	***CHARACTERISTICS— DATA ELEMENT***	***Sr-90 SEALED SOURCE***	***DATA DISCRIMINATOR***
SUPPLIER INFORMATION	**Packaging Type**	Al alloy backing covered with 0.05mm thick Al foil	High
	Drawings / Photographs (with scale)		
	Description and Dimensions	Active core deposited on Al alloy backing d=143mm × h=1.5mm	
DESCRIPTION OF SOURCE / PACKAGE	**Encapsulation or Cladding**	Active core deposited on Al alloy backing and covered by 0.05mm thick Al foil, d=143mm × h=1.5mm	High
	Serial Number	5C0-(801-218)	
	Radiograph / Photograph	Not Provided	
	Shipping / Receiving History	PDP Ltd. Waybill No. 40512432	
PHYSICAL CHARACTERISTICS OF SOURCE	**Activity (Bq)**	1 to 10 GBq	High
	Reference Date of Activity	31 March 2012	
	Description and dimensions	Diameter of emitting surface 113mm	
	Serial Number	5C0-(801-218)	
	Radiograph / Photograph	Not Provided	
CHEMICAL FORMS	**Compound Name**	$^{90}Sr/^{90}Y$	High
ELEMENT CONCENTRATION	**Element Name**	Strontium / Yttrium	High
	Element Concentration	Not Provided	
	Uncertainty	Not Provided	
ISOTOPES	**Isotope Name**	$^{90}Sr/^{90}Y$	High
	Activity, Uncertainty	Not Provided	

TABLE II-2. HYPOTHETICAL LIBRARY DATA SUMMARY FOR HIGHLY ENRICHED URANIUM (HEU) METAL

GENERAL INFORMATION
MATERIAL: Sample A-HEU
DATA RECORD DATE: 18 October 2012
CUSTODIAN/ OWNER: Special Uranium Inc. 7482 Fern Dr. Malibu, North City 45045
ANALYTICAL LABORATORY: Dunlap Lab
COUNTRY OF ORIGIN: Southland
SUPPLIER: Uran-E-Um, LLC 892 Elm Street. Geomat, Southland 20012
BATCH ID AND PROCESS DATE: Hollow Log 1943, 8 April 2003
SHIPPER/ CARRIER: PDP, Ltd Waybill No. V283HG4
DATE INFORMATION ACQUIRED: 25 April 2011

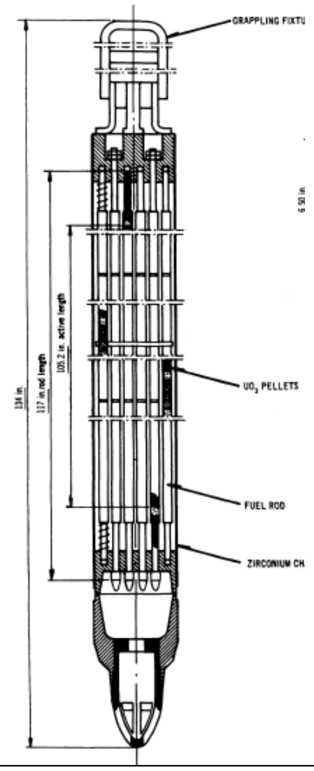
CHARACTERISTIC	***CHARACTER-ISTICS-DATA ELEMENTS***	***SAMPLE A—HEU***	***DATA DISCR-IMIN-ATOR***
PHYSICAL CHARACTERISTICS	**Rod/ plate/ pellet information**	4.5808-5.0915g	High
	Density (g/cm^3)	No density given for sample, only for angular inclusion	
	Surface roughness	Angular inclusions	
	Dimensions of nuclear fuel pellets	Large cylindrical mass of inner diameter ~32mm (~44mm actual)	
	Cladding (material, thickness)	Not Provided	
	Plans/ drawing		
ITEM DESCRIPTION	**Serial number format**	Hollow Log 1958	High
MORPHOLOGY	**Grain/ particle size**	0.0086 ±0.0035 (mm)	Medium
	Shape grains	Angular, dendritic, cuboidal	
	Colour	metallic silver	
CHEMICAL FORM	**Compound name**	Uranium metal	High
ELEMENTAL CONCENTRATION	**Element name**		Medium
	Element concentration	Total all %U-isotopes, get 100% U in sample, were measured	
	Uncertainty	n.a.[a]	
TRACE ELEMENT CONCENTRATION	**Trace element name**	Pu, Np, Al, B, C, Ca, Co, Cr, Cu, Er, Fe,Mg, Mn, Mo, Ni, P, Pd, Re, W, Zr	Medium
	Trace element concentration (µg/g)	Pu: 0.0063-0.0081, Al: 10-215, B: 7-10, C: 260-1700, Ca: 3.4-56.2, Co: 0.59-1.74, Cr: 9.99-115, Cu: 8.0-37.3, Er: 0.16-8.23, Fe: 77.8-220, Mg: 0.22-34.9, Mn: 3.78-22.5, Mo: 51-380, Ni: 38-164, P: 10.1, Pd: 0.31-3, Re: 17.5-18, W: 34.2-69, Zr: 1.62-2200, Np-237:4.41-5.5 (µg/g)	
	Uncertainty	Pu: 0.00024-0.0057 (µg/g)	
URANIUM ISOTOPIC COMPOSITION	**Isotopic ratios (^{238}U in the denominator)**	Ratios not given, % each isotope given ^{238}U: 5.49-6.35, ^{235}U: 92.5-93, ^{234}U: 0.89-1.1,	High

			^{236}U: 0.346-0.3884, ^{233}U: 32.9E-6-0.0006, ^{232}U: 0.1-1.25E-8 (atom %)	
		Isotope abundance uncertainty	^{238}U: 0.0026-0.5, ^{235}U: 0.004-2.64, 232U: 0.0004-0.09, ^{236}U: 0.00056-0.5, ^{233}U: 4.4E-6-0.0003, ^{232}U: 0.03-0.3E-8 (atom)	
	PROCESS INFORMATION	**Process type**	Cast on May 22, 2003	High
		Date and duration of the process	3 parent items all briquettes formed from machine turnings (made Hollow log 1943 cast on Apr 8, 2003) + pallet scrap (consolidation item 1046 created Mar31, 2003)	
		Location of processing site	Caesium Special Materials	

[a] n.a.: not applicable.

TABLE II-3. HYPOTHETICAL LIBRARY DATA SUMMARY FOR LOW ENRICHED URANIUM (LEU) NUCLEAR FUEL ASSEMBLY

MATERIAL: LEU FUEL ASSEMBLY	**DATA RECORD DATE: 18 OCTOBER 2012**
BATCH ID AND PROCESS DATE: MARCH 1959	**ANALYTICAL LABORATORY: NOT APPLICABLE, VENDOR DATA**
COUNTRY OF ORIGIN: EASTLAND	**SUPPLIER: EASTLAND ELECTRIC CO.**
CUSTODIAN/OWNER: **ELECTRO-NUCLEAR INC.** **STEADY POWER AVENUE** **NEW CITY, EASTLAND 82934**	**SHIPPER/CARRIER:** **CSP, INC** **2930 TRANSPORT LANE** **NEW CITY, EASTLAND 60032**
DATA VETTING: **VENDOR DATA: ASSEMBLY X320**	**DATE INFORMATION ACQUIRED: ARCHIVED INFORMATION, MARCH 1959**

CHARACTERISTIC	***CHARACTERISTICS — DATA ELEMENTS***	***ARCTIC REACTOR 1 (MARCH 1959)***	***DATA DISCRIMINATOR***
PHYSICAL CHARACTERISTICS	**Density of fuel pellets**	Not Provided	High
	Dimensions	0.494 d × 0.5 high (in) form segment, 0.563 o.d. × 28 long (in), 4 segments form a rod 117 long (in)	
	Cladding (material, thickness)	Zircaloy-2, 0.03 (in)	
	Rod information	6×6 fuel rods in square assembly	
	Assembly structure - plans, schematic drawings, or photographs (with scale)	488 fuel channels 	
SERIAL NUMBER	**Serial number**	Not Provided	High
CHEMICAL FORM	**Compound name**	UO_2	High

ELEMENT CONCENTRATION	**Element name**	Not Provided	High
	Element concentration		
	Uncertainty		
TRACE ELEMENT CONCENTRATION	**Trace element name**	Not Provided	Low
	Trace element concentration		
	Uncertainty		
URANIUM ISOTOPIC COMPOSITION	**Isotope ratios (^{238}U in the denominator)**	Uranium enrichment: 1.5% Enriched U-235	High
	Isotope ratio uncertainty	Not Provided	
PLUTONIUM ISOTOPES FOR MOX FUEL	**Isotope ratios (^{239}Pu, in the denominator)**	Not Provided	High
	Isotope ratio uncertainty		
PROCESS INFORMATION	**Date and duration of the process**	Not Provided	High
	Location of processing site	Arctic Electric Co.	

ANNEX III

DESCRIPTION OF UNITS FOR MATERIAL AND DATA CHARACTERISTICS TO SUPPORT A NATIONAL NUCLEAR FORENSICS LIBRARY

Using a standardized set of units for nuclear and radioactive material characteristics in a Library facilitates rapid comparative analyses. The conversion of units to a standardized set has the advantage of facilitating comparability between all materials in a Library. Additionally, if unit conversions are completed prior to entering data into a Library, a verification step can be completed to reduce the risks of unit conversion errors during Library queries.

The following is a list of units for describing material characteristics in a Library. Generally, they are SI or centimetre–gram–second system units, and were selected for ease of comparing a diverse set of materials from across the fuel cycle and a wide variety of radioactive sources. It is up to each State to decide if these units are appropriate for their Library, and in some cases, where a State only has a very limited number of materials; it might be simpler to use alternative units. For example, if a State only mines uranium ore, it might be more appropriate to express uranium concentration in ore in units of g/tonne or g/kg instead of the recommended units of g/g, which are generally more useful for comparing uranium concentrations for nuclear fuel cycle materials.

TABLE III-1. RECOMMENDED UNITS FOR DESCRIBING MATERIAL CHARACTERISTICS IN A NATIONAL NUCLEAR FORENSICS LIBRARY

Characteristic	Recommended Units	Rational
Elemental concentrations for major constituents	g/g	Used for elements with concentrations >0.1% by weight. Alternatively, it can include all elements intended to be a part of a material, for example all of the elements present in a metal alloy. For most fuel-cycle materials or large radioactive sources, expressing concentrations in g element / g material is suitable.
Trace element concentrations	μg/g	Used for elements with concentrations <0.1% by weight. Alternatively, trace elements are sometimes defined as those elements that are impurities, or elements present in a material but not intentionally added.
Uranium isotopic compositions	Atom ratios: $^{232}U/^{238}U$, $^{233}U/^{238}U$, $^{234}U/^{238}U$, $^{235}U/^{238}U$, $^{236}U/^{238}U$	While uranium isotopic compositions are often expressed as atom percent, mass percent, or even just ^{235}U enrichment level, these units are not ideal for Library use. By using ratios, all uranium materials in a Library are directly comparable, regardless of how many isotopes were determined in a particular material. If using atom or mass percent, materials with differing numbers of isotopes measured require isotopic compositions to be renormalized based on the sample with the fewest isotopes measured before they can be compared.

Characteristic	Recommended Units	Rational
Plutonium isotopic compositions	Atom ratios: $^{238}Pu/^{239}Pu$, $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$,	While plutonium isotopic compositions are often expressed in atom percent or mass percent, these units are not ideal for Library use. By using ratios, all plutonium materials in a Library are directly comparable, regardless of how many isotopes were determined in a particular material. If using atom percent or mass percent, materials with differing numbers of isotopes measured require isotopic compositions to be renormalized based on the sample with the fewest isotopes measured before they can be compared.
Density	g/cm^3	Alternately, the SI unit of kg/m^3 would also be appropriate.
Particle size	µm	Depending on the sophistication of the Library, this could capture average particle size, or complete histograms of particle size distributions.
Porosity or specific surface area	m^2/g	Typical units for porosity or specific surface area measurements using Brunauer–Emmett–Teller (BET) theory and similar methods.
Carbon stable isotopes	Per mil (‰)	Expressed as $\delta^{13}C$.
Nitrogen stable isotopes	Per mil (‰)	Expressed as $\delta^{15}N$.
Oxygen stable isotopes	Per mil (‰)	Expressed as $\delta^{15}O$.
Strontium stable isotopes	Atom ratio $^{87}Sr/^{86}Sr$	
Lead stable isotopes	Atom ratios $^{204}Pb/^{208}Pb$, $^{207}Pb/^{208}Pb$, $^{206}Pb/^{208}Pb$,	
Neodymium stable isotopes	ε_{Nd}	$^{143}Nd/^{144}Nd$ isotope ratios
Activity	Bq	Used for radionuclide activity in radioactive sources.
Specific activity	Bq/g	The activity of a radionuclide relative to the total mass of the element present (e.g. 50Bq ^{60}Co/g Co). Used to describe the radiochemical purity of radionuclides.
Neutron intensity	n/s	Used to express the intensity of neutrons from neutron sources, e.g. ^{252}Cf or $^{241}AmBe$ sources.

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