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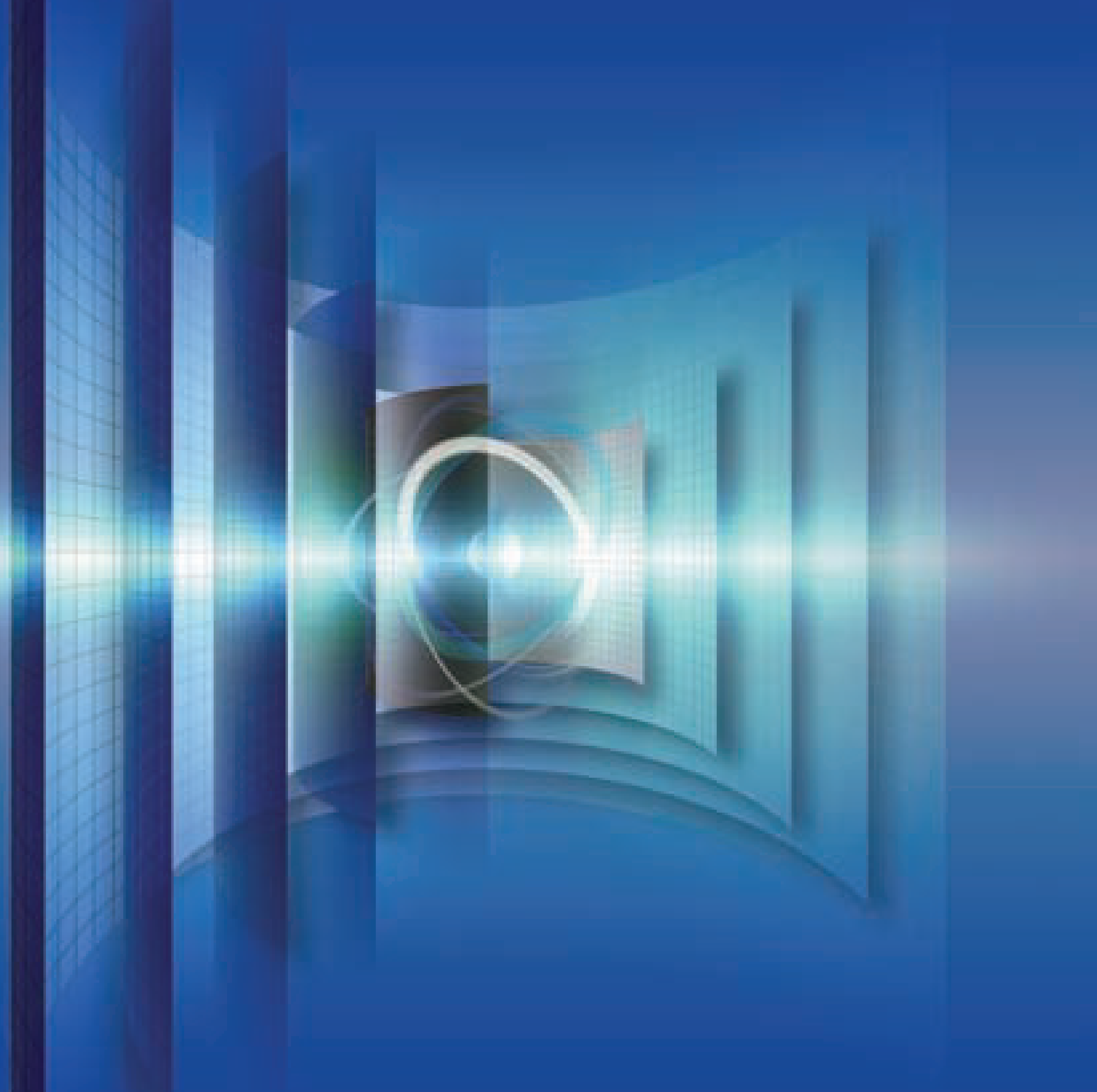
IAEA Nuclear Security Series No. 2

Technical Guidance

Reference Manual

Nuclear Forensics Support



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DRAFTING AND REVIEW

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Technical Guidance publications are developed in close consultation with international experts. Technical meetings are not required, but may be conducted, where it is considered necessary, to obtain a broad range of views.

The process for drafting and reviewing publications in the IAEA Nuclear Security Series takes account of confidentiality considerations and recognizes that nuclear security is inseparably linked with general and specific national security concerns. An underlying consideration is that related IAEA safety standards and safeguards activities should be taken into account in the technical content of the publications.

NUCLEAR FORENSICS SUPPORT

REFERENCE MANUAL

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA NUCLEAR SECURITY SERIES No. 2

TECHNICAL GUIDANCE

NUCLEAR FORENSICS SUPPORT

REFERENCE MANUAL

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2006

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International Atomic Energy Agency
Wagramer Strasse 5
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A-1400 Vienna
Austria
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tel.: +43 1 2600 22417
http://www.iaea.org/books

Printed by the IAEA in Austria
May 2006
STI/PUB/1241

IAEA Library Cataloguing in Publication Data

Nuclear forensics support. — Vienna : International Atomic Energy Agency, 2006.
p. ; 24 cm. — (IAEA nuclear security series, ISSN 1816–9317 ; no. 2)
STI/PUB/1241
ISBN 92–0–100306–4
Includes bibliographical references.

1. Radioactive substances — Security measures. — 2. Nuclear industry — Materials management. — 3. Forensic sciences. I. International Atomic Energy Agency. II. Series.

IAEAL 06–00428

FOREWORD

Illicit trafficking of nuclear and other radioactive material has been an issue of concern since the first seizures in the early 1990s. By the end of 2004 Member States had confirmed 540 cases, while about another 500 remain unconfirmed. Most of the confirmed cases have a criminal dimension, even if they were not for known terrorist purposes. The attacks of September 2001 in the USA dramatically emphasized the requirement for the enhanced control and security of nuclear and other radioactive material. In response to a resolution by the IAEA General Conference in September 2002 the IAEA has adopted an integrated approach to protection against nuclear terrorism. This brings together IAEA activities concerned with the physical protection of nuclear material and nuclear installations, nuclear material accountancy, detection and response to illicit nuclear trafficking, the security and safety of radioactive sources, emergency response measures — including pre-emergency measures in Member States and at the IAEA — and the promotion of State adherence to relevant international instruments.

States have the responsibility for combating illicit trafficking and the inadvertent movements of radioactive material. The IAEA cooperates with Member States and other international organizations in joint efforts to prevent incidents of illicit trafficking and inadvertent movements and to harmonize policies and measures by providing relevant advice through a range of technical assistance and documents. In this context, the IAEA issued a group of three technical documents, co-sponsored by the World Customs Organization, Europol and Interpol, on the inadvertent movement and illicit trafficking of radioactive material. The first is Prevention of the Inadvertent Movement and Illicit Trafficking of Radioactive Material (IAEA-TECDOC-1311), the second is called Detection of Radioactive Material at Borders (IAEA-TECDOC-1312) and the third is Response to Events Involving the Inadvertent Movement or Illicit Trafficking of Radioactive Material (IAEA-TECDOC-1313).

It was quickly recognized that much can be learned from the analysis of reported cases of illicit trafficking. For example, what specifically could the material have been used for? Where was the material obtained: in stock, scrap or waste? Was the amount seized only a sample of a much more significant quantity? These and many other questions can be answered through detailed technical characterization of seized material samples. The combination of scientific methods used for this purpose is normally referred to as 'nuclear forensics', which has become an indispensable tool for use in law enforcement investigations of nuclear trafficking.

This publication is based on a document entitled Model Action Plan for Nuclear Forensics and Nuclear Attribution (UCLR-TR-202675), prepared by

M.J. Kristo, D.K. Smith and S. Niemeyer of the Lawrence Livermore National Laboratory, and G.D. Dudder of the Pacific Northwest National Laboratory, under the auspices of the United States Department of Energy for the Nuclear Smuggling International Technical Working Group (ITWG). The document is unique in that it brings together, for the first time, a concise but comprehensive description of the various tools and procedures of nuclear forensic investigations that was earlier available only in different areas of the scientific literature. It also has the merit of incorporating experience accumulated over the past decade by law enforcement agencies and nuclear forensics laboratories confronted with cases of illicit events involving nuclear or other radioactive material. The work undertaken by the ITWG in this endeavour, and in particular by the above authors, is gratefully acknowledged.

The preparation of this publication in the IAEA Nuclear Security Series has involved extensive consultations with Member States, including an open-ended technical meeting in Vienna in February 2002, and a meeting in Cadarache, France, in July 2004. As a final step, the draft was circulated to all Member States to solicit further comments and suggestions before publication. The IAEA officer responsible for this publication was R. Abedin-Zadeh of the Office of Nuclear Security, Department of Nuclear Safety and Security.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The Nuclear Smuggling International Technical Working Group (ITWG) [1] was created in 1996, with the aim of combating the illicit trafficking of nuclear material and radioactive substances, under the auspices of the G-8 Non-Proliferation Experts Group (NPEG). The primary purpose of the ITWG is to provide technical cooperation and collaboration in the development of nuclear forensics. The members of the ITWG come from a broad range of backgrounds covering law enforcement, safeguards, customs agencies and the scientific community, including most of the laboratories that have the requisite equipment, personnel and experience to perform nuclear forensic analysis. Representatives from more than 28 States and organizations have participated in nine international meetings and round robin analytical exercises to date. In a meeting in Vienna in June 2000, the ITWG adopted a reference Model Action Plan that includes the use of nuclear forensics in response to the illicit trafficking of nuclear material or other radioactive material. The concept was tested with the concerned authorities of Bulgaria, the Czech Republic, Hungary and Ukraine. The European Union has developed similar initiatives with its Member States.

1.2. OBJECTIVE

Nuclear forensics and nuclear forensic interpretation have become increasingly important tools in the fight against illicit trafficking in nuclear and radiological material. This publication deals with these techniques in a comprehensive manner, summarizing tools and procedures that have heretofore only been available in different areas of the scientific literature. Its objective is to provide national policy makers, decision makers and technical managers with consolidated guidance for responding to incidents involving the interdiction of nuclear and other radioactive material, when nuclear forensic investigations are required. It complements another IAEA publication, Response to Events Involving the Inadvertent Movement or Illicit Trafficking of Radioactive Material (IAEA-TECDOC-1313), issued in 2002 [2].

Owing to the significant capital costs of the equipment and the specialized expertise of the personnel, work in the field of nuclear forensics has been restricted so far to a handful of national and international laboratories. In fact, there are only a limited number of specialists who have experience working with interdicted nuclear material and affiliated evidence. Most of the laboratories that have the requisite equipment, personnel and experience to perform nuclear forensic analysis are participants in the ITWG. Consequently, there is a need to disseminate information on an appropriate response to incidents of illicit trafficking of nuclear and other radioactive material, including a comprehensive approach to gathering evidence that meets appropriate legal standards and to developing insights into the sources and routes of contraband nuclear and radioactive material.

In addition to providing information on the process of nuclear forensic investigations, this publication also outlines a procedure that an IAEA Member State may follow to obtain the assistance of nuclear forensics laboratories or other relevant expertise, as needed.

1.3. STRUCTURE

Following this introduction and definitions of various key terms in the area of nuclear forensics, Section 2 describes the Nuclear Forensics Plan of Action. Section 3 deals with incident reponse, while Section 4 examines issues of sampling and distribution in nuclear forensics laboratories. Section 5 deals with nuclear forensic analysis, with Section 6 discussing traditional methods of forensic analysis. Nuclear forensic interpretation is discussed in Section 7, while Section 8 describes the issue of confidence in conclusions. Section 9 details the steps involved in requesting assistance from the IAEA in carrying out nuclear forensic investigations. Section 10 outlines other recommended activities in the area of nuclear forensics. The appendices provide information on various methods and procedures used in nuclear forensic investigations.

1.4. DEFINITIONS

Nuclear attribution is the process of identifying the source of nuclear or radioactive material used in illegal activities, to determine the point of origin and routes of transit involving such material, and ultimately to contribute to the prosecution of those responsible. Nuclear attribution utilizes many inputs, including: (1) results from nuclear forensic sample analyses; (2) understanding of radiochemical and environmental signatures; (3) knowledge of the methods used for producing nuclear material and nuclear weapons and the development pathway; and (4) information from law enforcement and intelligence sources. Nuclear attribution is the integration of all relevant forms of information about a nuclear smuggling incident into data that can be readily analysed and interpreted to form the basis of a confident response to the incident. The goal of the attribution process is to answer the needs, requirements and questions of policy makers for a given incident.

Nuclear forensics is the analysis of intercepted illicit nuclear or radioactive material and any associated material to provide evidence for nuclear attribution. The goal of nuclear analysis is to identify forensic indicators in interdicted nuclear and radiological samples or the surrounding environment, e.g. the container or transport vehicle. These indicators arise from known relationships between material characteristics and process history. Thus, nuclear forensic analysis includes the characterization of the material and correlation with its production history.

The response to specific nuclear incidents requires a graded approach.

Categorization is performed to address the threat posed by a specific incident. The goal of categorization is to identify the risk to the safety of first responders, law enforcement personnel and the public, and to determine if there is criminal activity or a threat to national security. Each State should strive to develop its own national capability to quickly categorize nuclear incidents to determine the appropriate response and follow-on actions. The magnitude of the threat posed by a specific incident may range from environmental contamination, through risk to public health and safety, to proliferation concerns, each requiring a different response. Further analysis will be guided by the initial categorization.

Characterization is performed to determine the nature of the radioactive and associated evidence. Basic characterization provides full elemental analysis of the radioactive material, including major, minor and trace constituents. For those major constituents of the radioactive material, basic characterization would also include isotopic and phase (i.e. molecular) analysis, if necessary. The basic characterization also includes physical characterization. The sample should be imaged at high magnification, using a scanning electron microscope, for example. The critical dimensions of solid samples and the particle size and shape distributions of powder samples should be measured. Characterization involves an iterative approach in which the results from one analysis are used to guide the selection of subsequent analyses. In this way, characterization proceeds in a manner not unlike that of traditional forensic analysis.

Nuclear forensic interpretation is the process of correlating the material characteristics with the production history. The goal of nuclear forensic interpretation is to determine the method and time of production. The interpretation may include reactor and process modelling and/or database searches to identify the method of production. The ability to match analytical data with existing information on methods used to produce radioactive material, and with prior cases involving smuggled and interdicted nuclear material, will aid in the analysis. Nuclear forensic interpretation is the end product of the nuclear forensics laboratories.

1.5. NUCLEAR AND OTHER RADIOACTIVE MATERIAL

Nuclear material can be divided into five general categories (Table 1):

(1) Unirradiated direct use material;
(2) Irradiated direct use material;
(3) Alternative material;
(4) Indirect use material [3];
(5) Commercial radioactive sources [4].

Direct use nuclear material includes high enriched uranium (HEU), ^{233}U, plutonium (Pu) containing less than 80% ^{238}Pu, and irradiated nuclear fuel material. Indirect use nuclear material includes depleted uranium (DU), natural uranium (NU) and low enriched uranium (LEU) and plutonium containing 80% or more ^{238}Pu .

Unirradiated direct use material can be used most readily to construct a nuclear weapon. It includes, in particular, uranium with ^{235}U enrichment greater than 20% and plutonium with less than 7% of the ^{240}Pu isotope. This material is an especially attractive target for States and terrorist organizations intent on developing a nuclear weapon, because possession of sufficient amounts of such material may eliminate the necessity of developing the advanced technology required for isotopic enrichment of uranium or plutonium separation [5]. However, States are expected to provide extensive security for their stockpiles of both unirradiated and irradiated direct use nuclear material in order to prevent its theft and use by terrorists. Material in these categories that are under IAEA safeguards is subject to higher inspection frequencies in order that potential diversions can be detected within a month for unirradiated or within three months for irradiated direct use material.

Nuclear reactor fuel typically consists of uranium or a mixture of uranium and plutonium. Uranium is usually present as uranium dioxide (UO_2), uranium alloy or uranium carbide and has either natural isotopic composition or is isotopically enriched to a few per cent ^{235}U. Plutonium is most often present as plutonium oxide (PuO_2) or in mixtures of uranium and plutonium dioxide ($UPuO_2$). Most reactor fuel cannot be used to make a nuclear weapon without undergoing further enrichment in ^{235}U or chemical separation of the plutonium from the fuel.

TABLE 1. CATEGORIES OF NUCLEAR [3] AND OTHER RADIOACTIVE MATERIAL [4]

Category	Type of material or device	Radioactive components
Unirradiated direct use nuclear material	High enriched uranium (HEU)	>20% U-235
	Plutonium and mixed U–Pu oxides (MOX)	<80% Pu-238
	U-233	Separated isotope
Irradiated direct use nuclear material	Irradiated nuclear fuel material	In irradiated nuclear fuel elements or in spent fuel reprocessing solutions
Alternative nuclear material	Americium (Am-241) Neptunium (Np-237)	Separated element or present in irradiated nuclear material, in separated plutonium or in mixtures of uranium and plutonium
	Depleted uranium (DU)	<0.7% U-235
Indirect use nuclear material	Natural uranium (NU)	0.7% U-235
	Low enriched uranium (LEU)	>0.7% U-235 and <20% U-235, (typically 3–5%) U-235
	Plutonium (Pu-238)	>80% Pu-238
	Thorium	Th-232
Radioactive sources Category 1	Radioisotope thermoelectric generators	Pu-238, Cm-244 and Sr-90
	Irradiators/sterilizers	Co-60 and Cs-137
	Teletherapy sources	Co-60 and Cs-137
Radioactive sources Category 2	Industrial gamma radiography sources	
	High/medium dose rate brachytherapy sources	
Radioactive sources Category 3	Fixed industrial gauges	Co-60, Cs-137 and Am-241
	Well logging gauges	
Radioactive sources Category 4	Low dose rate brachytherapy sources	
	Thickness/fill level gauges	
	Portable gauges (e.g. moisture, density)	
	Bone densitometers	
	Static eliminators	

TABLE 1. CATEGORIES OF NUCLEAR [3] AND OTHER RADIOACTIVE MATERIAL [4] (cont.)

Category	Type of material or device	Radioactive components
Radioactive sources Category 5	Eye plaques, permanent implants	
	X ray fluorescence devices	
	Electron capture devices	
	Mössbauer spectrometers	
	Positron emission tomographs	
	Medical diagnostic sources	Short lived radioisotopes, e.g. I-131
	Fire detectors	Am-241 and Pu-238

Spent reactor fuel is extremely radioactive and could be used as part of a radiological dispersion device (RDD) or ‘dirty bomb’. Fresh reactor fuel poses less of a radiation risk than spent fuel, although it is still dangerous if inhaled or ingested. Furthermore, the public perception of the radiation risk would most likely be much greater than the actual risk, so the psychological impacts engendered by detonation of an RDD manufactured from fresh reactor fuel could be just as great as that from an RDD made from spent fuel.

Commercial radioactive sources consist of chemically purified isotopes that decay by the emission of alpha, beta or gamma rays. These isotopes are most commonly produced in nuclear reactors, although some isotopes can be made in accelerators as well. They are produced either as a product of the fission process, e.g. ^{137}Cs and ^{90}Sr, or as a result of neutron capture, e.g. ^{60}Co and ^{241}Am. These radioactive isotopes are useful sources of radioactivity for medical diagnostics and therapy, non-destructive analysis (NDA) of material, sterilization of medical equipment and food, and generation of electricity in remote locations. The significant level of radioactivity in many commercial radioactive sources makes them attractive components of an RDD.

The IAEA has developed radionuclide specific activity levels for the purpose of emergency planning and response. These levels, or *D* values, are given in terms of an activity above which a radioactive source is considered to be ‘a dangerous source’ as it has a significant potential to cause severe deterministic effects if not managed safely and securely. The IAEA ranks the danger of a radioactive source according to the ratio of its activity *A* to its relevant *D* value [4]. Five categories of radioactive sources are considered (Table 1). Category 1 includes the most dangerous sources with A/D ratios exceeding 1000. The least dangerous ones come in category 5 with A/D ratios below 0.01. Radioactive sources of activity below the ‘exempt value’ [6] do not constitute a danger.

1.6. AVAILABILITY OF NUCLEAR AND OTHER RADIOACTIVE MATERIAL

Most States maintain tight regulatory oversight (control) over the nuclear material that they produce or use. However, political and economic turmoil can contribute to conditions where even the most rigorous controls can falter. Nuclear fuel is also a valuable asset, as nuclear fuel assemblies can cost in the range of $500 000. Commercial reactor fuel is therefore strictly controlled not only because of its economic value but also because of the large amount of fuel used in power reactors. Although reactor fuel is not directly usable to produce nuclear weapons, it would make an attractive feedstock for an undeclared enrichment process. Also, plutonium could be obtained from irradiated reactor fuel using undeclared reprocessing facilities.

Research reactor fuel tends not to be as tightly controlled as commercial reactor fuel. Research reactors are located at universities, institutes and private companies where security is often at the minimum level required by law. Many research reactors have been shut down, and security remains as an additional duty for an already burdened faculty or staff. The security of research reactor fuel is especially important because it is often HEU. Reduced Enrichment for Research and Test Reactors programmes in the USA [7] and the Russian Federation [8] have been implemented to mitigate the security risk posed by these reactors by converting the HEU based fuel with LEU. The HEU fuel is then returned to the USA or the Russian Federation.

Commercial radioactive sources are widely available. These sources vary in both activity and type of radiation (alpha, beta and gamma) and, therefore, pose different radiological hazards. Sources with low levels of radioactivity, such as the ^{241}Am or Pu sources used in smoke detectors, tend to be more widely available and are less tightly controlled than sources with high levels of radioactivity, such as ^{60}Co sources used in radiotherapy. Correspondingly, the threat posed by the ubiquitous low level sources is much smaller than that posed by high level sources. Until recently, governments have tended to focus more on the safety aspects of these radioactive sources and less on the security aspects. The regulations governing the accounting and control of commercial radioactive sources vary from country to country, but are typically less strict than those governing nuclear material. Consequently, it has been estimated that hundreds of sources are orphaned around the world each year [9, 10].

Both irradiated reactor fuel and high activity commercial radioactive sources present technical difficulties for the potential manufacturer of an RDD. The same high level of radioactivity that makes them attractive material for an RDD also makes them dangerous to the individual who transports the material or fashions it into an RDD. The most intense radiation sources might kill suicide bombers, and a dose of a few gray to part of the body may disable them before completion of their work. Therefore, sources of moderate to low radioactivity may be more attractive as an RDD component. Since the primary purpose of an RDD is social disruption, the psychological effects of the use of such a device, even involving low radiological doses, would be considerable.

1.7. EMERGING PROBLEMS

1.7.1. Illicit trafficking

Since 1995, the IAEA has been maintaining its Illicit Trafficking Database (ITDB) on cases involving the unauthorized use, transport and possession of nuclear and other radioactive material [11, 12]. The ITDB also includes incidents dating back to 1993. It records incidents that have been officially reported or confirmed by Member States, but also includes incidents that are still awaiting confirmation. As of 31 December 2005, the ITDB has recorded a total of 823 confirmed events involving illicit trafficking in nuclear and other radioactive material. Of those cases, 260 involved nuclear material. The number of confirmed nuclear trafficking incidents was highest in 1993–1994. Between 1995 and 2002, the number of such incidents was considerably lower, showing a general declining trend, but in 2003–2004 it increased again. In addition to confirmed cases of nuclear trafficking, more than 120 incidents — which are yet to be confirmed — allegedly involved nuclear material.

Although it is difficult to predict future unauthorized acts involving nuclear and other radioactive material, such activities are increasingly being viewed as significant threats that merit the development of special capabilities. As early as April 1996, nuclear forensics was recognized at the G-8 Summit in Moscow as an element of the response to illicit nuclear trafficking events. Given international events over the past years, the value and need for nuclear forensics seems greater than ever.

1.7.2. Orphan sources

‘Orphan’ sources are radioactive sources that have been abandoned, or are just being ignored, by their legitimate owner and have, therefore, fallen outside of any formal regulatory oversight. These sources could be easily diverted for more malevolent purposes. The lack of accountability for such sources, and the inherent expense and bureaucracy involved in safely and securely disposing of them, has led to their abandonment in a number of instances.

Orphan radioactive sources are frequently found in scrap metal yards or in recycling operations [13, 14]. In at least one case, an end user detected significant excess radioactivity in steel girders that was traced to the inadvertent recycling of a commercial source. More often, though, these orphan sources will become part of the general waste stream from a facility and end up in a local landfill. As of 31 December 2000, the ITDB contained information on 72 confirmed incidents involving the discovery of radioactive sources amidst metal scrap.

Commercial enterprises that use and control these radioactive sources may cease operations and go out of business. In such circumstances, corporate knowledge regarding these sources is lost as technical personnel are dismissed and move to other endeavours. Management is often unconcerned about the ultimate disposition of these radioactive sources. Turnover of faculty and students and changing research priorities may also similarly affect academic and university settings.

In some cases, sources will remain unsecured on the premises. In other cases, individuals not knowledgeable about the safety and security risks of the sources may determine their fate. The widespread contamination in Goiânia, Brazil, in 1987 with ^{137}Cs involved an unsecured radiotherapy source from an insolvent business, and its subsequent scavenging and disposal by people unaware of the radiological risks [15].

1.8. NUCLEAR FORENSICS AND NUCLEAR FORENSIC INTERPRETATION

Determining how and where the control of nuclear and other radioactive material was lost and tracing the route of the material from diversion to interdiction are important goals in nuclear forensics. It is equally important to determine whether additional devices or material that pose a threat to public safety are available by illegal means. The answer to these questions depends on determining the source of the material and its method of production.

Nuclear forensics provides essential insights into methods of production and sources of illicit radioactive material. It is most powerful when combined with traditional methods of investigation, including intelligence sources and traditional detective work. Nuclear forensics can play a decisive role in attributing and prosecuting crimes involving radioactive material.

Some of the current limitations of nuclear forensics are a result of the emerging nature and increasing urgency of this discipline. For example, Member States are only now beginning to share information about nuclear processes and material needed in nuclear forensic investigations. Numerous databases exist in many countries and organizations that could be valuable for the future development and application of nuclear forensics. The contents of many of these databases will never be directly shared, but the development of a ‘distributed’ comprehensive database (see Section 7.3) would benefit international efforts. In addition, countries are beginning to combine the expertise of traditional forensics experts, normally found in police organizations, and nuclear experts, normally found in universities and government laboratories.

Nuclear forensics will always be limited by the diagnostic information inherent in the interdicted material. For example, the clever criminal can minimize or eliminate the important markers for traditional forensics (fingerprints, stray material, etc.). Some nuclear material inherently has isotopic or chemical characteristics that serve as unequivocal markers of specific sources and production processes. Other nuclear material does not. Fortunately, the nuclear fuel cycle industry has a restricted number of identifiable process steps, which makes nuclear forensic interpretation possible. However, very specific information will be needed to differentiate material that reflects similar source or production histories but is derived from unrelated sites.

1.9. INTERNATIONAL COOPERATION

Many international nuclear forensics laboratories are already cooperating to develop common technical strategies and databases that catalogue nuclear processes for use in nuclear interpretation. The ITWG was formed in 1996 to foster international cooperation in combating illicit trafficking of nuclear material [1]. More than 28 nations and organizations have participated in nine international meetings and two round robin analytical exercises to date. The technical priorities of the ITWG included the development of accepted and common protocols for the collection of evidence and nuclear forensics laboratory investigations, the prioritization of techniques and methods for forensic analyses of nuclear and non-nuclear samples, the organization of inter-laboratory forensic exercises, the development of forensic databanks to assist in interpretation, and technical assistance to requesting countries.

1.10. ITWG NUCLEAR FORENSICS LABORATORIES

The nuclear forensics laboratories participating in the ITWG are committed to undertaking the characterization of nuclear or other radioactive material, which has been confiscated and submitted for analysis by legal prosecution authorities. These laboratories have pledged to cooperate closely among themselves and with prosecuting authorities to facilitate the elucidation of illicit events involving nuclear and other radioactive material, in accordance with the guidelines of the present publication. These commitments have been formalized in the charter of the ITWG Nuclear Forensics Laboratories (INFL), which was adopted in September 2004. A description of the INFL, its charter and contact points is given in Appendix IV.

2. NUCLEAR FORENSICS PLAN OF ACTION

An IAEA publication (IAEA-TECDOC-1313 [2]) provides information to front-line officers on the response to events involving the detection of unauthorized acts involving nuclear and other radioactive material. Detailed scientific information has been kept to a minimum in IAEA-TECDOC-1313 [2] as the majority of law enforcement personnel are not expected to have the background necessary to use such information effectively. On the other hand this report presents the relevant technical information in more detail, as it addresses itself to the authorities that request a nuclear forensic investigation and also to the competent laboratories called for assistance in such investigations.

Nuclear forensic investigations will start after a suspect radioactive source has been interdicted and the initial and operational responses indicate a possible breach of the law, and confirm the need for a tactical response. Nuclear forensic investigations are initiated to answer specific questions raised by the legal prosecution authority and its *investigation team*. It is essential that they closely interact with all other investigation measures. According to the Model

Action Plan developed by the ITWG [16], it is recommended that nuclear forensic investigations be conducted according to the following plan of action:

(a) The site is cordoned off and guarded by the law enforcement service.
(b) The competent service confirms the nuclear or radioactive nature of the material and determines whether a potential nuclear, radiological or chemical hazard exists.
(c) The authority permitted to initiate the action plan is informed.
(d) On-site, the following actions take place:
   — Health physics examination for occupational and public radiation hazard;
   — Law enforcement actions to check for hidden explosives and preserve evidence, and chain of custody in accordance with State law;
   — On-site categorization of seized material by mobile NDA instrumentation;
   — Safe storage of material until transportation.
(e) The following investigations are to be foreseen at the specialized national nuclear forensics laboratory:
   — Checking for hidden explosives before unpacking;
   — Preservation of evidence and classical forensic analysis of non-radioactive material;
   — Detailed investigation according to the laboratory's capabilities (visual, quantity, sampling, nuclear properties, etc.);
   — The data from the in-depth analysis by the specialized nuclear forensics laboratory should be interpreted in terms of the processes used to create or manufacture the material — from this interpretation attribution of the origin of the material might be possible.
(f) If the national nuclear forensics laboratory is not in a position to carry out certain analyses, a sample of the material could be shipped to an external specialized nuclear forensics laboratory, such as one from the INFL.
(g) The results are compared with an appropriate database, possibly resulting in further investigations.
(h) An analytical expert opinion of the analysed seized material is to be written for the national law enforcement authorities where the seizure occurred. An expert from the requesting organization should participate in drafting the expert opinion.
(i) A synopsis and evaluation of all evidence is to be made by the national legal authority.
(j) The case will be treated by the national courts and closed.
(k) The competent authority will make arrangements for disposition of the material.

In this report, the measures spelled out in the above plan will be grouped and discussed according to five categories with the aim of examining:

- Incident response;
- Nuclear forensics laboratory sampling and distribution;
- Nuclear forensic analysis;
- Traditional forensic analysis;
- Nuclear forensic interpretation.

3. INCIDENT RESPONSE

3.1. SECURING THE INCIDENT SITE

There are three key goals in securing an incident site:

- Minimization of any radiological hazards associated with the incident site;
- Control of nuclear or other radioactive material;
- Preservation of both nuclear and associated traditional forensic evidence.

The incident commander will have to make decisions that involve the often competing concerns of public safety, environmental protection, safety of response personnel, and the preservation and collection of evidence. In order to understand the requirements of the nuclear forensic investigation, the incident commander should form an incident investigation team at an early stage (Fig. 1). The incident investigation team should — to the extent possible — include experts in all relevant disciplines and provide advice and support to the incident commander. The incident investigation team should include a person knowledgeable in nuclear forensics, if at all possible, or, if not, a law enforcement forensics specialist. The experts in the incident investigation team will often reflect competing interests, so their consensus will provide the best balance between those interests. The incident commander can adjudicate any irreconcilable disputes within the incident investigation team.

The incident commander should sequence activities to prevent the destruction or contamination of evidence. For example, the legitimate goal of site decontamination should occur after the collection of evidence, if at all possible. The collection of traditional forensic evidence should be performed in a manner that preserves the integrity of the nuclear forensic evidence and vice versa. All significant evidence should be photographed before removal from the scene.

3.2. ON-SITE ANALYSIS

The collection of evidence assumes that appropriately qualified explosive ordnance disposal personnel can first render any explosive device safe. The availability of a portable X ray radiography device can expedite this process by allowing the imaging of solid samples and containers in the field to confirm the absence of hidden explosives or other threats. Only after stabilization and release by explosive and weapons experts will access be provided for nuclear forensics.

In addition, on-site NDA using gamma ray spectrometry and neutron detection can categorize the suspected radioactive material without affecting the evidence. The goal of categorization is to identify the bulk constituents of the material.

The categorization analysis can be performed quickly. A very important outcome of in-field categorization is the insight into what laws may have been broken, which forms the basis for the continued investigation. Therefore, a portable gamma ray detector is an important piece of equipment for the incident investigation team. Categorization can also provide important

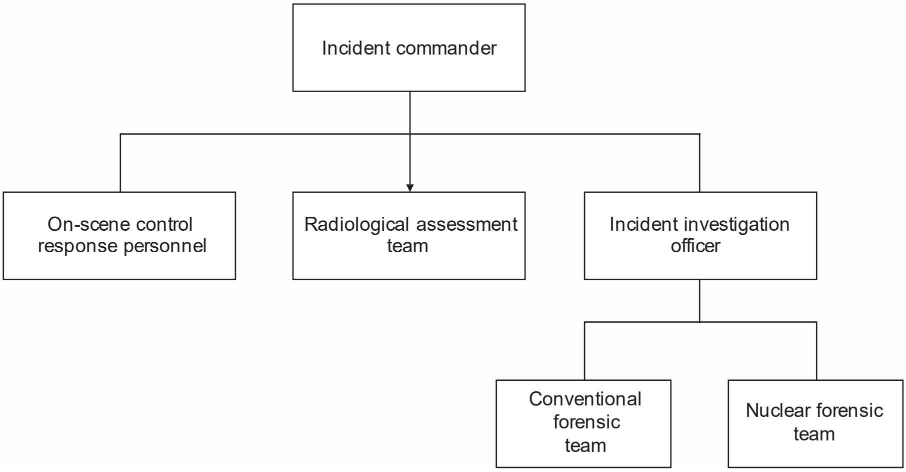

FIG. 1. Example of a tactical response command structure [2].

information for both the radiological assessment team and the incident investigation officer.

Member States may request assistance from the IAEA with operations and analysis at the incident site. A Member State can call on the IAEA to initiate contact with the INFL (see Step 1 in Appendix I) in order to evaluate the need for nuclear forensic assistance. In addition, the IAEA — through the INFL — can provide advice regarding such activities as collection and preservation of evidence and categorization of radioactive material (see Step 2 in Appendix I). IAEA or INFL experts can even serve as an adjunct to the incident investigation team by providing remote consultation via telecommunications on nuclear forensic issues that may arise. Depending on the nature of the incident, assistance can also be requested from the IAEA under the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the 'Assistance Convention') [17]. The procedures for requesting IAEA assistance during an emergency (medical treatment, monitoring, source recovery, etc.) are described in Ref. [18].

3.3. COLLECTION OF RADIOACTIVE EVIDENCE

The radiological assessment team can help locate radioactive evidence at the incident site through use of radiation survey instrumentation. The use of a grid system will aid in the radiological survey of the site, and individual readings could be referenced to these squares. It is advisable to draw an accurate diagram of the incident scene (including the compass orientation or GPS coordinates) that shows the location of any radioactive material or other evidence, the extent of the contamination, and the establishment of cordon and control areas. The use of a grid system can assist with the production of such a drawing. Photographic documentation is advisable.

Suitable arrangements (e.g. training, procedures and equipment) need to be made to ensure that radiation protection is provided consistent with IAEA requirements for the protection of workers (including emergency workers). Some of the key elements of the requirements are listed below:

- Arrangements need to be made — in accordance with international standards — for managing, controlling and recording doses received by emergency workers [6, 19].
- Arrangements need to be made in advance to designate as emergency workers those who may undertake actions to save lives, prevent serious injury, avert a large collective dose or prevent the development of catastrophic conditions. The requirements set different dose levels for

different activities, and at the higher levels workers should be informed of the associated risks and thus be deployed on a voluntary basis.

— Arrangements need to be made for taking all practicable measures to provide protection for emergency workers for the range of anticipated hazardous conditions in which they may have to perform response functions. These include: arrangements to continually assess and record the doses received by emergency workers; procedures to ensure that the doses received and contamination are controlled in accordance with established guidance in compliance with international standards; and arrangements for the provision of appropriate specialized protective equipment, procedures and training for emergency response in the anticipated hazardous conditions. This guidance will include default operational levels of dose for emergency workers for different types of response activities, which are set in quantities that can be directly monitored during the performance of these activities (such as the integrated dose from external penetrating radiation). In setting the default operational levels of dose for emergency workers, the contributions to doses through all exposure pathways need to be taken into account. These levels are called turnback levels.
— Once the emergency phase has ended, workers undertaking non-emergency operations, such as the recovery of sources, are subject to the full system of detailed requirements for occupational exposure prescribed in Appendix I of Ref. [6].
— Once the emergency has ended, the doses received and the consequent health risk have to be communicated to the workers involved [6].
— The person within each response organization responsible for ensuring the protection of workers will be specified in emergency plans and procedures [6].

If the radioactive evidence is well contained, for example LEU powder inside a lead shielded container, the investigating officials should secure only the sample and remove it from the scene with due attention to preserving any traditional forensic evidence. On the other hand, if the evidence is widespread or scattered, the investigating officials should take care to be as comprehensive as possible in the collection. It is hard to predict a priori what portion of the evidence might prove to be critical to the interpretation.

The incident investigation officers should be trained as — or accompanied by — forensic collection specialists. They should take as much care as is reasonable, given the tools at hand and time limits due to radiation levels, to extricate the radioactive material from non-radioactive material (local dirt, grass, or leaves) and evidence. If there is any doubt as to what is evidence and what is contamination, incident investigation officers should err on the side of being comprehensive and collecting too much material, rather than not enough. IAEA publications [20, 21] describe standardized procedures used by IAEA safeguards inspectors to obtain samples of nuclear material, including swipe samples. They can provide a good basis for the training of officers who may be called to join an investigation team.

Incident investigation officers can scoop solid samples into clean plastic bags using a spatula or shovel. If there appear to be several types of material located in different areas, then, if practical, the incident investigation officers should try to minimize cross-contamination by using a different spatula or shovel to collect each type of material or, at least, cleaning the spatula or shovel between samplings. All plastic bags need to be appropriately labelled with their contents and the appropriate reference designator.

Radioactive liquid samples can be collected in clean plastic bottles. The incident investigation officers can use syringes or pipettes to transfer the liquid from the scene into the plastic bottles. If there appear to be several types of liquids, then, if possible, the incident investigation officers can try to minimize cross-contamination by using a different syringe or pipette to collect each liquid or, at least, cleaning the syringe or pipette between samplings. Extremely large volumes of liquid may need to be collected using an industrial wet vacuum. The vacuum would then require decontamination when finished. All bottles need to be appropriately labelled with their contents and the appropriate reference designator. Collection apparatus, including spatulas and syringes, has to be decontaminated or disposed of as radioactive waste.

The initial plastic containers may be sufficient to contain and transport radioactive samples that are only alpha or beta emitters. If the samples are strong beta or gamma ray emitters, however, the radiological assessment team may require that the samples be transported inside a lead shielded container.

If immovable or large objects, such as buildings or cars, have become contaminated with radioactive evidence, then it will be necessary for the incident investigation officers to ‘swipe’ these objects. A swipe is a filter material and swiping is a convenient method for collecting particulate samples. Sticky tape is a convenient means to collect particulates from the surface of objects. The incident investigation officers should attempt to swipe as large an area as possible to remove all of the radioactive evidence. A fresh swipe or sticky tape should be used to sample new objects. When finished, each sample should be appropriately packaged and labelled.

The collection of radioactive samples by swiping may destroy traditional forensic evidence, such as fingerprints. Therefore, it is essential that appropriate thought be given to the timing of the collection of radioactive evidence relative to traditional forensic evidence. The ultimate decision rests with the incident commander, with input from the incident investigation team.

The incident investigation officers need to maintain appropriate chain of custody procedures during the evidence collection process. In particular, each sample container (plastic bag or bottle) should be labelled with a unique designator. The evidence recovery log should tie the designator to a particular location on the incident site and date/time, as well as to the particulars of the collection method. The nuclear forensics laboratory will then maintain chain of custody paperwork that will tie the analytical results and conclusions to that unique designator. All evidence has to be secured and protected while awaiting transportation from the incident scene.

3.4. COLLECTION OF TRADITIONAL FORENSIC EVIDENCE

Again, it is advisable to draw an accurate site diagram of the incident scene, including the compass orientation together with GPS coordinates, that shows the location of any radioactive material or other evidence, the extent of the contamination, and the establishment of cordon and control areas. The use of the grid system can assist with the production of such a drawing. This diagram could become an essential item of information in a judicial process. Photographic documentation is again advisable.

The collection of traditional forensic evidence should be consistent with good radiological safety practice. Traditional forensic evidence is frequently cross-contaminated with radioactive evidence. Radiation and toxic exposure of the incident investigation officers can be minimized through the principles of time, distance and shielding as described earlier.

As the incident investigation team approaches the incident scene, it should be alert for any discarded evidence. The team members need to make pertinent notes as they survey and take control of the scene. With the help of the radiological safety officer, they should continually assess the safety of all operations. The team should determine the extent to which the incident scene has been protected so far and be alert for any signs of tampering with the evidence.

The first task for the incident investigation team is to initiate a preliminary survey that delineates the extent of the search area, then note any physical or environmental constraints bearing on the collection of evidence, and obtain information necessary to organize the detailed search.

A full forensic search of the scene should be conducted, if possible. If a grid system is implemented, then a systematic search of each square may uncover relevant forensic evidence. All evidence associated with the radioactive sample, such as the original sample container, associated paperwork, etc., should be collected. Such evidence is often important for the purposes of interpretation and may constitute the only evidence relevant to the material loss of control.

The collection of traditional forensic evidence might interfere with the collection or analysis of radioactive/toxic evidence. Therefore, it is essential that appropriate thought be given to the relative timing of the collection of radioactive evidence versus traditional forensic evidence. The ultimate decision rests with the incident commander, with input from the incident investigation team.

As with the collection of radioactive evidence, the incident investigation officers have to maintain appropriate chain of custody procedures during the evidence collection process. This includes the logging of all samples into the evidence recovery log. In addition, all evidence is to be secured and protected while awaiting transportation from the incident scene.

3.5. FINAL SURVEY AND RELEASE OF SCENE

The incident investigation team should conduct a final survey before releasing the incident scene to the proper authorities. In the final survey, all participants should critically review all aspects of the search to ensure completeness. They should make sure that any potential hiding places or difficult to access areas have not been overlooked.

The documentation should also be checked for inadvertent errors or omissions. The photographer should document the final condition of the incident scene. All evidence should be accounted for before departing from the scene. Finally, the team should gather all of the equipment used in the search.

When the final survey is complete, the incident commander can release the incident scene to the proper authorities. This release should be documented, including date, time, to whom the scene was released, and who released it. The scene should not be released until the incident investigation team is ready, because once a scene is released, re-entry may require a warrant.

3.6. EVIDENCE HOLDING SITE

Depending on local regulations and the procedures of the nuclear forensics laboratory, it may be necessary to store the evidence after collection and before ultimate transportation to the nuclear forensics laboratory. Therefore, it may be necessary to establish an intermediate storage facility or holding site. This facility needs to have the security necessary to store the evidence, and the radiological/chemical permits necessary to handle the level of radioactivity present in the samples. Member States can request IAEA and INFL assistance with the establishment and operation of the holding site (see Step 2 in Appendix I).

Solid evidence, e.g. closed containers, should once again be imaged using X ray radiography at the holding site to understand the nature of the evidence and confirm the absence of hidden explosives or other threats. If material categorization was not performed at the incident site, it should definitely be performed at the holding site before transportation to the nuclear forensics laboratory. Even if material categorization was performed at the incident site, it may be useful to confirm the categorization, perhaps using more advanced instrumentation, e.g. gamma ray spectrometry with a high resolution germanium detector rather than a sodium iodide detector. The additional categorization could provide additional information, as well as an evaluation of the efficacy of the on-site categorization. The Member State can request advice from the IAEA regarding the categorization of radioactive material (see Step 2 in Appendix I).

3.7. TRANSPORTATION OF EVIDENCE

In transporting evidence, either to a predetermined intermediate storage facility or to the nuclear forensics laboratory, the incident commander, in consultation with the radiological advisor, needs to consider safety, security and preservation of evidence. Most radioactive samples can be kept in their collection containers for shipment. However, these primary containers have to be packed inside another container certified for the shipment of such material. In all cases, the packaging and transportation needs to satisfy legal, safety and security requirements. Precautions should be taken to avoid potential cross-contamination from the shipping container

Member States may also request assistance from the IAEA with the transportation of radioactive material from the incident site or holding site to the nuclear forensics laboratory (see Step 3 in Appendix I). The IAEA can, in consultation with the INFL, provide advice on packaging to prevent contamination or cross-contamination of evidence. These requirements are expected to be consistent with IAEA recommendations on the physical protection of nuclear material [22] and safe transport of radioactive material [23]. These requests for assistance from the IAEA with transportation need to be differentiated from those involving the Assistance Convention [17].

4. NUCLEAR FORENSICS LABORATORY SAMPLING AND DISTRIBUTION

4.1. NUCLEAR FORENSICS LABORATORY

The evidence should be sent for analysis to a nuclear forensics laboratory equipped to receive and process such samples. It may be possible to send the traditional forensic evidence to a police crime laboratory and the nuclear forensic evidence to a nuclear analysis laboratory. However, it is highly likely that the two types of evidence are mixed, so that the traditional forensic evidence is contaminated with radioactive material and the radioactive material contains some forensic evidence. Therefore, the receiving nuclear forensics laboratory should be able to handle radioactive material and carefully separate the traditional forensic evidence from the radioactive material for later analysis by experts in each discipline. Consequently, it is advisable to send the sample to a laboratory skilled in nuclear forensic analysis that combines the capabilities of the crime laboratory and the nuclear forensics laboratory. Nuclear forensics laboratories are outfitted and staffed to handle contaminated evidence and to accommodate the requirements of both the traditional forensic and nuclear analyses.

The nuclear forensics laboratory should be an appropriately qualified and recognized facility with analytical procedures and staff qualifications that are documented and can withstand both scientific peer review and legal scrutiny. In addition, the nuclear forensics laboratory needs to be appropriately licensed to receive the evidence being shipped. The receiving facility needs to be able to handle large amounts of nuclear material, yet still be able to analyse trace levels of the material constituents and environmental types of material. Consequently, the nuclear forensics laboratory has to be free from fixed and dispersible background contamination to ensure that there is no chance of cross-contamination between samples.

Another requirement is that the nuclear forensics laboratory be fully qualified for the current standards in environmental, safety and health protocols, hazardous waste disposal procedures, and hazardous material handling and storage. The laboratory should be provided with the appropriate physical protection measures and proper procedures in place for the accounting for and control of nuclear material. The nuclear forensics laboratory should be intimately familiar with the requirements of a legal investigation, including the ability to perpetuate the sample chain of custody that began in the field.

Staff experts at the nuclear forensics laboratory need to be able to provide varying levels of response, depending on the requirements of the interdicting authorities. This might involve just consultation or increasing levels of data acquisition and analysis, ranging from characterization to full nuclear forensic interpretation.

Member States may also request assistance from a laboratory with the nuclear forensic analysis. The INFL can identify an appropriate member nuclear forensics laboratory to provide assistance (see Step 4 in Appendix I) and to determine the level of analysis required (characterization versus interpretation). The actual investigation will be carried out on the basis of a bilateral arrangement. The INFL nuclear forensics laboratory will work with the requesting authority to define an appropriate statement of work (SoW) for the nuclear forensic analysis. Step 5 in Appendix I lists the issues to be addressed in an SoW. The SoW will establish the requirements of the Member State, including rules of evidence, sharing of information, confidentiality and non-disclosure agreements. An expert from the requesting authority should also participate in planning and execution of the analysis and in drafting the final report. The SoW will also establish expectations about timelines and the frequency and type of communication. Appendix V gives an example of a relevant SoW.

4.2. FORENSIC MANAGEMENT TEAM

It is recommended that a forensic management team (FMT) be established before any nuclear forensic or traditional forensic analysis is performed. In addition to nuclear forensic experts, the FMT should contain laboratory staff with training in criminology, and also the appropriate law enforcement and State officials. In the case where a Member State requests assistance from the INFL, the FMT would be established upon finalizing the SoW, which will govern the nuclear forensics laboratory analysis of the evidence. In this case, the FMT would include the nuclear forensics experts at all participating laboratories, and law enforcement and government officials from the requesting Member State. The participants in the FMT should be bound by the SoW, especially with regard to the conditions covering any confidentiality or non-disclosure agreement.

4.3. SAMPLING AND ALIQUOTING IN A NUCLEAR FORENSICS LABORATORY

The FMT should develop the initial experimental plan. The plan should include methods for preventing contamination or cross-contamination of the evidence. Because of the dynamic nature of the nuclear forensic process, the FMT will modify the plan as new information about the sample or the investigation is obtained.

The experimental plan should not assume that the nuclear material is homogeneous or that the material from different samplings from the incident site is identical. Consequently, a single bulk analysis may not be appropriate to fully categorize, characterize or interpret the sample. The nuclear forensics laboratory needs to establish good sampling techniques to adequately characterize the radioactive evidence. In the extreme, this could mean analysis of individual particles, but, more commonly, it would mean separate bulk analyses for individual components of the radioactive evidence.

When the amount of material being sampled is small, the experimental plan needs to allocate the limited amount of sample. In this case, it is important that all NDAs be performed first. In addition, trace and micro-analytical techniques are more appropriate than techniques that require large amounts of material.

Solid evidence, e.g. closed containers, should be imaged using X ray radiography before sampling in the nuclear forensics laboratory to understand the nature of the evidence and confirm the absence of hidden explosives or other threats to examiners. Assuming that the X ray analysis shows no danger, the sampling can then proceed.

It is, once again, useful to categorize the material. The additional categorization could provide new information, including the total amount of nuclear or radioactive material, and also an evaluation of the efficacy of the on-site and holding site categorizations. High resolution gamma ray spectrometry and isotope ratio mass spectrometry are essential for the categorization at the nuclear forensics laboratory. For bulk samples, isotope ratio mass spectrometry can be performed using either thermal ionization mass spectrometry (TIMS) or inductively coupled plasma mass spectrometry (ICP-MS).

5. NUCLEAR FORENSIC ANALYSIS

5.1. OVERVIEW

Nuclear forensics does not consist of routine procedures that can be universally applied to all evidence. Rather, it involves an iterative approach, in which the results from one analysis are used to guide the selection of subsequent analyses. In this way, radioactive material analysis applied to nuclear forensics proceeds in a manner not unlike that of traditional forensic analysis.

It is important to emphasize that all sampling and analyses have to be performed with due regard for preservation of evidence and maintaining the chain of custody. The sampling process can equally extract and obliterate evidence. Many of the analytical tools used in radioactive material analysis are destructive, i.e. they consume some amount of sample during analysis. Therefore, the proper selection and sequencing of analyses is critical.

Further analysis will be guided by the initial categorization. The FMT should choose the next analysis based upon the ultimate goals of the investigation (see the discussion of basic characterization versus interpretation in the next section), the information uncovered so far, the potential signatures (physical, chemical, elemental, isotopic) that might lead to precise interpretation, the amount of sample available for analysis, and methods for measuring forensic signatures.

5.2. CHARACTERIZATION

The goal of characterization is to determine the nature of the radioactive evidence. Characterization provides full elemental analysis of the radioactive material, including major, minor and trace constituents. For major constituents of the radioactive material, characterization would also include isotopic and phase (i.e. molecular) analysis, if necessary. Characterization may not include analysis of traditional forensic signatures or reactor modelling and database searches to identify probable sources of the material.

However, characterization does include physical characterization. The sample should be imaged at high magnification, by a scanning electron microscope, for example. The critical dimensions of solid samples and the particle size and shape distributions of powder samples should be measured.

The characterization will take less time than the full interpretation. The length of the process will depend on the workload of the nuclear forensics laboratory, but could be completed within two to four weeks after receipt of the samples.

5.3. NUCLEAR FORENSIC INTERPRETATION

Nuclear forensic interpretation is one factor in attributing material on the basis of analyses conducted in the nuclear forensics laboratory. It includes the ability to match analytical data with existing information on sources and methods used to produce radioactive material and with prior cases involving interdicted nuclear material. While analytical protocols have improved systematically with advances in technology, the ability to interpret radiochemical data for the purposes of interpretation has not progressed equally. The challenge for the future is to develop and apply tools for data interpretation that provide combined and credible determinations of locations and methods of material production. The information obtained from nuclear forensic interpretation will be used for attribution.

5.4. ATTRIBUTION

The goal of attribution is to analyse all radioactive and traditional forensic evidence in order to attribute the nuclear material, including origin, method of production, probability that more of the material exists, transit route and the way that regulatory oversight was lost. This includes analysis of the traditional forensic evidence and a comprehensive analysis of the radioactive evidence. Full attribution analysis would include database searches to identify the method of production and probable sources of the material.

5.5. SUMMARY OF AVAILABLE TOOLS

The nuclear forensic scientist has a wide array of analytical tools to use for detecting signatures in radioactive material. Appendix II provides a listing and description of many of the techniques used in radioactive material analysis. These individual techniques can be sorted into three broad categories: bulk analysis tools, imaging tools and microanalysis tools.

Bulk analysis tools allow the forensic scientist to characterize the elemental and isotopic composition of the radioactive material as a whole. In some cases, bulk analysis is necessary to have sufficient material to adequately detect and quantify trace constituents. The presence and concentration of trace constituents are often vitally important as signatures for certain manufacturing processes, for determining the time since chemical separation, and for determining whether the material has been exposed to a neutron flux.

Imaging tools provide high magnification images or maps of the material and can confirm sample homogeneity or heterogeneity. Because bulk analysis provides an integrated compositional measurement of the sample as a whole, if the material is inhomogeneous, the resulting analysis could obscure important signatures in the individual components. Imaging will capture the spatial and textural heterogeneities that are vital to fully characterize a sample.

If imaging analysis confirms that the sample is heterogeneous, then microanalysis tools can quantitatively or semi-quantitatively characterize the individual constituents of the bulk material. Microanalysis tools also include surface analysis tools, which can detect trace surface contaminants or measure the composition of thin layers or coatings, which could be important information for interpretation.

5.6. SEQUENCING OF TECHNIQUES AND METHODS

The ITWG has achieved a general consensus among the members of the nuclear forensics community on the proper sequencing of techniques so as to provide the most valuable information as early as possible in the analysis process. This consensus was achieved through discussion and consultation at meetings, and from experience developed from two round robin analyses by INFL laboratories. Table 2 shows the generally accepted sequence of analysis, broken down into techniques that should be performed within 24 hours, one week, or two months from arrival at the nuclear forensics laboratory.

TABLE 2. SUGGESTED SEQUENCE FOR LABORATORY TECHNIQUES AND METHODS

Techniques/methods	24 hours	One week	Two months
Radiological	Estimated total activity Dose rate (α, β, γ, *n*) Surface contamination		
Physical	Visual inspection Radiography Photography Weight Dimensions Optical microscopy Density	SEM/EDS XRD	TEM (EDX)
Traditional forensic	Fingerprints, fibres		
Isotope analysis	γ spectroscopy α spectroscopy	Mass spectrometry (SIMS, TIMS, ICP-MS)	Radiochemical separation
Elemental/chemical		ICP-MS XRF Assay (titration, IDMS)	GC-MS

SEM/EDS: Scanning electron microanalysis with energy dispersive sensor; TEM: transmission electron microscopy; SIMS: secondary ion mass spectrometry; TIMS: thermal ionization mass spectrometry; ICP-MS: inductively coupled plasma mass spectrometry; XRF: X ray fluorescence analysis; IDMS: isotope dilution mass spectrometry; GC-MS: gas chromatography-mass spectrometry. (See Appendix II for further references.)

6. TRADITIONAL FORENSIC ANALYSIS

6.1. OVERVIEW

Traditional forensic analysis, like radioactive material analysis, can be an iterative process, in which the results from one analysis are used to guide the selection of subsequent analyses. The forensic analyst is required to carefully examine all items seized at the incident site in order to uncover as much information as possible. Unlikely and apparently unrelated evidence is often key to the successful prosecution of a case.

Once again, all sampling and analysis need to be performed with due regard for the preservation of evidence. The sampling process could contaminate or destroy some evidence while pursuing other evidence. The collection of traditional forensic evidence on radioactively contaminated material should also be performed in a manner consistent with good radiological safety practices.

6.2. SUMMARY OF AVAILABLE TOOLS

The variety of traditional forensic evidence, and also the methods of collection and evaluation, are almost limitless. Appendix III provides a representative, but not exhaustive, summary of traditional forensic evidence. For example, evidence such as tissue, hair, fingerprints and shoeprints can often associate an individual with a specific place or object. The analysis of fibres, pollen, or chemical substances found at the incident scene can provide information about motives or transportation routes. Documentary evidence provides useful information not only in the content of the communication itself, but also in the incidental details of its creation (paper, ink, film type, extraneous noises and accents).

6.3. SEQUENCING OF TECHNIQUES AND METHODS

In a manner similar to the collection of radioactive evidence, the international community has agreed upon a sequence for the collection of traditional evidence. Table 2 shows that the collection of fingerprint and fibre evidence should occur within the first 24 hours after sample receipt. The chemical analysis of other evidence, using such techniques as gas chromatography-mass spectrometry (GC-MS), may occur up to two months after the recovery of evidence. Priority should be given to the collection of more individualized signatures (DNA or hair) or those more sensitive to environmental degradation (HEU residue).

7. NUCLEAR FORENSIC INTERPRETATION

7.1. RELEVANT SIGNATURES

Signatures are the characteristics of a given sample of nuclear or radioactive material that enable one to distinguish that material from other nuclear or radioactive material. These signatures facilitate the identification of the processes that created the material, aspects of the subsequent history of the material, and potentially the specific locations in the history of the material. Much of the research and development in nuclear forensic interpretation centres on the discovery and understanding of these signatures. Two important approaches to delineating signatures are:

(1) Discovery using an empirical approach through the systematic analysis of nuclear and radioactive material;
(2) Modelling based on the chemistry and physics of nuclear processes.

Signatures include physical, chemical, elemental and isotopic characteristics of the material.

Physical characteristics of the material include the texture, size and shape of solid objects and the particle size distribution of powder samples. For example, the dimensions of a fresh nuclear fuel pellet are often unique to a given manufacturer. The particle size distribution of uranium oxide powder can provide evidence about the uranium conversion process. Even the morphology of the particles themselves, including such anomalies as inclusions or occlusions, can be indicative of the manufacturing process.

The chemical characteristics of the material include the exact chemical composition or the association of unique molecular components. For example, uranium oxide can be found in many different forms, e.g. UO_2, U_3O_8 or UO_3, each of which can be found at various points in the uranium fuel cycle. The association of some organic compounds, such as certain light kerosene oils or tributyl phosphate, with the nuclear material can be indicative of a reprocessing operation.

Elemental signatures of the material include the determination of major, minor and trace elements in the material. Major elements can of course help define the identity of the nuclear material, but minor elements, such as erbium or gadolinium that serve as burnable poisons, or gallium that serves as a phase stabilizer for plutonium metal, also help define its function. Trace elements can also prove to be indicative of a process, e.g. Fe and Cr residues from stainless steel tooling or Ca, Mg, or Cl residues from a water based cleaning process.

Isotopic signatures of the material include the detection of fission or neutron capture products, which indicate that the material has been in a nuclear reactor and serve as a fingerprint for the type and operating conditions of a given reactor. Other isotopes are decay products from radioactive parent isotopes in the material. For example, ^{230}Th is a decay product of ^{234}U, and ^{235}U is a decay product of ^{239}Pu. Because radioactive isotopes decay at a rate determined by the isotope in the material and the half-life of the parent isotope, the relative amounts of decay products and parent isotopes can be used to determine the 'age' of the material (the time since the parent isotope was last chemically separated from its decay products). Table 3 lists some of the relevant signatures in a plutonium sample and what those signatures might reveal.

7.2. COOPERATION WITH OTHER NUCLEAR FORENSICS LABORATORIES

Cooperation between nuclear forensics laboratories on specific cases enhances the quality of endogenic information, i.e. information derived from the analysis of the sample material and interpretation of the resulting data. Access to knowledge from the broadest collection of experts increases the chances of a unique and successful interpretation of the data. Sharing of information between international nuclear forensics laboratories, consistent with non-disclosure requirements specified in the SoW, makes use of the extensive experience and newly developed capabilities of each laboratory to derive new and valuable information from the material analysis. The participation of other nuclear forensics laboratories also allows for a peer review of the nuclear forensic interpretation process, increasing confidence in the validity

TABLE 3. EXAMPLES OF RELEVANT RADIONUCLIDE SIGNATURES

Signature	Information revealed
In-growth of daughter isotopes	Chemical processing date
Pu isotope ratios	Enrichment of U used in Pu production Neutron spectrum and irradiation time in the reactor
Residual isotopes	Chemical processing techniques
Concentration of short lived fission product progeny	Chemical yield indicators

and impartiality of the interpretation effort. It is, therefore, highly recommended that the SoW (see Step 5 in Appendix A) include the approval for the responsible nuclear forensics laboratory to share information, questions and opinions with other nuclear forensics laboratories around the world to advance the state of the art in nuclear forensics.

Cooperation among nuclear forensics laboratories on specific cases also promotes the exchange of exogenic information, i.e. information germane to the incident, but external to analysis of the material and interpretation of the results. As noted in Section 1.8, international collaboration is essential for the worldwide problem of control of nuclear material. By their very nature, incidents involving loss of nuclear material can be international in scope, with nuclear material sourced in one location and transported to another. The ability to share some of the details of specific incidents, unique analytical capabilities and knowledge databases is important for countering the threat of nuclear incidents.

7.3. KNOWLEDGE BASES OF NUCLEAR PROCESSES

Extensive knowledge bases of nuclear processes and nuclear forensic data are necessary for the effective interpretation of laboratory results (endogenic information) and for application to existing information on the sources, methods and origin of nuclear material throughout the world. This ability to compare signatures with existing knowledge and data is at the heart of the interpretation process. These knowledge bases are currently maintained by a variety of international, national and non-governmental entities. There are also current efforts to develop and organize databases that catalogue nuclear processes for use in nuclear forensics.

In some cases, these knowledge bases contain information that can be freely shared among the participants, and also proprietary or classified information for which access is restricted. Experts from each participating country or organization, as part of a worldwide network, maintain access to their own databases and knowledge bases to which they have full access. In response to queries for information from other experts in the network, they can respond by releasing the results of the queries without compromising any of the controlled information or data that underlie the response. Thus, distributed data can be used to create information for the network with due consideration for data security.

7.3.1. Archived material

Comparative analyses of archived nuclear and other radioactive material, including interdicted material, can be particularly helpful. These analyses allow the nuclear forensic expert to establish connections between the material and the processes used to create it. As new signatures are discovered that depend on new analytical methods, it becomes increasingly important that archived data be accompanied by archived material. Then, the old material can be re-analysed using the new analytical methods and the resulting data analysed for the presence or absence of the newly discovered signatures. Sample archives can include 'real world' interpretation samples, reactor fuel stock, other nuclear material and radioactive sources.

7.3.2. Open literature

Many of the basic nuclear processes are documented in textbooks, reports and papers in the open literature. These documents can be found in technical libraries and on the Internet. The IAEA web site (http://www.iaea.org/), for example, has a number of databases that document publicly available information about nuclear facilities around the world.

7.3.3. Closed literature

Proprietary or classified processes may only be documented in 'closed' literature. Companies are often willing to share proprietary information with national nuclear forensics laboratories after the execution of an appropriate non-disclosure agreement. In addition, national laboratories are usually able to access the classified literature of their own country but, obviously, not those of other countries. This makes international cooperation between nuclear forensics laboratories of vital importance in resolving certain incidents.

7.4. ITERATIVE PROCESS

Analytical results from both radioactive material and traditional forensic analyses should be interpreted by experts representing a spectrum of all forensic specializations. Results from radioactive material analysis and traditional forensic analysis guide the development of the nuclear forensic case. Nuclear forensics experts use both an empirical approach, through the previous analysis of nuclear and other radioactive material, and a modelling approach, based upon the chemistry and physics of nuclear processes, to predict relevant signatures from those processes. They also use their knowledge of analytical science to select the appropriate methods to verify the presence or absence of these signatures.

At the beginning of the nuclear forensic process, the results from the radioactive material and traditional forensic analyses will most likely be consistent with many incident scenarios. As the process continues and new results prove inconsistent with those scenarios, certain scenarios are excluded. In the optimum case, only a single scenario will eventually prove consistent with all results.

Case development is very much a deductive process (see Fig. 2). The nuclear forensics expert develops a hypothesis or set of hypotheses based upon the results at that point. This hypothesis suggests additional signatures, which either might or must be present if the hypothesis is true. The expert then devises tests to verify the presence or absence of the signatures. Access to other experts around the world, to nuclear forensic knowledge bases and to archived sample libraries are important tools that allow the nuclear forensics expert to formulate the hypothesis and the method to test it. If these tests show that the signature is absent, then the nuclear forensics scientist has to abandon or adjust his/her hypothesis to fit the new results. If the tests show that the signature is present, then either a unique interpretation has been achieved or additional tests have to be devised to exclude other possible scenarios.

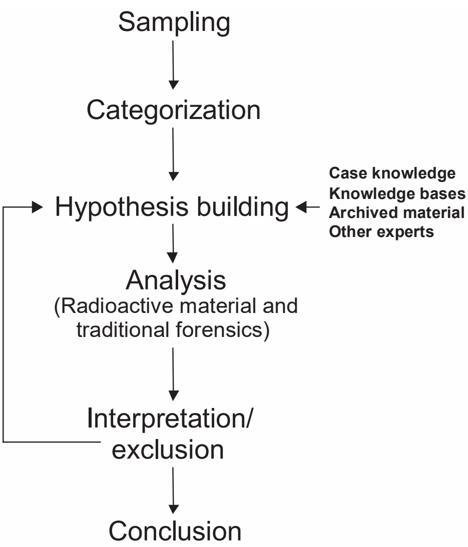

FIG. 2. The nuclear forensics process.

The ongoing results of the analysis provide guidance and leads, aiding the police investigation by focusing efforts. A more focused police investigation may then uncover further evidence that can be used to link the material to particular people or places, aiding the nuclear forensic process.

Some results, such as isotopic analysis, may provide only general clues that serve to place the material in a broad category, like direct use material, or perhaps narrow the field of potential countries of origin. Other results, such as the identification of characteristic dimensions or markings, may provide specific clues to identify a specific facility or date of manufacture. Sometimes, a result might only provide useful information about the interpretation when combined with other results. In the same way, independent results that provide the same general or specific clue increase the expert's confidence in the interpretation, while results that provide different or even conflicting results decrease this confidence. Nevertheless, a result that seems confusing or insignificant at first may become crucial as the case develops.

All interpretations are required to follow the rules of evidence appropriate to the jurisdiction of the case. In the USA, for example, the interpretations must meet the criteria of the Daubert standard, which allows for the introduction of theory or techniques that have been generally accepted in the particular scientific field during a trial [24].

7.5. TYPICAL EXAMPLES

To better illustrate the process and complexities of nuclear forensics and interpretation, several examples are reported from the open literature (see Refs [25, 26]). These examples describe cases involving the discovery of illicit nuclear material and the subsequent steps to determine the origin of the material and to develop evidence for prosecution. The reader may also wish to review the hypothetical example given in Ref. [27]. While the case is hypothetical, it incorporates data and circumstances from actual experience.

8. CONFIDENCE IN CONCLUSIONS

8.1. ANALYTICAL DATA QUALITY OBJECTIVES

Because the results of a nuclear forensic investigation could be used as evidence in a criminal prosecution, or can affect international estimates of proliferation and threats of terrorism, it is essential that the data and their interpretation be credible. Adherence to chain of custody procedures should ensure that the analytical results correspond to evidence collected at the incident site. Proper quality assurance (QA) and quality control (QC) procedures within the nuclear forensics laboratory will ensure confidence in the analytical data.

Nuclear forensics laboratories should consider the implementation of a quality system, such as ASCLD International, ISO 9000 [28] or ISO 17025 [29]. A quality system encourages the establishment of documented procedures for sample control and analysis, which improve repeatability and traceability of results and provides an enabling mechanism for continuous quality improvement. The establishment and registration of a quality system is important not only for its internal benefits but also for the confidence that it inspires externally.

As part of the QC system, laboratories should also place their analytical instruments under a relevant statistical process control (SPC) program wherever feasible. A valid SPC program engenders confidence in the analytical results by demonstrating that the instrument was under statistical control before and after the acquisition of data.

8.2. PRECISION AND ACCURACY

As required by good analysis protocol, all analytical results should state the precision of the measurement and any potential sources of error not reflected in the precision. In the absence of bias, the precision of the measurement can place bounds on which sources and processes could produce material with the given signature. Although increasing the precision of a given measurement could narrow the field of potential sources or processes that produced the material, as shown in Fig. 3, it is often more efficient to perform additional measurements using independent techniques (techniques that verify the presence or absence of different signatures than those verified by the initial technique).

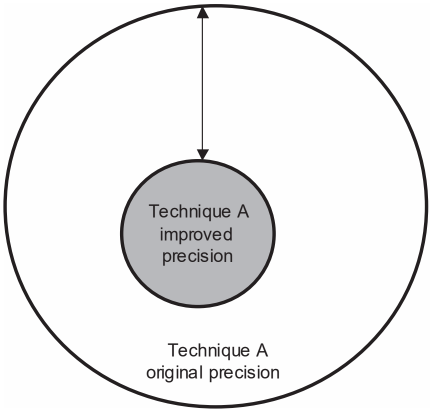

FIG. 3. Effect of improved precision on conclusions.

The confidence in, and specificity of, the interpretation often increase as more independent measurements are made, as shown in Fig. 4.

8.3. SENSITIVITY

The sensitivity of the analytical techniques will be particularly important when the amount of evidence is small. In some cases, perpetrators may initially

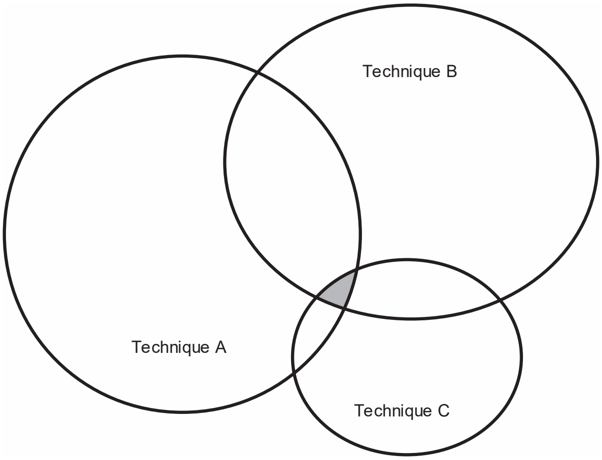

FIG. 4. Effect of multiple analyses on conclusions.

deliver only a tiny sample, which is purportedly representative of a much larger batch of material, to their potential customer. Even for interdictions of large amounts of material, the analytical techniques should be as sensitive as possible because trace species are often significant components of a signature. However, as the sensitivity of the analysis increases, so does the susceptibility to contamination and other material. For example, the analyst might have to decide whether the Fe and Cr detected in the analysis is the signature of a certain manufacturing process or merely contamination from a stainless steel spatula used to collect the evidence.

8.4. COMMUNICATION OF RESULTS

All results and assessments should be communicated in the form of a technical report. The confidentiality of the report should be in accordance with the SoW. For investigations in which the INFL provides assistance to the Member State, communication of the final report constitutes completion of the nuclear forensic assistance (see Step 6 in Appendix I). Any particular requirements that the Member State may have regarding the final report, such as accompanying meetings or verbal briefings, should be included in the SoW.

Reports may be issued periodically during and after the conclusion of an interdiction event to keep decision makers apprised of recent data and insights from the investigation. For example, the nuclear forensics laboratory could issue reports to coincide with the availability of results from the sequence of techniques and methods in Table 2 (24 hours, one week, two months). However, a final report is also to be issued after the conclusion of the event. The laboratory should identify all data and other information used in the assessment and include the rationale for the conclusion. The laboratory should also identify any information that conflicts with the assessment, and reasons why they are choosing to disregard or discount that information.

Ideally, there should be an unambiguous method of identifying the confidence level of all conclusions to decision makers. It is difficult to summarize a vast body of evidence, each with its own uncertainty, in a single statement of expert opinion. However, such a statement should be made to communicate the strength of the evidence to decision makers who might not have the requisite technical background to rigorously evaluate all stages of data acquisition and analysis.

9. REQUESTING ASSISTANCE IN NUCLEAR FORENSIC INVESTIGATIONS THROUGH THE IAEA

Appendix I lists the steps which might be taken to request assistance in nuclear forensic investigations through the IAEA, including early assistance. It includes a number of options, which have already been discussed, as they apply to specific points in the Plan of Action outlined in Section 2. Optional support can be provided at any stage of the response, starting from initial contact, to on-site and holding site activities, transportation of material or samples thereof, and actual nuclear forensic analysis or interpretation. The requestor can initiate any one of these options by contacting the Office of Nuclear Security of the IAEA. These requests for assistance from the IAEA for nuclear forensic support are different from those involving the Assistance Convention [17].

The SoW, mentioned in Step 5 of Appendix I, provides the basis for a bilateral arrangement that permits the assistance of a nuclear forensics laboratory. However, because nuclear forensics and nuclear forensic interpretation are dynamic and iterative processes, an FMT, which includes a representative from the requestor and from the participating INFL laboratory, will operate throughout the entire investigation to make decisions about the course of analysis.

As described in Section 7.2, allowing the broadest set of experts possible to participate in the process will increase the chance of a successful nuclear forensic analysis. Therefore, it is highly recommended that the requestor authorize the participation of multiple INFLs or, at least, the sharing of information between them, in the SoW. A good practice is to include other authorities that could have additional information relevant to the material under investigation. However, the requestor (or requesting Member State) always controls access to the evidence and the sharing of information through the SoW.

10. OTHER RECOMMENDED ACTIVITIES

10.1. STANDING INCIDENT RESPONSE PLANS AND PROCEDURES

Incident response plans need to foresee a programme of training to ensure that response personnel are familiar with the procedures and equipment foreseen in cases of unauthorized acts involving nuclear or other radioactive material. Along with the present publication, Refs [2, 30, 31] can be useful in establishing appropriate response plans, procedures and training modules.

10.2. BILATERAL ARRANGEMENTS

The process for nuclear forensic investigations described in Sections 2–9 and Appendix I points out the importance and benefits of international cooperation in nuclear forensics. In particular, a State, as part of its national response plan, could have a bilateral arrangement covering the legal and financial conditions under which an INFL could provide the requested assistance. As such arrangements involve multiple and complex issues, it is advisable that, within its national response plan, each State define the arrangements that may be needed in an actual incident.

The arrangements should clearly identify the purpose, scope and limits of cooperation. As far as possible they should also consider:

— Means and procedures for the export and transport of samples of nuclear or other radioactive material from the requesting State and into the territory of the assisting State;
— Arrangements for future use or disposal of sample residues and analytical wastes;
— Rights and limitations of members of FMTs to access potentially restricted facilities and information;
— Mutual obligations regarding notification of the results of the investigations to national and international authorities;
— Restrictions on confidentiality of information and non-disclosure agreements.

10.3. EXERCISES

Since the discovery and interdiction of nuclear and other radioactive material often involve overlapping jurisdictions (local and national law enforcement, nuclear and hazardous material regulatory bodies, etc.), it is important for a State to address any potential legal or political obstacles prior to the occurrence of an actual incident. For example, national regulations for transporting radioactive material may prevent the shipment of interdicted material outside the country to a nuclear forensics laboratory. Safety regulations may preclude the seizure of radioactive material without steps that destroy potential forensic evidence. Executing a ‘tabletop’ exercise allows all participants to work through a hypothetical incident on paper to discover potential problems without the serious consequences associated with an actual incident. Such an exercise also allows the formulation of policies and procedures with the benefit of more time and deliberation than an actual incident might allow.

In addition to the tabletop exercises, it is recommended that demonstration exercises be regularly conducted under realistic conditions. These exercises should involve actual material, relevant authorities and organizations. Such exercises could be conducted at a border location and involve international cooperation.

10.4. RESEARCH AND DEVELOPMENT

The field of nuclear forensic analysis is an emerging discipline. Most of the initial work has been performed independently, with some collaboration by national and international laboratories in the developed world. There is a general agreement on the iterative approach to nuclear forensics. This approach takes advantage of a knowledge base of processes to predict physical, chemical, elemental, or isotopic signatures that can be measured and the ‘tool box’ of analytical techniques that can verify the presence or absence of these signatures.

Although there is general agreement on the approach to nuclear forensic analysis and interpretation, continuing R&D is essential because the field is so new. International collaboration in nuclear forensics, leading to international R&D efforts, will provide maximum return for each country’s investments. The existing threat posed by diverted nuclear material in the hands of criminals or terrorists makes these investments highly rewarding.

One area that requires continuing effort is the development of knowledge databases for nuclear sites and processes. Because each country often uses its own material and processes, which are either classified or proprietary, this effort requires international collaboration. States are encouraged to maintain process records of nuclear material production for R&D and for industrial uses. Attention should be focused on developing the databases and search tools necessary to access comprehensive national and international databases and worldwide nuclear expertise. Such databases need to be designed to provide the maximum amount of information to participating countries without compromising restricted information.

Additional effort is also needed in identifying and exploiting new radioactive and traditional forensic signatures. For example, there has been promising research into using natural variations in stable isotopes or the presence of trace organic or biological material as unique forensic signatures. More extensive work is required to make such methods routinely useful for nuclear forensic interpretation.

Furthermore, improvements in analytical instrumentation and methods, particularly in the areas of increased precision, improved sensitivity and decreased spatial scale, will lead to concomitant improvements in the data used for nuclear forensics.

Appendix I

PROCEDURE FOR REQUESTING ASSISTANCE IN NUCLEAR FORENSIC INVESTIGATIONS THROUGH THE IAEA

I.1. PURPOSE

In preparation for a possible incident, States should determine the capability of national forensics laboratories and the potential need for IAEA assistance, and set up contracts with a forensics laboratory for assistance. The following checklist provides a series of steps to be taken by a Member State to evaluate the need for and to request nuclear forensic assistance through the IAEA. Depending on the nature of the incident, assistance can also be requested from the IAEA under the Assistance Convention [17]. The procedures for requesting IAEA assistance during an emergency (medical treatment, monitoring, source recovery, etc.) are described in Ref. [18].

I.2. INITIATE CONTACT WITH NUCLEAR FORENSICS EXPERTS

— Contact the IAEA Office of Nuclear Security for assistance in evaluating the need for nuclear forensics, and to obtain INFL contact information;
— Communicate to the IAEA the potential need for nuclear forensic assistance;
— Identify the relevant contact persons for the State, IAEA and INFL;
— Set up communication channels between State, INFL and IAEA contacts.

I.3. ON-SITE AND HOLDING SITE ADVISORY ASSISTANCE

Informal assistance can be quickly provided on-site (or later at a holding site) via telecommunications with a team of nuclear forensics experts:

— Request advice on categorization of radioactive material (i.e. nuclear material, reactor fuel material and/or commercial/radioactive sources):
  • Advice on radiation detectors for performing categorization analysis;
  • Assistance in interpreting spectra from on-site radiation detectors;
  • Availability of experts to perform categorization analysis.
— Request advice or assistance of experts on collection of evidence (nuclear and non-nuclear);

— Request advice or assistance of experts on preservation of evidence.

I.4. ASSISTANCE IN TRANSPORTING MATERIAL

This section covers requests for assistance in transporting material from a holding site to a nuclear forensics laboratory (or laboratories) capable of nuclear forensic analysis, i.e. an INFL. Transportation of the material from the incident scene to an appropriate holding facility within the country will presumably be needed so quickly that external assistance may not be feasible:

— Request guidance on packaging and transport to meet legal requirements (IAEA assistance);
— Obtain guidance on preventing cross-contamination in packaging and transport (IAEA and INFL);
— Request IAEA assistance for packaging and transport to an identified INFL (see next step).

I.5. IDENTIFICATION OF THE INFL TO PROVIDE ASSISTANCE

This step involves identifying the desired level of nuclear forensic analysis and the laboratory (or laboratories) that will provide it:

— Obtain from the INFL contact the current list of laboratories that can provide a nuclear forensic analysis of the sample;
— Determine the desired level of analysis:
  • Basic characterization determines the nature of the material, i.e. physical structure, and major element composition (by optical and scanning electron microscopy) and isotopic composition (by gamma spectroscopy and mass spectroscopy);
  • Technical interpretation of material origins:
    o Potential types of additional analyses are given in Sections 5.5 and 7.1, as well as in Appendix II of this publication;
    o Interpretation may include non-nuclear forensics on associated material;
    o Interpretation may include classical forensics on material contaminated with radioactivity.
— Identify potential INFLs for nuclear forensic assistance (with INFL and IAEA contacts);

— Contact potential INFLs to verify that the potential nuclear forensics laboratory/State will not decline to offer assistance;
— Start the process of establishing a bilateral agreement with the selected nuclear forensics laboratory;
— Ensure that the actual investigation will be carried out on a State to State basis.

I.6. DEVELOPMENT OF THE SoW

The SoW includes provisions for the following issues:

— Identify the samples to be analysed, the aim and scope of the analyses and their evaluations for the purpose of nuclear interpretation;
— Establish the nuclear forensic management team (FMT), which:
  • Is expected to operate throughout the investigation, from transportation to final report;
  • Should include one contact person for the State and each participating nuclear forensics laboratory;
— Detail the organization and functioning of the FMT;
— Consider including more than one nuclear forensics laboratory for best interpretation (either by multiple bilateral agreements or by allowing a primary nuclear forensics laboratory to work with other identified laboratories);
— Establish special requirements, e.g. rules of evidence, chain of custody, sharing of information, non-disclosure agreements and confidentiality of information;
— Establish expectations for communication, e.g. frequency of communication, types of decision points that require prior approval, initial reporting of results;
— Identify 'phases' for investigation, e.g. start with characterization, possibly followed with technical interpretation of origins;
— Specify the desired sensitivity, accuracy or resolution, and the expected timeline for the nuclear forensic analysis and reports;
— Specify types of information to be included in the final report;
— Agree on disposition of the material remaining after the investigation is completed;
— Obtain necessary government approval for each party to the agreement.

A number of these issues will have to be part of a State to State bilateral agreement. Appendix V gives an example of a relevant SoW.

I.7. COMPLETING THE WORK

Communication of the final report by the INFL to the requesting State constitutes the completion of nuclear forensic assistance. In addition,

- The final report may be accompanied by a verbal briefing;
- The requesting State is encouraged to provide feedback to the IAEA.

Accordingly, an evaluation survey needs to be provided by the Member State to the IAEA. In addition, at the discretion of the requesting State, the final report should be released to the IAEA.

Appendix II

TOOLS FOR NUCLEAR FORENSICS

This appendix describes some of the most commonly used tools in nuclear forensic analysis. However, this description is not exhaustive (see also Table 4).

TABLE 4. EXAMPLES OF ANALYTICAL TOOLS FOR NUCLEAR FORENSICS

Measurement goal	Technique	Type of information	Typical detection limit	Spatial resolution
Survey	HRGS	Isotopic	ng–μg	
Elemental and isotopic bulk analysis	Chemical assay	Elemental	Mg	
	Radiochemistry/RA Counting methods	Isotopic Elemental	fg–pg	
	TIMS	Isotopic Elemental	pg–ng	
	ICP-MS	Isotopic Elemental	pg–ng	
	GD-MS	Isotopic Elemental	0.1 ppb–10 ppm	
	XRF	Elemental	10 ppm	
	XRD	Molecular	~5 at%	
	GC-MS	Molecular	ppm	
	Infrared	Molecular	ppm	
Imaging	Visual inspection	Macroscopic	0.1 mm	
	Optical microscopy	Microscopic Structure		1 μm
	SEM			1.5 nm
	TEM			0.1 nm

TABLE 4. EXAMPLES OF ANALYTICAL TOOLS FOR NUCLEAR FORENSICS (cont.)

Measurement goal	Technique	Type of information	Typical detection limit	Spatial resolution
Microanalysis	ICP-MS	Elemental Isotopic	pg–ng	
	TIMS	Isotopic	pg–ng	
	SIMS	Elemental Isotopic	0.1 ppb–10 ppm	0.2–1µm
	SEM/EDS or WDS	Elemental	0.1–2 at%	1 µm
	XRD	Molecular	~5 at%	

mg: milligram = 10^{-3} g; µg: microgram = 10^{-6} g; ng: nanogram = 10^{-9} g; pg: picogram = 10^{-12} g; fg: femtogram = 10^{-15} g; at%: atom per cent; ppm: parts per million by weight; ppb: parts per billion by weight; µm: micrometre = 10^{-6} m;

HRGS: high resolution gamma spectrometry; TIMS: thermal ionization mass spectrometry; ICP-MS: inductively coupled plasma mass spectrometry; GD-MS: glow discharge mass spectrometry; XRF: X ray fluorescence analysis; XRD: X ray diffraction analysis; GC-MS: gas chromatography-mass spectrometry; SEM: scanning electron microscopy; TEM: transmission electron microscopy; SIMS; secondary ion mass spectrometry; SEM/EDS: scanning electron microanalysis with energy dispersive sensor; SEM/WDS: scanning electron microanalysis with wavelength dispersive sensor.

II.1. ELEMENTAL AND ISOTOPIC BULK ANALYSIS TOOLS

Chemical assay

Chemical titration and controlled potential coulometry are standard methods for determination of the element concentrations of uranium, plutonium, neptunium or other major components of nuclear fuel material for accountability measurements or accountability verifications. In chemical titration, the sample is made to react with an exactly measured amount of a selective reagent of known composition, leading to the completion or characteristic end point of a well known stoichiometric reaction. Titration methods are designated, inter alia, according to the mode of detection of the end point, e.g. potentiometric and spectrophotometric titrations. In controlled potential coulometry, the element to be analysed is selectively oxidized or reduced at a metallic electrode maintained at a suitably selected potential. The number of electrons used in the oxidation or reduction is a measure of the amount of element present in the sample.

The precision and accuracy of these methods is better than 0.1%. They are well established and used routinely in nuclear accountancy and safeguards laboratories. They can therefore be very effective for the characterization of interdicted material, provided that samples of at least a few tenths of a gram can be made available.

Radiochemistry

Many samples are too complex for all the radioactive isotopes present to be measured directly. By utilizing the differences in chemical properties of the elements, it is possible to devise schemes of chemical reactions to separate and purify elements, or groups of elements, to allow measurement of the isotopes present by radioactive counting methods, or mass spectrometry. The isotopes measured are related back to the original sample by referencing to an internal isotopic standard called a ‘spike’. The chemical separation and purification steps increase both the sensitivity and selectivity of the technique. Radiochemistry is especially important to allow measurement of isotopes that are present at low activity and are best measured by their alpha or beta emissions or by mass spectrometry. Radiochemistry in combination with radioactive counting techniques and mass spectrometry has the potential to measure down to 10^6 atoms or lower of certain isotopes.

Radioactive counting techniques

Each radioactive isotope emits radiation of known types and energies at a known rate. By measuring the radiation emitted by a sample, it is possible to quantify the amount of each measured isotope present. There are three types of radiation that are usually considered for measurement: alpha, beta and gamma radiation. Each type of radiation has its own properties and methods of detection. Silicon surface barrier detectors commonly detect alpha radiation, beta radiation by scintillation techniques or gas ionization detectors, and gamma radiation by germanium crystals.

Mass spectrometry

Mass spectrometry can be used to determine the isotopic composition of elements in the material. It can also provide quantification (often called an ‘assay’ when applied to major constituents of the sample) of these elements by adding a known quantity of a specific isotope; this is known as isotope dilution mass spectrometry. Mass spectrometric methods are able to determine both radioactive and stable isotopes. In mass spectrometry, atoms or molecules are converted into positively or negatively charged ions. The resulting ions are then separated according to their mass to charge ratio, and the intensities of the resulting mass separated ion beams are measured. Elemental mass spectrometric techniques generally have high selectivity due to the mass analysis step, except in specific cases of isobaric interferences. Mass spectrometry offers extremely high precision and accuracy of analysis as well as high abundance sensitivity.

Thermal ionization mass spectrometry

In thermal ionization mass spectrometry (TIMS), a sample is deposited on a metal filament, which is heated in a high vacuum by passing a current through it. If the ionization potential of a given element is low enough, compared with the work function of the filament, then a fraction of the atoms of that element are ionized via interaction with the filament surface at high temperature. The specificity of the TIMS analysis can be provided both by chemical separation steps and by the ionization temperature. TIMS is capable of measuring isotopic ratios on picogram (10^{-12} g) to nanogram (10^{-9} g) samples, or down to tens of femtograms (10^{-15} g) using special pre-concentration techniques. TIMS routinely measures differences in isotope mass ratios of the order of 1 in 10^6.

Inductively coupled plasma mass spectrometry

In inductively coupled plasma mass spectrometry (ICP-MS), the sample is aspirated as a solution into an inductively coupled plasma, where the high temperature of the plasma breaks the sample down into its constituent atoms and ionizes these species. In addition to measuring isotope ratios, ICP-MS is useful both as a sensitive elemental survey tool and as a method for precisely quantifying trace elemental constituents of a sample. The detection limits range from 0.1 parts per billion (ppb) to a few tens of ppb in solution. ICP-MS has difficulty measuring some elements due to background, interferences or poor ionization efficiency, e.g. C, O, P, K, S and Si.

Glow discharge mass spectrometry

In glow discharge mass spectrometry (GD-MS), the sample serves as the cathode of a glow discharge (argon is usually the support gas). The sample is sputtered by argon ions, and the sputtered neutrals from the sample diffuse into the plasma. In the plasma the neutrals are ionized either by electron impact or, more typically, by collision with metastable argon atoms (penning ionization).

GD-MS can be an effective technique for directly measuring bulk samples, such as dirt. GD-MS is highly quantitative, suffering from very few matrix effects. It can be used as a sensitive survey tool with detection limits ranging from less than 1 ppb to a few parts per million (ppm), depending on the element. However, it lacks the precision associated with radiochemistry, TIMS or ICP-MS. It also can provide misleading results for some heterogeneous samples, since the sampled volume is small, and there is no sample homogenization provided by dissolution or a similar process.

Gas chromatography-mass spectrometry

Gas chromatography mass spectrometry (GC-MS) is a technique useful for detecting and measuring trace organic constituents in a bulk sample. In GC-MS, the components of a mixture are separated in the gas chromatograph and identified in the mass spectrometer. The primary component of a gas chromatograph is a narrow bore tube (called a ‘column’), which is maintained inside an oven. In the simplest arrangement, the mixture is flash vaporized in the heated introduction port. The various components of the mixture are swept onto, and through, the column by the carrier gas (usually He). The components of the mixture are separated on the column, based upon their volatility and relative affinity for being on the column material versus the carrier gas. Columns are usually coated with a special material to enhance separation of the components of interest. In the ideal case, all components are separated and introduced into the mass spectrometer one at a time. At low flow rates, the column effluent can be introduced directly into the mass spectrometer. At higher flow rates, the GC requires an interface to match the flow requirements of the mass spectrometer, usually by selectively removing the carrier gas.

The mass spectrometer ionizes and fragments each component as it elutes from the column. Many different ionization methods can be used, but the most common for GC-MS is electron impact (EI). In EI, an energetic (70 eV) beam of electrons bombards the sample molecules. Some of these electrons will hit a sample molecule and knock out an electron, leaving the molecule positively charged. This ionizing collision tends to impart some energy to the molecule. This energy is sometimes great enough to cause the ion to fragment (usually into an ion and a neutral fragment) in ways characteristic of the molecule’s structure. The relative abundance of ions of various masses (strictly mass to charge ratio, although the typical ion charge in EI is usually 1) is characteristic of the intact molecule. The mass spectrometer measures the intensity of ions of various masses, either by simultaneous or sequential detection, depending on the type of mass spectrometer. The resulting plot of relative intensity versus mass to charge ratio is a ‘mass spectrum’. There are now extensive libraries of

EI mass spectra that help identify unknown compounds that are separated and detected by GC-MS.

X ray fluorescence analysis

X ray fluorescence (XRF) analysis can also be useful for the broad and non-destructive elemental quantification of a sample. An incident X ray beam excites characteristic secondary X ray wavelengths and energies in a solid sample that are counted on a solid state or proportional counter. The detection limits for XRF are in the range of 10 ppm. Analysis of the light elements is possible but more problematic due to low characteristic X ray energies. However, XRF is strictly an elemental analysis tool, while ICP-MS or GD-MS, which are more sensitive, are able to measure isotopic composition. XRF can be performed directly on solid samples, although dissolutions are often analysed to provide homogenization of the sample.

X ray diffraction analysis

X ray diffraction (XRD) analysis is the standard method for identifying the chemical structure of inorganic and organic crystalline material. X ray beams that impinge on regularly ordered lattices undergo constructive and destructive interference that depends on the spacing of the lattice, the wavelength of the X rays and the angle of incidence of the X ray beam. By rotating the sample relative to a fixed X ray source, variations in interference occur, leading to characteristic diffraction patterns. These diffraction patterns can be compared to reference spectra to identify the specific crystalline phase. Note that XRD cannot generate diffraction patterns from amorphous (non-crystalline) material.

II.2. IMAGING TOOLS

Visual inspection and photography

Visual inspection of a sample can give an expert information as to its possible identity, especially in conjunction with data from NDA techniques, e.g. gamma spectrometry and survey data. Size and shape can be sufficient to identify some items, especially if serial numbers or other identifying marks can be seen. For chemicals, the colour and form of the material can be important clues.

Optical microscopy

Optical microscopy is often the first method to examine the sample at high magnification. An optical microscope uses magnifying light optics and reflected or transmitted methods of sample illumination to present magnified images of the sample to the user's eyes. Viewing samples under polarized light can also reveal information. Light microscopes can readily magnify an image up to 1000 times.

Scanning electron microscopy

Scanning electron microscopy (SEM) can provide image magnifications of up to 10 000 times with a conventional thermal filament source, or 500 000 times with a field emission source. In SEM, a finely focused electron beam is rastered or scanned over the sample. The interaction of the energetic incident electron beam and the sample produces backscattered electrons, secondary electrons and X rays. By measuring the flux of one of these types of particles as a function of raster or scan position, an image or map of the sample can be reconstructed and displayed. Each type of particle conveys different information about the sample and, therefore, offers a different contrast mechanism. For instance, secondary electrons carry information about sample topology. Backscattered electrons carry information about average atomic number of the area being imaged and can be used to quickly detect spatially resolved phases of contrasting chemical composition.

Transmission electron microscopy

In transmission electron microscopy (TEM), the energetic electron beam is transmitted through an ultra-thin sample (~100 nm thickness). TEM is capable of higher magnifications (several million times) than SEM and is able to image extremely fine structure, but at the expense of tight restrictions on sample thickness. In most cases, thin sections of the sample need to be made. Transmitted electrons can undergo diffraction effects, which can be used like XRD to determine crystal phases in the material.

II.3. MICROANALYSIS TOOLS

X ray microanalysis

The X rays generated during SEM or electron microprobe analysis carry elemental information and are a convenient way of measuring the elemental composition of micro-samples or particles. The X rays can be analysed by either of two methods. First, an energy dispersive spectrometer (EDS) uses a solid state detector (typically an Si(Li) detector) to measure simultaneously the energy and rate of incident X rays. Second, a wavelength dispersive spectrometer (WDS) uses a synthetic analysing crystal to sequentially diffract selected X rays into a gas proportional counter. Due to the interaction mechanics of the electron beam with the sample, X rays are generated over an approximately ~1 μm tear-drop shaped region. Thus, X ray analysis is limited to spatial resolution of around 1 μm. The detection limits of X ray analysis are approximately 0.01–0.1%, depending on the element. X ray microanalysis is an assay technique to measure the elements at greater than 0.01% rather than a trace element analysis technique.

Secondary ion mass spectrometry

Secondary ion mass spectrometry (SIMS) can be used for both elemental surveys and isotopic analysis of small samples, even particles. SIMS uses a finely focused primary ion beam, e.g. O_2^+, Cs^+ or Ga^+, to sputter the sample surface. The sputtering process produces secondary ions (ions characteristic of the sample) that can be analysed by a mass spectrometer. SIMS is capable of acquiring microscopic images of isotopic distributions (which can correspond to elemental images for known elements of known isotopic abundance). In the ‘microscope’ mode, a relatively large primary ion beam bombards the sample, and the spatial position of the resulting secondary ions is maintained and magnified throughout the mass spectrometer. An imaging detector then displays and records the resulting isotopic image. In the ‘micro beam’ mode, a finely focused primary ion beam is rastered or scanned across the sample in a manner similar to an electron microscope. The resulting secondary ion signal is then measured and correlated with the position of the primary ion beam to generate the isotope image. Sample ablation of the focused ion beam on the sample yields a depth profile through the sample surface that is extremely valuable in documenting compositional gradients or surface alterations.

Infrared spectroscopy

Infrared (IR) spectroscopy is useful for the identification of organic compounds. Through the use of a specialized microscope, IR spectroscopy can be performed on samples as small as 15 µm and is an important microanalytical technique. Molecular bonds vibrate at characteristic frequencies. If a particular molecular vibration results in a change in the bond's dipole moment, then the molecule can absorb infrared radiation of that characteristic frequency, exciting that vibration.

In IR spectroscopy the sample is irradiated with a broad band of infrared frequencies, and the intensity of the reflected or transmitted infrared radiation is measured as a function of frequency. From the knowledge of incident intensity and reflected/transmitted intensity as a function of infrared frequency, an infrared absorbance spectrum can be reconstructed. Absorption at specific frequencies is characteristic of certain bonds. Thus, the IR spectrum identifies the various bonds and functional groups within the molecule. In addition, there are vast libraries of IR spectra that help identify unknown compounds or, at least, place them into certain classes of molecules.

Today, Fourier transform IR (FTIR) instruments are used to perform most IR spectroscopies. These instruments measure the intensity of IR radiation as a function of frequency by use of an automated interferometer. The interferometer produces a signal whose intensity varies with time. The Fourier transform of that signal yields a spectrum of intensity versus wavelength. FTIR is more sensitive than other methods of IR spectroscopy, in that it produces a better quality spectrum in a shorter amount of time.

Appendix III

EXAMPLES OF TRADITIONAL FORENSIC EVIDENCE

The following discription is not exhaustive.

III.1. DOCUMENTARY EVIDENCE

Documents or recordings (from an answering machine, for example) can provide information not only through the message itself, but also through other evidence that ties the document or recording to a person or place. A thorough examination of a document would include detailed analysis of the handwriting on written documents, the type characteristics and anomalies on typed documents, photocopier characteristics and anomalies on photocopied documents, and mechanical impressions for typeset documents. Examination of a recording would include an analysis of the language, dialect and stray background sounds.

Analysis of the paper used for a document can itself provide valuable clues. Paper analysis should include careful examination of the origin of and inclusions in the paper stock, any altered or obliterated writing, the use of carbon paper or correcting ink, evidence of the writing instrument used, and the true age of the document. Even the analysis of burned or charred paper can provide valuable information.

If a computer or a data storage medium, for example a computer disk, is recovered from the incident scene, then the forensic analyst has to try to recover all of the information stored on the computer. Programs and files may document the perpetrators' plans and methods or implicate other people. Mobile phones could also provide useful information.

III.2. IMPRESSIONS

Latent fingerprints, palm prints, or prints from other body areas, for example ear prints from listening at windows, tie a person to a location or an object seized in the incident. Shoe prints discovered at the incident site can also link a specific person to the incident site, through the unique tread pattern of their shoes. Tire treads serve to link a car to the incident site in a similar manner.

III.3. CHEMICAL ANALYSIS

Unique or special chemical substances seized at the incident site can provide valuable evidence. Controlled substances or poisons may provide useful information about the perpetrators or their motives. Accelerants used for arson or explosive residues provide evidence about methods and purpose. Characteristic dyes and petroleum products can tie the seized evidence to particular locations, perhaps serving as a marker for route interpretation.

III.4. TISSUE AND HAIR EVIDENCE

Human tissue recovered at the incident scene can also tie a specific individual to the scene or seized evidence. Blood can be typed through serology. Blood and other tissue can be subjected to either nuclear or mitochondrial DNA analysis, again helping to implicate an individual. Hair samples provide information about race and body characteristics. The morphology of the hair sample may indicate how the hair was lost. Even animal hair or tissue might provide useful evidence, linking a particular type of animal with the perpetrators.

III.5. WEAPONS EVIDENCE

In the event that a bomb is detonated or seized, the bomb remains and explosive residues can provide a pattern for determining the type of bomb and its method of manufacture. Unique material in the remains may pinpoint the exact perpetrator or, at least, restrict the number of potential perpetrators through purchase records for such material.

In the event that firearms are seized, examination of the projectile lead, cartridge cases, gunshot residues and any altered function may tie the perpetrator to a given location, a fact useful in route interpretation, or it may provide evidence of method or purpose.

III.6. TOOL MARKS

Alterations in objects that appear to have been made by the perpetrators themselves are highly significant. The forensic analyst should look for fractures (particularly those that match up with other fractures in the evidence), odd marks in wood, the use of stamps and dies, and the modification of locks and keys. The forensic analyst should attempt to restore any obliterated markings.

III.7. EXAMINATION OF FIBRES

Fibres can serve to tie objects and perpetrators to specific locations. The forensic analyst needs to pay particular attention to fibre evidence, such as fabrics, cords and ropes, and determine its type: animal (wool), mineral (glass), synthetic or organic (cotton).

III.8. BOTANICAL EVIDENCE

The forensic analyst should examine evidence for feathers, plant material, pollen or spores that are indicative of a location other than the incident site. These pieces of evidence can be important for route interpretation.

III.9. OTHER MATERIAL EVIDENCE

Other associated evidence should be carefully examined for possible clues for methods and route interpretations. Such materials as glass, soil, dust, cosmetics, paints, inks and dyes, plastics, polymers, metal objects and tapes often vary in chemical composition from place to place. Unique characteristics in this material might tie the perpetrators to a specific location, again a fact that can be important for route interpretation. In the same way, unique minerals found on the evidence might be diagnostic of specific geology and location (i.e. geolocation).

Appendix IV

ITWG NUCLEAR FORENSICS LABORATORIES: INFL CHARTER (AUGUST 2004)*

Purpose

The ITWG Nuclear Forensics Laboratories (INFL) is an international association of active practitioners of nuclear forensics. The objective of the INFL is to advance the science of nuclear forensics for attributing nuclear and radiological material and to serve the needs of States and law enforcement agencies that need this type of capability.

Activities of the INFL include:

— Establishing guidelines for best practices in nuclear forensics;
— Conducting international exercises;
— Promoting research and development activities;
— Communicating with external organizations and publishing INFL reports;
— Providing a point of contact for nuclear forensic assistance;
— Assisting one another in nuclear forensic investigations.

Relationship to ITWG

The INFL is a subset of the Nuclear Smuggling International Technical Working Group (ITWG), and accordingly the ITWG Terms of Reference also apply to the INFL. This INFL charter further spells out its activities and organization. The general intent is that the INFL will focus on the technical development and application of nuclear forensics. The ITWG and its plenary meetings will provide the forum for end users, stakeholders and policy makers to engage with scientists to address the contextual issues involving the application of nuclear forensics.

Organization

An Executive Committee will provide direction and oversight for the INFL. The Executive Committee may implement an internal structure to facilitate its work, e.g. chair, co-chair, secretary, etc. The Executive Committee

* Reproduced verbatim.

functions include (but are not limited to): inviting new members to join, planning meetings, forming Task Groups to perform specific INFL functions, communicating to external entities, oversight for web site content and publication of documents, and point of contact for receiving requests for nuclear forensic investigations. The Executive Committee will track progress of INFL tasks between meetings and maintain regular communications with one another.

Initial members of the INFL will be laboratories that have participated in a previous ITWG Round Robin. The Executive Committee may invite additional members.

The INFL will hold at least one meeting per year, typically just prior to plenary ITWG meetings. The Executive Committee can call additional INFL meetings. The INFL may also arrange for special sessions or participation in other workshops and scientific conferences.

As for the ITWG, participants are responsible for obtaining funding to support their participation in the INFL. In addition, the Executive Committee may seek additional funding for INFL functions from sponsoring countries and organizations.

Guidelines for Nuclear Forensic Investigations

A primary goal of the INFL is to give credence to nuclear forensic results and conclusions by developing guidelines for nuclear forensic investigations. Consensus will be developed for guidelines in terms of “best practices”. Consensus means that the INFL members can support the guidelines; it does not mean that all members believe that it is the best guideline.

The guidelines will be linked to a capability profile template. These capability profiles will be used to summarize the demonstrated capability of specific laboratories. The guidelines may include specifying different levels of capability.

The INFL will also develop approaches for demonstrating laboratory capability to execute according to these guidelines. The general approach to demonstrating capability of a given laboratory will be to use a combination of results for actual case exercises, along with existing quality assurance processes at participating laboratories. A specific process for validating member capability profiles will be developed by the INFL.

Exercises can serve a variety of purposes, e.g. training, protocol development, validation. Past exercises have been used as a means of cooperative learning. Such exercises should continue, but in the future some exercises will be designed as the preferred means of demonstrating laboratory capability. An

Exercise Task Group will be responsible for design and implementation of exercises.

Communications and Reports

Communications include a wide variety of activities that fall outside the actual ITWG and INFL meetings. The INFL will develop and maintain a website as a primary means of communication. An open access website will provide general information, while a controlled access website will be used for communication among INFL/ITWG participants and their respective governments. The website will be augmented by email communications.

Communications include providing guidelines and best practices to States and international regulatory bodies. The INFL will provide the current list of nuclear forensics laboratories that can provide assistance upon request, along with supporting information. Communications also includes training to implement the ITWG Nuclear Forensics Model Action Plan.

A special part of communications is to leave a record of the work of the INFL and ITWG. The INFL will establish and execute a process for reviewing and publishing official reports by the INFL. These reports will be posted on the INFL web site.

Research and Development

An ongoing activity of the INFL will be to encourage and guide the continued development of nuclear forensics through research and development (R&D). Specifically, the INFL will assess current state of knowledge for nuclear forensics, establish recommendations for future R&D, and coordinate, where possible, R&D done by different laboratories.

Assisting Nuclear Forensics Investigation

A goal of the INFL is to provide nuclear forensic assistance to requesting governments. The co-chairs of the Executive Committee will be the contacts for requesting assistance. Each of the laboratories listed as being able to provide such assistance should have an identified point of contact (PoC), and each laboratory PoC should have a specific channel established by which the request for assistance is routed.

Listed laboratories are required to be capable of providing the type of assistance requested, and also to have approval of their government to provide this type of assistance. Participating nuclear forensics laboratories will be responsible for obtaining funding for their work. Laboratories may refuse to offer assistance based on specifics of request and their available funding resources.

Actual casework will be undertaken via a State to State arrangement between the requesting State and the State(s) of the selected laboratory(ies). Each nuclear forensics laboratory will, a priori, establish a protocol and approval for its participation in assisting other countries in order to expedite response to requests; the laboratory capability profile will provide details on the laboratory's request and approval process. The actual investigation will be planned and executed according to a statement of work (SoW). A template of the SoW will be provided by the INFL to serve as a basis for developing the case-specific SoW.

The SoW should include a recommendation to requestors that measurement and interpretative products might benefit from the involvement of more than one nuclear forensics laboratory in the analysis and production of the final report. The INFL will seek to create memorandums of understanding and confidentiality agreements between INFL laboratories/States to facilitate information sharing and collaboration to advance a case. The SoW template will strongly recommend that an expert from the requesting State should participate in the planning and execution of the analysis and in the drafting of the final report. Finally, the SoW template will include a request for permission that, upon completion of the case, the experience and information gathered in the case could be shared with other INFL members for the purpose of advancing the state of the art.

ITWG Nuclear Forensics Laboratories

Assistance for nuclear forensic support can be requested by contacting either one of the INFL co-chairs (currently the co-chairs are Sidney Niemeyer, niemeyer1@llnl.gov, and Klaus Mayer, mayer@itu.fzk.de). The INFL will maintain a set of Laboratory Capability Profiles that summarizes the assistance that can be provided by the various Nuclear Forensics Laboratories. These profiles will also specify different levels of assistance that can be provided, e.g. categorization, basic characterization, and full nuclear forensics. The co-chairs can provide requesters with the current set of Laboratory Capability Profiles, give additional information regarding the types of analyses and interpretation that can be provided, and answer other questions.

Appendix V

EXAMPLE OF A STATEMENT OF WORK

STATEMENT OF WORK

……………………………

……………………………

hereinafter referred to as 'the requestor', represented for the purpose of signing this agreement by …………………..

AND

……………………………

……………………………

hereinafter referred to as 'the nuclear forensics laboratory', represented for the purpose of signing this agreement by ……………………

Have agreed as follows:

In order to gain information on the nature of nuclear/radioactive material seized by the competent authorities in the requestor's State, nuclear forensic assistance will be provided by the nuclear forensics laboratory.

To achieve this goal, the requestor will do the following:

1. Take the necessary measures to preserve the classical and nuclear forensic evidence on the seized items throughout the process of securing, storing, packing and shipping the material.
2. Make the seized material (or representative subsamples thereof) available to the nuclear forensics laboratory.
3. Organize the transport of the material, if necessary calling upon IAEA experience and expertise or seeking IAEA assistance in transport organization.

4. Share with the nuclear forensics laboratory any additional information related to the circumstances of seizure and to the material itself that may help in the investigations.

The nuclear forensics laboratory will assume the following responsibilities:

1. Advise and participate in any of actions 1 to 3 above, if requested and it is practical so to do. This may include assistance with in field categorization and analysis.
2. Upon request, the nuclear forensics laboratory will provide consultancy or assistance in sub-sampling the material and in appropriate primary packing in order to preserve classical and nuclear forensic evidence.
3. Accept the seized nuclear or radioactive material, ensuring that the material can be handled within the existing licence, in full compliance with the legal requirements and using appropriate facilities.
4. Enable a national expert nominated by the requestor to participate in the nuclear forensic investigations, granting access to the laboratories and sharing all observations, findings and data.
5. Carry out the nuclear forensic analysis using the techniques listed in Appendix 1. Note: the list is indicative of the types of analysis that may be carried out. The techniques to be used depend on the sample and the progress and findings of the analysis.
6. Ensure funding for the carrying out of these investigations.
7. Ensure that excess sample material will be stored, disposed of or returned to the requestor.
8. Consider all data and findings related to the investigations of the seizure confidential and ensure that will not be shared with third parties without the approval of the requestor (See points 1 and 2 below).

There are occasions when sharing data and findings may be of benefit to the successful completion of the analysis, and to the science of nuclear forensics.

1. As the analysis progresses, the nuclear forensics laboratory may find that it needs to talk to external experts to fully interpret the data collected, or to ask an external laboratory to perform measurements. Any data and findings used would be subject to the conclusion of confidentiality agreements by the recipients of the information.
2. The experience gained from the analysis may be relevant to other cases in future for other countries. It would be of benefit if this experience could be conveyed to other laboratories on completion of the legal proceedings.

For the requestor	For the nuclear forensics laboratory
....	....
Date	Date
....	....
Name	Name
....	....
Position	Position

REFERENCES

[1] NUCLEAR SMUGGLING INTERNATIONAL TECHNICAL WORKING GROUP (ITWG), Terms of Reference, (1997).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Response to Events Involving the Inadvertent Movement or Illicit Trafficking of Radioactive Material, IAEA-TECDOC-1313, IAEA, Vienna (2002).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Safeguards Glossary, 2001 Edition, International Nuclear Verification Series No. 3, IAEA, Vienna (2002) Sections 4, 5, 12.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Categorization of Radioactive Sources, IAEA Safety Standards Series No. RS-G-1.9, IAEA, Vienna (2005).

[5] BRAGIN, V., CARLSON, J., LESLIE, R., "Categorization of nuclear material in the context of international safeguards", Proc. Int. Symp. Bruges, 2001, ESARDA, Ispra (2001).

[6] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

[7] ARGONNE NATIONAL LABORATORY, Reduced Enrichment for Research and Test Reactors, http://www.era.anl.gov/natsec/rertr.html

[8] Funding for the U.S.–Russia RERTR program, Analytical Center for Non-proliferation Problems, Review Issue 9, http://npc.sarov.ru/english/digest/92003/appendix8p2.html

[9] FERGUSON, C.D., KAZI, T., PERERA, J., Commercial Radioactive Sources: Surveying the Security Risks, Occasional Paper No. 11, Center for Nonproliferation Studies, Monterey, CA (2003).

[10] VAN TUYLE, G.J., STRUB, T.L., O'BRIEN, H.A., MASON, C.F.V., GITOMER, S.J., Reducing RDD Concerns Related to Large Radiological Source Applications, Rep. LA-UR-03-6664, Los Alamos National Laboratory, Los Alamos, NM (2003).

[11] ANZELON, G., HAMMOND, W., NICHOLAS, M., "The IAEA's Illicit Trafficking Database programme", Measures to Prevent, Intercept and Respond to Illicit Uses of Nuclear Material and Radioactive Sources (Proc. Int. Conf. Stockholm, 2001), C&S Papers Series No. 12, IAEA, Vienna (2002).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Illicit Trafficking Database (ITDB), IAEA, Vienna (2003) http://www.iaea.org

[13] STEEL MANUFACTURERS ASSOCIATION, Radioactive Scrap, http://www.steelnet.org/public_policy/public_policy_environment.html

[14] Report of the Joint Committee on European Affairs, Sub-committee on European Scrutiny, 27 March 2003, http://www.irlgov.ie/oireachtas/Committees-29th-D%C3%A1il/jeasce-debates/JEASCES270303.rtf

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, The Radiological Accident in Goiânia, IAEA, Vienna (1988).

[16] JANSSENS, W., et al., "Assisting Eastern European Countries in the setting up of a national response to nuclear smuggling", Measures to Prevent, Intercept and Respond to Illicit Uses of Nuclear Material and Radioactive Sources (Proc. Int. Conf. Stockholm, 2001), C&S Papers Series No. 12, IAEA, Vienna (2002).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Convention on Early Notification of a Nuclear Accident and Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, Legal Series No. 14, IAEA, Vienna (1987).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Emergency Notification and Assistance: Technical Operations Manual, EPR-ENATOM 2004, IAEA, Vienna (2004).

[19] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE CO-ORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Destructive Analysis and Evaluation Services for Nuclear Material Accountability Verifications, STR-69/Rev. 4, IAEA, Vienna (2003).

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Sample Collecting Procedure for Swipe Samples, Safeguards Manual, Form WP EM1 Rev. 3, IAEA, Vienna (2002).

[22] The Physical Protection of Nuclear Material and Nuclear Facilities, INFCIRC/225/Rev.4, IAEA, Vienna (1999).

[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, IAEA Safety Standards Series No. TS-R-1, IAEA, Vienna (2005).

[24] SUPREME COURT OF THE UNITED STATES, Daubert, W., et al. versus Merrell Dow Pharmaceuticals, Inc., No. 92-102, LEXSEE 509 US 579 (1993).

[25] Measures to Prevent, Intercept and Respond to Illicit Uses of Nuclear Material and Radioactive Sources (Proc. Int. Conf. Stockholm, 2001), C&S Papers Series No. 12, IAEA, Vienna (2003)

[26] Advances in Destructive and Non-destructive Analysis for Environmental Monitoring and Nuclear Forensics (Proc. Int. Conf. Karlsruhe, 2002), IAEA, Vienna (2003).

[27] KRISTO, M.J., SMITH, D.K., NIEMEYER, S., DUDDER, G.D., Model Action Plan for Nuclear Forensics and Nuclear Attribution, Rep. UCLR-TR-202675, Lawrence Livermore National Laboratory, Livermore, CA (2004).
[28] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management Systems — Fundamentals and Vocabulary, ISO 9000:2000, ISO, Geneva (2000).
[29] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:1999, ISO, Geneva (1999).
[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Method for the Development of Emergency Response Preparedness for Nuclear or Radiological Accidents, IAEA-TECDOC-953, IAEA, Vienna (1997).
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Procedures for Assessment and Response During a Radiological Emergency, IAEA-TECDOC-1162, IAEA, Vienna (2000).

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 92–0–100306–4
ISSN 1816–9317