

Nuclear Forensics

Role, State of the Art, and Program Needs

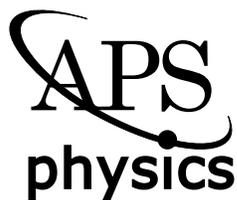
Joint Working Group of the American Physical Society
and the American Association for the Advancement of Science



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The American Physical Society was founded in 1899, with a mission of advancing and diffusing the knowledge of physics. APS is now the nation's leading organization of research physicists with more than 46,000 members in academia, national laboratories, and industry.

This paper was overseen by the APS Panel on Public Affairs (POPA). POPA occasionally produces reports on topics currently debated in government in order to inform the debate with the perspectives of physicists working in the relevant issue areas. Indeed, APS has long played an active role in federal government with its members serving in Congress and having held positions such as Science Advisor to the President of the United States, Director of the CIA, and Director of the NSF.

Nuclear Forensics Working Group of the American Physical Society's Panel on Public Affairs and the American Association for the Advancement of Science

Michael May, Chair, Stanford University

Reza Abedin-Zadeh, International Atomic Energy Agency (retired)

Donald Barr, Los Alamos National Laboratory (retired)

Albert Carnesale, University of California, Los Angeles

Philip E. Coyle, Center for Defense Information

Jay Davis, Hertz Foundation

William Dorland, University of Maryland

William Dunlop, Lawrence Livermore National Laboratory (retired)

Steve Fetter, University of Maryland

Alexander Glaser, Princeton University

Ian D. Hutcheon, Lawrence Livermore National Laboratory

Francis Slakey, American Physical Society

Benn Tannenbaum, American Association for the Advancement of Science

Charter and Background

This report was produced by a joint working group of the American Physical Society (APS) Panel on Public Affairs and the American Association for the Advancement of Science (AAAS) Center for Science, Technology, and Security Policy. The primary purpose of this report is to provide the Congress, U.S. government agencies, and other institutions involved in nuclear forensics with a clear unclassified statement of the state of the art of nuclear forensics; an assessment of its potential for preventing and identifying unattributed nuclear attacks; and identification of the policies, resources, and human talent to fulfill that potential. The working group formally met twice, once in Washington, D.C., and once in Palo Alto, California, to hear presentations from staff of the Department of Energy/National Nuclear Security Administration (DOE/NNSA), the Department of Homeland Security (DHS), the Department of State (DOS), the Defense Threat Reduction Agency (DTRA), and Congress. The sessions were unclassified, although several members of the working group have access to classified material.

Nuclear forensics, the analysis of nuclear materials recovered from either the capture of unused materials, or from the radioactive debris following a nuclear explosion, can contribute significantly to the identification of the sources of the materials and the industrial processes used to obtain them. In the case of an explosion, nuclear forensics can also reconstruct key features of the nuclear device.

Nuclear forensic analysis works best in conjunction with other law enforcement, radiological protection dosimetry, traditional forensics, and intelligence work to provide the basis for attributing the materials and/or nuclear device to its originators. Nuclear forensics is a piece of the overall attribution process, not a stand-alone activity.

A believable attribution capability may help to discourage behavior that could lead to a nuclear event. The chain of participants in a nuclear terrorist event most likely includes a national government or its agents, since nearly all nuclear weapons usable material is at least notionally the responsibility of governments. A forensics capability that can trace material to the originating reactor or enrichment facility could discourage state cooperation with terrorist elements and encourage better security for nuclear weapon usable materials. In addition, most terrorist organizations will not have members skilled in all aspects of handling nuclear weapons or building an improvised nuclear device. That expertise is found in a small pool of people and a credible

attribution capability may deter some who are principally motivated by financial, rather than ideological, concerns.

There is an important difference between nuclear forensics as it is practiced today and the analysis of foreign nuclear tests as it was practiced during the Cold War and for some time thereafter, even though both rest on the same scientific base. Nuclear forensics for attribution involves comparing data and analyses from the samples recovered to data and analyses from samples from identified sources. Forensic analysis for attribution therefore requires that data concerning foreign-origin material be available. Some of these data exist in the United States but many more reside abroad, in international and national databases, in sample archives, and elsewhere. Therefore, nuclear forensic analysis would benefit from as much international cooperation as possible.

Following a nuclear explosion, trained forensics teams would need to promptly gather highly radioactive samples from fallout and from the atmosphere. These samples then would have to be safely and promptly transported to United States and possibly other laboratories. Close coordination among the FBI (if the explosion occurs in the United States) and/or local authorities (if elsewhere), first responders, and forensics teams is necessary.

Nuclear forensics results such as origin and history of materials and type of explosive device are not available immediately. Some constraints come from nature; some from personnel and equipment availability; some are due to the iterative nature of interpreting nuclear data, where initial results are fed into computer codes before being subject to further analysis. Political leaders will face a period of uncertainty that could range from days to months, during which forensics and other attribution information gradually becomes available.

Nuclear forensics relies on physical, isotopic, and chemical analyses of radioactive and sometimes microscopic quantities of materials, including impurities and such things as crystal structures and surface finishes where available. Facilities for such analyses exist at the U.S. DOE laboratories and, on various scales, at a number of International Atomic Energy Agency (IAEA), foreign government, and university laboratories around the world. A number of these facilities participated in the analysis of intercepted nuclear weapon usable materials in the past several years. In the event of a nuclear detonation or other nuclear emergency, U.S. facilities would be badly stretched in several respects. The trained specialists needed are too few and would be overcommitted; a high proportion of them are close to retirement age and the ability to replace them and augment their number is inadequate and under-funded. Laboratory facilities are not up to the most modern and effective standards that prevail in some other countries such as Japan and France. Specialized field-deployable equipment to make key early measurements in the affected area needs to be improved and tested. As a result, there could be unnecessary delays of days or more in getting forensic results of importance to the overall process of attribution, at a time when it can be readily foreseen that there would be very high pressure for reliable attribution data if the origin of a nuclear explosion were undetermined.

Nuclear forensics remains a technically complex challenge for the scientific and law enforcement communities. The difficulty in successful forensics work, especially as part of an attribution process, should not be underestimated. However, the potential for nuclear forensics to play a crucial role in analysis of both pre- and post-detonation materials is enormous. The problems of a declining pool of technically competent scientists, the need for new technology, and the utility of international cooperation, all point to the need for a set of new initiatives in order to maximize the potential impact of nuclear forensics.

Conclusions

International Cooperation

The U.S. government should extend its ongoing initiatives to counter terrorism that threatens to make use of weapons of mass destruction (WMD) to include provisions for prompt technical and operational cooperation in the event of a nuclear detonation anywhere in the world. Such cooperation should include enlarging and properly gaining access to existing international and other databases and linking them so as to enable prompt data access. The wider the participation in this effort, the more confident the processes of nuclear forensics will be. It should be borne in mind that, because of widespread fallout following a nuclear detonation, analyses, and interpretations will be available from many different laboratories; all governments would be well-served by having an existing, prompt, and technically informed method of coordinating with other governments. The present Global Initiative could be a vehicle for undertaking this effort. The effort may involve the IAEA, which has much relevant data and capabilities.

Availability of trained personnel

The training of appropriate personnel should be accelerated. A program to do this would involve funding research at universities in cooperation with the relevant laboratories, funding graduate scholarships and fellowships, and funding internships at the laboratories. The program should be sized to produce at least three to four new Ph.D.s per year in the relevant disciplines for the first 10 years, and to maintain skilled personnel levels thereafter. Additional personnel could be drawn from the related fields of geochemistry, nuclear physics, nuclear engineering materials science, and analytical chemistry.

Development of laboratory and field equipment and numerical modeling

A program should be undertaken to develop and manufacture advanced, automated, field-deployable equipment that would allow the necessary measurements to be made rapidly and accurately at a number of sites. Such field equipment is not now readily available. A program to upgrade instrumentation at DOE and other laboratories to world standards is also needed. These two programs, together with more adequate staffing, would result in measurably shortening the time needed before reliable forensics findings could be available.

Similarly, support is needed to extend and improve the present use of nuclear weapons design codes to attempt the reverse engineering of devices from debris. Such applications involve use of the codes in ways for which they were not designed, e.g., creating libraries of results from candidate devices that can be accessed quickly.

Exercises

The existing programs to exercise U.S. capability against terrorist events, such as the TOPOFF exercises, should be reviewed for their adequacy at testing what actions, coordination, communication, and policies would be needed at all levels in the event of a nuclear detonation anywhere in the world. The United States will find itself deeply involved at the political, humanitarian, military, law enforcement, and technical levels wherever a nuclear detonation occurs. Exercises should be structured so as to test capability and coordination realistically in light of both the urgent needs of the situation and also to test the ability, at levels ranging from local command center to political leadership, to communicate effectively and manage operations and expectations on a continuing basis with the American public

and with other governments and publics. An educational program is needed to make senior and other concerned levels of government aware of the time between generating forensic input and decision-making.

Review and evaluation groups

The U.S. government should establish two kinds of review and evaluation groups. One would be a permanent organization that would review and evaluate the exercises recommended above on a continuing basis and keep records of them. That group would include members of the major participating entities. The other would be similar to the Cold War Bethe Panel that advised the U.S. government as to the physical results of foreign nuclear tests and the implications of those results. The panel would consist of scientists and former or present senior government members and would have a similar goal to that of the Bethe Panel: to advise decision makers regarding what is known, how confidently it is known, and what is still not known, and clarify any inconsistencies or differences of opinion among agencies concerned as to the meaning of the information obtained.

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Introduction

This report was produced by a joint Working Group (WG) of the American Physical Society's (APS) Panel on Public Affairs (POPA) and the American Association for the Advancement of Science (AAAS) Center for Science, Technology, and Security Policy.

The primary purpose of this report is to provide the Congress, U.S. government agencies and other institutions involved in nuclear forensics with a clear unclassified statement of the state of the art of nuclear forensics; an assessment of its potential for preventing and identifying unattributed nuclear attacks; and identification of the policies, resources, and human talent to fulfill that potential. The working group formally met twice, once in Washington, D.C., and once in Palo Alto, California, to hear presentations from staff of the DOE/NNSA, the DHS, the DOS, the DTRA, and Congress. The sessions were unclassified, although several members of the working group have access to classified material.

The working group's approach was to first learn about the status of nuclear forensics from active participants in the nuclear forensic program and then use what it learned, along with the group's collective experience, to judge the credibility and value of various options. All of the group's members have been involved in the technical work, management, or review of nuclear weapons and/or forensics activities, most for several decades. Some are still working with the NNSA or the weapons laboratories in consultant roles, and some are part of other review mechanisms. The working group's focus has been to examine the status and needs of the U.S. nuclear forensics effort.

The working group dealt only with nuclear weapons, deciding that "dirty bombs" or radiological dispersal devices, are beyond the scope of its effort.

Nuclear Forensics and the Nuclear Attribution Process

Nuclear forensics is the technical means by which nuclear materials,¹ whether intercepted intact or retrieved from post-explosion debris, are characterized (as to composition, physical condition, age, provenance, history) and interpreted (as to provenance, industrial history, and implications for nuclear device design). This characterization and interpretation results from field work to obtain representative samples of the device materials, laboratory analyses, computer modeling, and comparison with databases that contain empirical data from previous analyses of materials samples or that may be the result of numerical simulations of device performance or both. It requires a combination of technical data, relevant databases, and specialized skills and knowledge to retrieve, analyze, and interpret the data.

Nuclear forensics, when combined with law enforcement and intelligence data, can suggest or exclude the origin of materials and of nuclear devices or device designs, and thereby contribute to attribution of the material or device to its source. As part of the overall attribution process, it may be more or less helpful, depending on circumstances. Recognition of the role and limitations of nuclear forensics and nuclear attribution is necessary if errors in both understanding and expectations are to be avoided.

During the first 50 years of the nuclear weapons era, radiochemistry techniques were developed and used to determine the characteristics (such as yield, materials used, and design details) of nuclear explosions carried out by the United States and by other countries. That application can still come into play if a nuclear explosion is detonated and debris recovered. Generally, however, the current principal emphasis is on applying nuclear forensic techniques to help attribute either intercepted materials or an actual explosion to its originators. This emphasis places different and new requirements on the technical analysis. In particular, it makes the availability of databases and libraries that include samples from various countries much more important than was the case when the principal application was diagnosing an explosion from a known source.

Nuclear forensics can come into play in several different scenarios. The first scenario is interception of nuclear material contraband or an intact device. A second scenario involves a “dirty bomb” or radiological dispersal device (RDD). Several possible scenarios could play out with RDDs. In one often discussed case, an ordinary high explosive is mixed or in close juxtaposi-

tion with a radioactive substance, which is then dispersed when the high explosive is set off. Because of limitations on how much radioactive material can be incorporated into such a device, this scenario, while the easiest for a terrorist group to carry out, is likely to lead to no more or few more casualties than would occur from the explosion alone. On the other hand, the presence of radioactivity will complicate rescue and recovery efforts and will require a program of public education so that the public can realistically assess the risks. It will also result in an expensive and time-consuming cleanup program. In both of these cases, forensic analysis, especially of radioactively contaminated evidence, will play a large role.

A third scenario involves a fizzle or primitive device, in which a nuclear explosion takes place but the yield is sufficiently low that destruction and contamination are limited to a few blocks. Such an event could cause hundreds to thousands of casualties and would require a major response along all the dimensions discussed in this report, but would still be within the range of destruction of prior terrorist incidents.

The fourth scenario is a nuclear explosion with yield in the kiloton range. Such an event would be a major disaster, unparalleled outside of war, with tens to hundreds of thousands of casualties and large-scale destruction if the explosion occurs in a city.

In the following section, two examples will be sketched to show how forensic data are developed and how they can tie to other data for attribution.

Example 1: Material intercepted in transit

Incidents such as these occur quite regularly.² A credible sequence of events following interception would be as follows.

Field measurements on site: The material can be characterized to a significant degree by measurements from portable instruments on-site. Questions that could be answered by such on-site measurements include:

- Is the material a radiation source such as might be diverted from a hospital or industrial installation or even obtained from a waste dump?
- Is it nuclear waste or spent reactor fuel such as might be diverted from a nuclear waste storage, cooling pond, or transport facility?
- Is it weapons-usable material, such as separated plutonium (Pu) or highly enriched uranium (HEU)? These

materials can come from government-owned facilities in several countries, one of very few civilian plutonium storage facilities, or a research reactor.

Laboratory measurements within a few days of returning a sample: At one of several laboratories in the United States and abroad, further questions can be answered:

- If the material is uranium, has it been enriched and to what degree? What contaminants are present? The degree of enrichment and nature of contaminants can indicate not only whether the material could be used for a weapon but also possibly its provenance.
- If it is plutonium, what is its isotopic mix?

Laboratory measurements within a week to a month:

- If the material is in the form of powder or liquid, what stage of metal production does it represent, what might be the geographic source, and how might it have been processed?
- Are alloying or cladding materials present? Do they indicate who the producer might be? Comparison to databases occurs at this stage.
- What is the material's "age"?³

Law enforcement and intelligence data developed in parallel can and should be integrated for complete attribution: All of the information, whether from nuclear forensics and/or from other sources of intelligence, can serve to answer questions such as:

- What are the identities and residences of individuals and groups connected with the material?
- What are their histories?
- What are their organizational allegiances?
- What is the registration of the transporting vehicle?
- What analysis of trace contaminants (hair, fibers, soil, particles, etc.) from the vehicle may allow inference of its recent past movements?
- Is information available on the individuals and their movements?

All of this information, combined and evaluated by perhaps several different organizations and governments, goes into an attribution of the source of the material.

Example 2: Detonation of a weapon or device

While every effort should be made to make sure that such an event never occurs, nevertheless it might. Should it occur, adequate preparation and practice are essential to assure that credible results and decisions are produced in the climate following such an event. Nuclear forensics can answer these questions.

- Within hours: Was the event really a nuclear explosion? What was the yield?
- Within hours to days: Was uranium or plutonium used, or both? Was the device simple or sophisticated? Were high-energy neutrons or tritium present, which would denote the presence of thermonuclear reactions?
- Within several days of sample receipt by laboratories: What were the isotopic compositions of the fuel components? What can be inferred about provenance and history? Does the debris match any from known weapons tests?
- Within approximately a few weeks of sample return: What was the most probable device design? Does it

match any existing designs? What other materials were in the device that may suggest a source?

- Law enforcement and intelligence data developed in parallel: Were there recent threats of such an event? Has electronic traffic indicated movement of materials or people associated with a threat? Was there information from domestic surveillance indicating a threat in the area? Was the location a particularly attractive or significant venue? Has any nuclear state been unstable or expressed concern about its materials or weapons controls?

At present, the U.S. nuclear forensics program would deliver information to the FBI, which has the lead role for counterterrorism and domestic nuclear events. Unless the U.S. government involves other countries or international institutions in the analysis, any conclusions would be those of the U.S. government alone, without participation or vetting of any other government or international body.

Roles of Forensics and Attribution in Preventing Nuclear Terrorism

Identifying sources of intercepted materials can prevent or make more difficult terrorist acts that would use material from the same source. Beyond this, can the perception of effective nuclear forensics deter some of the actors that would need to be involved in any act of nuclear terror and provide incentives to states to better guard their materials and facilities? Because deterrence and other incentives exist only in the minds of the actors involved, no verifiable answer can be given. In addition, the ability to deter increases with the sophistication of the device, as simple devices will require less deterrable expertise to construct. Nevertheless, an informed estimate can be made, based on two kinds of analysis:

1. What are the motivations of the actors involved both for and against committing an act of nuclear terrorism? Why are they contemplating the action and what can dissuade or deter them?
2. What are these actors likely to believe about United States and other nuclear forensics capabilities and what do they think nuclear forensics contributes to the resolve of the United States and others to take effective action against them?

We examine each in turn.

Motivations and Prevention

At least four different kinds of groups are needed for an act of nuclear terrorism:

1. The terrorist group itself, which can be a complex organization and may already include some of the following groups
2. Specialists whose assistance was obtained for a nuclear operation
3. A supplier state, whose participation may be witting or not, in whole or in part
4. Intermediaries to provide transport, funding, shelter, cover activities, etc

Each of these groups has a different motivation and can be stopped by different means. The *terrorist organization* itself might not be deterred by the possibility that it will be identified after a terrorist act through nuclear forensics or through the overall attribution process. It might identify itself after the fact. For terrorist organizations that would want to take credit for a nuclear event,

failure, not discovery, is likely to be the main deterrent. For such groups, nuclear forensics contributes to prevention by increasing the chances of failure: it increases the likelihood that, if the material or the weapon is intercepted prior to the terrorist act, it will be traced to its original source and possibly to the group that designed the weapon. That in turn is likely to close off that source of material supply and weapon expertise and it may also jeopardize the terrorist organization itself, particularly if individuals in the supply or design chain are identified as a result of successful forensics and captured. This is an important argument for improving the ability to trace intercepted intact material.

Specialists are needed to utilize either a nuclear weapon or weapon-usable materials. Those skills range from scientists and engineers with some nuclear training to machinists with experience with the necessary materials. They may be part of the terrorist organization themselves. However, the organization may not already possess the necessary skills, and thus would need to employ some specialists. The specialists needed exist worldwide but form a much smaller and more easily identified group than the specialists needed to put together other more typical terrorist devices. An increased likelihood of identification might deter members of this group, particularly if they lend their skills for money rather than out of conviction.

Can nuclear forensics help identify nuclear specialists? The answer depends on circumstances. If an intact nuclear weapon is intercepted, its design may possibly help identify those who worked on it; however, some generic designs exist. If forensics can narrow the range of possible sources either on intercepted nuclear material or post-event debris, intelligence and law enforcement efforts can focus on people associated with that kind of source. If forensics together with intelligence can identify where the device was made, the experts that helped with the machining, assembly, etc. may be more easily identified, since those operations, when carried out on uranium or plutonium or on high explosives, are anything but routine.

States own all the nuclear weapons and most weapon-usable materials in the world, so far as is known. The physical security of weapons and weapon material is the responsibility of the state that owns the material. How well that responsibility is discharged varies with the state, as has been documented elsewhere.⁴ In some cases, material could be obtained with or without the cognizance of the state owning it. It is considered less likely that an intact nuclear

weapon could be so obtained and most nuclear weapons have security features that make them difficult to use as they are without additional knowledge of those features.

Nuclear forensics can, with high reliability, reach certain conclusions but those may not be sufficient to uniquely identify the source. The more extensive the databases and libraries of sample materials and associated isotopic analyses are, the more specific attribution can be.

In most cases, it will be important to work cooperatively with states to which intercepted nuclear materials or a weapon used by another party might be attributed to prevent further diversion or use. In the case of a hostile state contemplating an anonymous transfer of nuclear materials or weapons to another state or a sub-national group, an increase in the perceived effectiveness of nuclear forensics could strengthen the threat of punitive deterrence.

Lastly, a group planning a nuclear terrorist act must secure the cooperation of a number of *intermediaries* who can provide money, materials other than the nuclear materials, a safe space to work in for at least weeks and more likely months, some basic instrumentation, transport, including transport across guarded borders, people who can evade law enforcement in the target country and who speak its language, and others, depending on the details of the operation.⁵ Some of those intermediaries will belong to the terrorist organization and some will not. Those who do not can again be motivated by money, conviction, or fear. Whether such individuals are deterred by an increased likelihood of being caught depends on individual characteristics so that no conclusion can be drawn.

Degrees of Belief

Assessing the state of mind of terrorist groups and allies in governments and elsewhere, including the degree to which they are risk averse and the degree to which they fear effective, subsequent action against them, cannot be done with any accuracy, at least not by the authors of this report, but certain points relevant to this assessment come out of our analysis.

1. The ability to trace the origin and history of materials intercepted before a terrorist act takes place can lead to shutting off sources of such materials, a major step toward preventing nuclear terrorism. Pre-event forensics can also have a significant deterrent effect on even a terrorist organization dedicated to destroying United States or other cities by heightening the chances of failure and

subsequent hostile action. Present evidence shows that major terrorist organizations have a calculated strategy and are sensitive to the chances of failure.⁶ They prefer to carry out actions where the odds of success are high even if those actions are less destructive than they might prefer. As with small groups facing much larger groups in any circumstance, the highest priority goes to preserving the group's fighting ability. Thus, making sure that successful nuclear material interceptions get wide and believable international publicity increases this aspect of deterrence. Research and development programs in this area should also be well-advertised; although some details may be obscured by security requirements, useful and believable demonstrations can be carried out.

2. Wide international collaboration to implement and improve the nuclear forensics effort, both pre-event and post-event, can enhance incentives for governments to be vigilant about physical security and against infiltration by or influence from terrorist elements. Such international collaboration is already mandated by several international agreements as well as the Global Initiative chaired by the United States and Russia.⁷ The IAEA is already the agent for some of these initiatives. Several aspects of international collaboration are or could be particularly helpful in enhancing the credibility of nuclear forensics as a deterrent, including encouraging the IAEA to take a more active role combating nuclear terrorism and promoting the development and sharing of international nuclear forensic databases.

Conclusions

An effective, believable nuclear forensics capability can, depending on the specific circumstances, encourage or deter states that are sources of materials, individuals working for those states who might otherwise be negligent or corrupt, and nuclear specialists needed to carry out the operation who are motivated by money rather than conviction. Credible forensic capability, demonstrated by successful attribution of intercepted materials,⁸ increases the chances that the perpetrators of a nuclear terrorist act will fail and be apprehended and prosecuted, thereby possibly deterring the terrorist organization itself. It can also have an indirect deterrent effect on other intermediaries.

Advertising interception successes, broadening international participation in both databases and forensics activities, and systematically following up the conclusions reached by the several U.S. government agencies involved can help to dissuade those who might be tempted to participate in terrorist activities. To that end, we recommend a systematic examination at the classified level of what is done with information from intercepts.

These conclusions are overall less pessimistic than those of some other studies,⁹ and more in line with findings that focus on the complexities of a nuclear operation.¹⁰

Roles of Forensics and Attribution: Post-Event Measures and Policies

Following a nuclear detonation anywhere in the world, but especially on U.S. territory, the strongest possible urgency will attach to four main and equally essential objectives:

1. Prevention of additional detonations
2. Identification of and response to the entire chain of actors responsible for the detonation
3. Response and recovery efforts at the affected site if in the United States and lending appropriate assistance if abroad
4. Management of public and foreign government expectations and determination of the basis for further action

For nuclear forensics to play its role, qualified personnel must be able to access sites for prompt sample collection. Some of those sites will be within the affected areas and highly radioactive; others will not. Repeat visits, while to be avoided wherever possible, may be needed as understanding is developed. Prompt, safe, protected transport of samples to the laboratories is essential, as is protecting the chain of custody. Regardless of whether the detonation is in the United States or abroad, international transport of samples and of people, Americans and others, will likely be needed.

All of these objectives will generate time pressure and the resulting priorities may well conflict. For instance, law enforcement authorities may want to restrict access to sites and/or the sharing of information to avoid revealing intelligence that may be of use in preventing another detonation, while emergency rescue personnel and forensic field analysts may need information or access. Pre-agreed policies and protocols will help but informed realistic policies and protocols can only come from realistic exercises.

1. Prevent additional detonations

An immediate priority for nuclear forensics will be to determine if the attackers have additional devices or the means to produce them. The burden of preventing additional detonations will fall most immediately on the intelligence and law enforcement capabilities of the United States and cooperating governments. Forensic information may assist intelligence and law enforcement personnel in assessing the likelihood of the existence of another device. For instance, if the deto-

Table 1: Nuclear forensic activities following a terrorist explosion

INFORMATION	TIME SCALE	METHODS
Was radioactivity involved?	An hour or less	Dosimetry at scene
Detonation was nuclear	An hour or less	Visual, seismic, radiation
Uranium or plutonium fuel	Hours to days	Possible field measurement
Nuclear device design	Weeks to months	Reconstructive analyses
“Age,” production, history	A week to months	Iterative analyses

nated device used plutonium, search efforts could focus on detecting the plutonium radioactive signature at other possible detonation sites and along transit routes. Nuclear device signatures can, however, only be detected over a short range, so that the search for other nuclear devices will be carried out principally by the more traditional intelligence and law enforcement methods.

Table 1 gives the approximate times at which different types of information will be gained as part of the forensics analysis.

2. Identify the entire chain of actors responsible for the detonation

Nuclear forensics will not be able to provide all the needed answers immediately. However, after 24 hours, 72 hours, a week, and so forth, nuclear forensics will add valuable information and significant insights. As new nuclear forensic information develops, it can increase certainties in some areas but may not be able to reduce uncertainties in other areas.

It may be possible, through nuclear attribution, to determine the source materials of the nuclear device and the pathway by which it was produced and assembled. Determining the source and how the device came into being are both important. Certain raw materials may have been obtained from a country without that country’s knowledge or knowledge of the intended use for those materials.

Nuclear forensics can also rule out certain possible originating sources or pathways. Following any accident or catastrophe, misinformation about the cause or the perpetrators can sap valuable resources needed to determine the facts as quickly as possible. After a nuclear explosion, nuclear forensics can help to minimize such misinformation.

The ability to use this information to attribute an event

to a certain state or non-state group would depend in large measure on databases available beforehand. A number of organizations are acquiring background information on the characteristic signatures of materials and their differences around the world that could be used for nuclear forensics. While not all countries might agree to participate in a nuclear forensics database, and while the database would be a work in progress, it would have value in all cases as it could serve to eliminate some potential sources.

In the event of an actual nuclear incident, there will be enormous pressures on state and local governments to provide answers. Nuclear forensics can provide some – albeit limited – information relatively quickly. However, if the appropriate tools or personnel (including radiation protection for them) are not promptly available, if access to the sites and suitable transport of evidence to the laboratories are delayed, and if the entire system has not been adequately exercised, the times given in the table above could stretch out.

Perhaps the most important point for post-event policy is that forensics information will become available gradually and some of it is likely to require revision as more information is developed. As a result, post-event policies and measures must be structured to deal with continuing, if narrowing, uncertainty in the face of considerable public and political pressure to take action.

3. Lead the response and recovery effort at the affected site if in the United States and lend appropriate assistance if abroad

The response and recovery efforts will vary depending on the yield of the nuclear detonation. An explosion of a few tons might devastate a few city blocks and kill a thousand people. An explosion in the kiloton range would destroy much of the downtown area of a city and perhaps kill as

many as hundreds of thousands of people. In every case, federal leadership coordinated with state and local efforts would be needed to take maximum advantage of the national capabilities.

Nuclear forensics can determine the yield, help define the extent of the affected area, and help identify where post-event resources are most needed. An information sharing plan among authorities on site, first responders, and nuclear forensics teams will be needed. If communicated in terms that are relevant to public concerns, nuclear forensics, along with other technical information, may play a role in calming those who have not suffered physical or medical trauma but who are concerned about follow-on consequences. With other technical information, nuclear forensics also can discourage exaggeration of those consequences by the media or governments, while providing a realistic appraisal of the situation and clarifying needed actions.

4. Provide leadership to the public and to other governments and help lay the basis for further action

How to provide leadership to the public and other governments goes beyond the mandate of this group. We may call attention, however, to mistakes stemming from the misinterpretation of technical data made in past nuclear disasters and perceived disasters and to measures that might have prevented those mistakes. These past instances are not commensurate in either the devastation or the public pressure that a nuclear detonation in a city would cause, but they are instructive nonetheless. Two such instances are the nuclear accidents at Chernobyl and Three Mile Island. The first event killed more than 30 first responders and may have shortened the lives of thousands of others. The second event killed no one and probably did not have a measurable effect on the lives of people surrounding the event. Similar mistakes, however, were made in both cases. Here are a few, which could also be made in the event of a nuclear detonation.

1. Premature and mistaken announcements were made by agencies that were supposedly informed and responsible.
2. Unnecessary evacuations were undertaken and necessary ones were not, mainly because responders were ignorant of both the degree of danger of evacuation relative to not evacuating and the areas likely to be affected.
3. The institutions in charge of responding at the various governmental levels did not coordinate effectively and did

not pass along needed information. There was no effective incident command, backed by the top authority, and that authority was not in touch with those in the field who had necessary information and needed to take action.

4. There was no continuing, informed, self-correcting source of official information generally available to those affected so as to counter the inevitable rumors and misinformation that occur in the wake of a traumatic event. This was true in both the open society of the United States and the closed society of the Soviet Union.

The devastating nature of a nuclear detonation could easily lead to far worse situations. Forensic efforts may have to operate in a chaotic environment, as people clog roads, overload phone networks, do not show up for work at power plants, airlines, etc. There will be enormous pressure on the leadership both to identify the culprits and to prevent another detonation. Because prompt attribution is unlikely, a source of continuing information, addressing the goals outlined here and transmitted by all modern means of communication, would likely have a calming effect on the general public.¹¹ Exercises involving top decision-makers could prepare the way for dealing with this quandary. Otherwise, the political pressure on governments to promptly identify the perpetrator could lead to mistaken or opportunistic identification of the originating source.

Nuclear attribution, including its forensic component, will have considerable political consequences. A careful scientific examination of the forensic facts behind an attribution is critical to prevent a mistaken accusation of a group or nation. These facts will include information from law enforcement agencies, U.S. government departments, medical sources, and state and local agencies. Together, these various sources of information can help to identify the responsible nation(s) or group(s) and provide a sound basis for making that conclusion public.

To the fullest extent possible, standards should be developed for the nuclear forensic laboratories, including the procedures to be followed, chain-of-custody requirements, and the mechanisms to be used for review and validation. Historically, in past high-profile accidents or nuclear incidents, the United States has convened high-level expert panels to review the analyses done by the laboratories and others before considering the work to be complete.

Because of the potentially enormous consequences of a nuclear event, any announcement of attribution will be a

presidential-level decision and announcement. Scientific peer review can help to avoid mistaken judgments, and can be invaluable in providing advice to the president and other senior decision makers. An expert panel can also help describe what has happened and what is known about it to the public and media.

In addition, it may be appropriate to consider an international dimension to the peer review. International support could provide a more balanced statement, bring in additional insights and information, give a truly more independent

perspective, and establish a global basis for any future attribution arguments. On the other hand, international participation raises issues of classification that do not arise with cleared American reviewers. If international review is judged to be of assistance in a particular situation, a balance will have to be struck between what should be released and what should be kept secret. The cleared reviewers could recommend to the relevant government authorities where specifically to strike that balance for the situation at hand.

State of Forensics Art

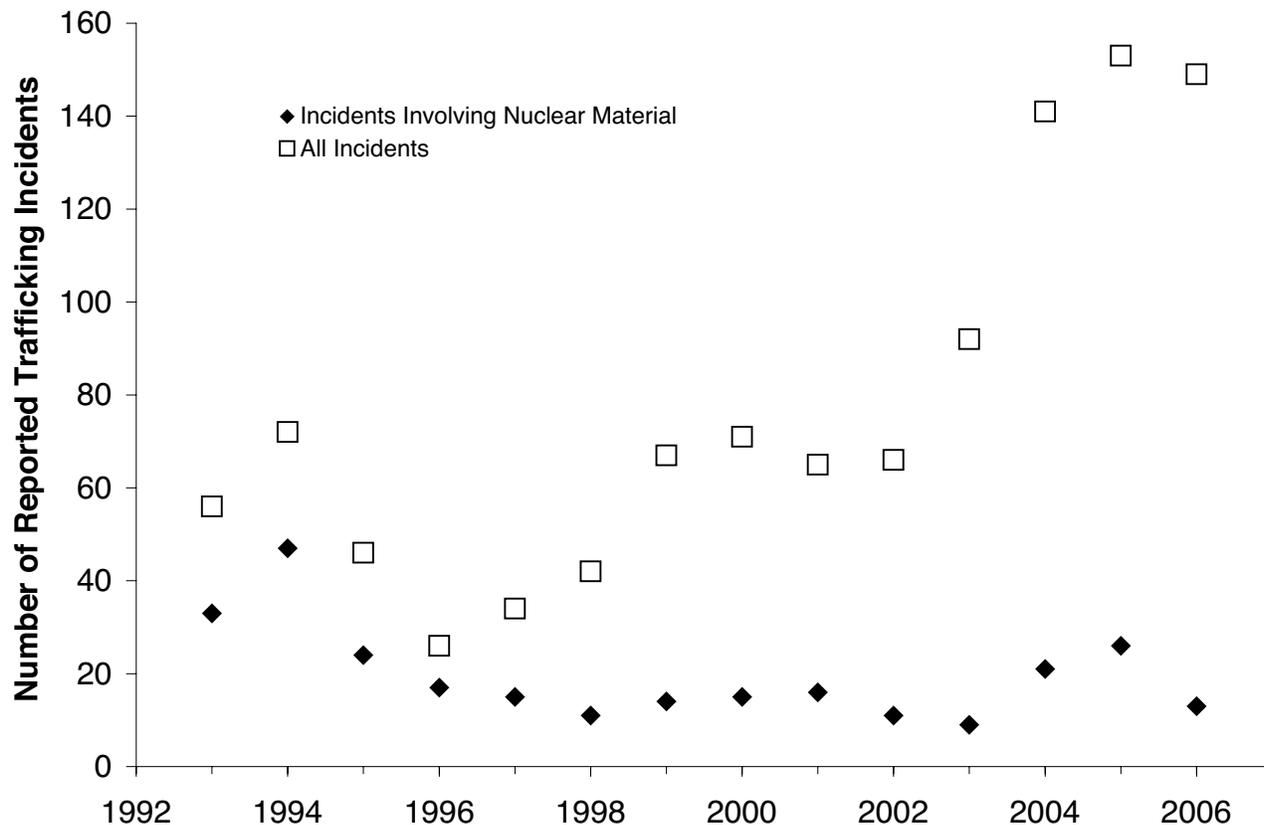
The present state of the art of nuclear forensics presents a mixed picture. The underlying scientific disciplines, radiochemistry, nuclear physics, and others, are understood adequately for the purpose of forensics. The scientists at the nuclear weapons laboratories, which carry the bulk of the scientific part of forensics responsibility, are the equals of any in the world. Very advanced equipment that allows the investigation of materials almost down to the molecular level exists at these laboratories. However, too few scientists can meet the sort of emergency that would result from a large release of radioactive materials, particularly if it resulted from a nuclear explosion. Even fewer new personnel are available to augment and replace them. Specialized field-deployable equipment that could save days in making results available to decision makers is either not available or incompletely tested. The transportation to make people and equipment available rapidly worldwide is inadequate. Intercepted nuclear and other radioactive material can be and usually is subjected to analysis by the most modern instruments. More work is needed to integrate the use of these instruments into post-detonation forensics. Post-detonation forensics, if needed today, would have to rely heavily on radiochemistry techniques developed during the nuclear test program, which are necessary but not adequate to deliver the greatest amount of data as rapidly as possible.

Nuclear forensic analysis related to nuclear terrorism is usually separated into two areas, the analysis of intercepted materials and the analysis of the debris and fallout that result from a terrorist nuclear detonation.

Nuclear forensics for interdicted materials

Nuclear material in various forms that could be used by terrorist organizations to build a crude nuclear weapon is found in at least 40 countries. Studies by the Nuclear Assessment Program (NAP) at the Lawrence Livermore National Laboratory (LLNL)¹² indicate that over the past 15 years, more than 17 kg of HEU and 400 g of Pu have been interdicted through an international effort to control nuclear smuggling. The total amount of weapon-usable material diverted from lawful ownership is poorly known but comparisons with drug trafficking suggest that interdictions account for only a small fraction of material available on the black market. As shown in Figure 1, the IAEA's Illicit Trafficking Database (ITDB)¹³ contains a record of 1,080 confirmed events involving illicit trafficking and other unauthorized activities in nuclear and other radioac-

Figure 1: Illicit trafficking cases recorded by the IAEA; adapted from Figure 21 of the IAEA Nuclear Security Series No. 6



tive materials between 1993 and 2006; approximately 25% of those cases involve nuclear materials.

A nuclear forensic investigation involving the interdiction of nuclear or radiological material prior to a detonation differs from the post-detonation situation in two important respects. First, the samples available for laboratory analysis retain their original chemical and physical structure, and, second, for intercepts of small quantities such as most of the ones that have occurred, the speed of analysis leading to attribution is generally not a critical issue. Should the interdicted material quantity be large enough to be dangerous or be associated with an unexploded explosive device (something that has not happened to date), the material or device is first rendered safe by ordnance disposal personnel. Only after stabilization and release by explosive and weapons experts is access provided for nuclear forensics and attribution.

Preservation of all types of evidence is vital. The knowledge among law enforcement and other first responders of how to recognize and preserve evidence associated with

radioactive materials is not widespread, although progress has been made in the United States under cooperative FBI-DHS programs. Intercepts, however, have more often taken place in or at the borders of countries where appropriate training has been less available or non-existent. Maintaining and recording the chain of custody of the evidence through the collection and transportation processes is equally important and also not always adequately done. On-site non-destructive analysis can categorize interdicted radioactive material without affecting the evidence. The goal of this categorization is to identify the bulk constituents of the material and determine whether it is nuclear weapon-usable material (such as HEU or Pu, also called special nuclear material or SNM), naturally occurring radioactive material (e.g., uranium ore or ore concentrate), radioactively contaminated material, a commercial radioactive source, or nuclear reactor fuel. Categorization is essential for confirming the seized material as contraband and for ensuring samples are sent to a suitable laboratory for characterization.

If the radioactive evidence is well-contained, for example, low-enriched uranium oxide (LEU) powder inside a lead container, the sample should be secured and removed from the incident scene with due attention to preserving the forensic evidence. If the evidence is widespread or scattered, care must be taken to collect evidence in as many locations as possible; it is very difficult to predict *a priori* what evidence may prove critical to the forensic investigation. If immovable or large objects, such as buildings or cars, have become contaminated with radioactive evidence, then it may be necessary to collect swipe samples.

Interdicted samples should be sent to an accredited nuclear forensic laboratory familiar with the requirements of a law enforcement investigation, including the ability to perpetuate chain of custody. The initial step in a nuclear forensic investigation is a basic characterization of the nature and type of material present to supplement information collected at the point of interdiction and allow forensic scientists to develop a detailed analytical plan. Beyond this step, nuclear forensics does not incorporate 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. Additional information about forensic analyses of interdicted nuclear material may be found in Appendix E.

The goal of the nuclear forensics investigation is to determine the physical, chemical, elemental, and isotopic characteristics of nuclear or radiological material that distinguish a particular sample from other nuclear or radiological materials. These signatures identify the processes that created the nuclear material, aspects of the subsequent history of the material, and, potentially, specific locales in the material's history. While most plutonium-producing reactors and enrichment facilities fall into a few generic types, individual facilities and processes used for uranium-rich materials differ in a number of potentially telltale details. Such details affect the materials in ways that include isotopic makeup, abundance of daughter nuclei, and impurities. Uranium, for example, varies in isotopic composition and impurities according to where the uranium was mined and how it was processed. Weapons-grade plutonium can be exposed during its production to different neutron fluxes and energies, depending on the particular reactor used. It is also possible to establish the length of time plutonium spent in the reactor. The differences would not allow as specific identification as would fingerprints or DNA samples for an individual, but

they would in most cases allow for ruling in or out broad classes of possible sources for the intercepted or detonated materials. Much of the research and development in nuclear forensics and attribution centers on the identification and understanding of these signatures.

Nuclear forensics for post-detonation analysis

The post-detonation application of nuclear forensics would differ in several important ways from the application of forensics to unexploded intercepted material. The first step in the nuclear forensic activities following a nuclear explosion is to collect debris samples. In the case of a nuclear detonation, the debris collected is a condensation of the very hot plasma created by the explosion. Some of it will remain in the crater created by the explosion, mixed with glass-like material from melted rocks. Much of the nuclear explosive device debris will be thrown into the air and condense on particles of dust and fall back to the ground as "fallout" in the region down wind from the explosion. Some will be suspended as a cloud in the atmosphere and travel with the prevailing winds.

The two easiest places to collect debris are from the fallout downwind from the detonation point and the radioactive cloud drifting with the prevailing winds. Sample collection from the crater will be very difficult for some period of time because high radioactivity will inhibit access to the crater. But even collection from the fallout area will require special precautions both for the safety of personnel involved and to preserve evidence. Time in the high fallout area must be tracked and limited. Rapid transport suitable for transporting radioactive evidence must be available. All this will require coordination with the FBI, which would be in charge overall in the United States, and with the federal and local agencies in charge of response and recovery. Collection of airborne debris requires specially equipped aircraft.

A collection of a sample with only one billionth of the fission fragments (a few hundred nanograms) and initial material in the device is sufficient to perform the radiochemical analysis. An estimate of whether the collected sample obtained is adequate for that task can be made by measuring its total radioactivity. While not trivial, the activity can be measured and corrected for the decay since the time of the explosion to provide a determination of the approximate number of fissions that is present in a particular sample.

It is important to take multiple samples from the fallout areas and from the radioactive cloud: during the condensation process, some of the elements will condense more quickly than others, resulting in what is known as chemical fractionation. Thus, some of the samples will have more of the refractory (non-volatile) elements, and samples from the radioactive cloud will be more likely to have more of the volatile elements. These differences in the composition of the debris are important to understand, as much of the analysis is based on ratios of fission fragments isotopes before the fractionation occurred.

As samples are taken, they need to be cataloged as to where each sample was taken and the level of activity present, and then packaged in a container for shipping.

Following a nuclear incident, first responders armed with basic radiation detectors would be able to quickly determine whether the damage was associated with nuclear fission. This could probably be determined within an hour of when first responders reached a controlled perimeter. If the nuclear explosion produced nuclear yield in the kiloton range, it would be obvious from the widespread physical destruction. However, if an improvised nuclear device were a dud or produced very little nuclear explosive yield (fizzle), then it might take longer to determine what type of device was used.

The next step, taking a few days, is to determine whether the main fuel for the bomb was uranium or plutonium. This knowledge limits the possible sources of nuclear material. Seven countries are known to have successfully detonated

a nuclear bomb using plutonium¹⁴, another six are known to have sufficient reactor-grade plutonium for weapons¹⁵, and over 40 countries possess enough highly enriched uranium to make one or more nuclear weapons.

Other nuclear forensic information about the nature of the bomb-making effort, such as the chemical and physical materials employed, including impurities and contaminants, could generally be obtained within several weeks following an event, although in certain circumstances this may take longer.

By analyzing radioactive debris from an explosion and measuring the decay, nuclear forensics can determine the history of the fissile material, including when the plutonium underwent chemical separation and the uranium's radiochemical history. This, in turn, may indicate from where the fissile material came. Analysis of the debris may also identify other, non-fissionable materials used to construct the device, and something about the sophistication of the design, or lack thereof. The particular alloys or compounds used in making a device, or the impurities and contaminants found to be present, may also indicate the source of those materials or the industrial processes used to make them, which in turn may be indicative of the practices or techniques in certain parts of the world.

Much more can be done with the explosion debris. Some of the tools and techniques used for further research are classified; some unclassified details are presented in the appendices. Some of the tools referred to above need further development.

Improving the State of the Art

Neither equipment nor people are at the level needed to provide as prompt and accurate information for decision makers as is possible. Current post-detonation debris analysis techniques derive largely from the nuclear weapons test programs of the Cold War. Leveraging the Cold War infrastructure enabled a baseline forensics capability to be established quickly, but has resulted in a capability that relies largely on science and technology developed in the nuclear-testing era, with timelines and priorities sometimes distinct from those of nuclear forensics. In addition, current analysis methods are often labor-intensive, and rely on education and training that are no longer prominent in the U.S. university system.

Key areas for research and development

Research and development are needed in four areas: equipment, databases and knowledge management, sample archives, and nuclear device modeling.

Equipment. Advanced, automated nuclear forensic equipment should be developed to speed the collection and analysis process to meet the desired timeline of the post-detonation nuclear forensics mission. During the Cold War, the U.S. nuclear test program had no need to accelerate the delivery of the radiochemical results. A significant research and development program is needed to produce a nuclear forensics system capable of providing results as quickly as possible.

The area that needs particular investment is the development of automated, field-deployable instrumentation providing accurate sample analysis on shorter timescales. Although an initial capability to collect samples of debris following a terrorist nuclear explosion exists, there is a need to improve this capability to provide an all-weather, all-scenario rapid response capability. For this need to be met, automated, portable instruments that provide accurate sample analysis on short timescales should be developed. Field-deployable instruments capable of automated radiochemical and mass spectrometric analysis for the isotopes of interest are a good example of what is needed. These capabilities would significantly shorten the timeline to provide critical analytical information with high confidence to decision makers.

Databases. Databases and knowledge management systems are needed to support nuclear forensics. This effort has begun in the United States and elsewhere but needs systematic ad-

ditional support. For example, the DOE has created a database containing information about uranium compounds (U ores, U ore concentrates, etc.), including trace element concentrations, isotopic composition of uranium and other elements, and other descriptive parameters. Various other groups hold substantial data, but the consolidation of these data into an accessible nuclear forensics database has not taken place and the tools to utilize the database have not been developed. Developing the desired database will require significant cooperation with foreign governments and corporations.

Sample Archives. Sample archives containing physical samples of the nuclear materials cataloged in the databases would be extremely helpful in a number of circumstances. The samples will contain more information (e.g., about impurities) than may have been analyzed and stored and this additional information could be of use in a forensics investigation. In addition, new and more accurate laboratory instrumentation is constantly being developed and can be brought to bear if samples are available. The IAEA has a sample archive, as do some U.S. and foreign nuclear laboratories, but again these archives are incomplete.

Nuclear device modeling. The existing modeling capability used to reverse engineer devices based on the nuclear forensic data also rests largely on the existing capabilities of the nuclear weapons design laboratories. While, in general, the existing capability for reverse engineering is good, the nuclear design computer codes were not designed for this purpose. There are numerous additional developments that are needed to improve this capability to meet the goals of the nuclear forensics and attribution community.

Personnel Issues

Approximately 35 to 50 scientists⁴⁶ are working in nuclear forensics at U.S. national laboratories. At least 10 more staff members are needed in the program even under routine conditions. Between one-third and one-half of those scientists are likely to retire in the next 10 to 15 years. Moreover, in the next 10 years, about a third of those in the 40- to 50-year-old group will take other assignments that remove them from the nuclear forensics cadre. This assessment is exacerbated by the realization that, to meet an emergency, two to three times the present number would be needed in order to provide adequate qualified personnel both on

site and at the forensic laboratories. Some of the qualified people will also be obligated to other emergency tasks, such as looking for a second nuclear explosive device and assisting first responders. While full staffing for an emergency is probably an unrealistic prospect, a 50% increase in personnel could readily be justified on the basis of routine needs and readiness alone. An important use of more modern equipment and analytical protocols is to reduce the number of personnel needed in an emergency.

Thus, to achieve the staffing levels we believe to be appropriate, the national labs require at least 35 new Ph.D. scientists trained in disciplines in support of nuclear forensics over the next 10 or so years, or a minimum of three to four Ph.D. hires per year into the nuclear forensics or radiochemistry areas for the next 10 years.

The scientific expertise and skills applied to nuclear forensics can be acquired within many academic disciplines, loosely referred to as the “nuclear and geochemical sciences.” The staff at the national labs devoting most of their time to this field have earned their advanced degrees in a variety of disciplines, including chemistry and geochemistry, nuclear and radiation physics, nuclear engineering, and radiochemistry. While university enrollment in chemistry and physics majors has remained steady, and nuclear engineering enrollment has increased in recent years⁴⁷, the decline in radiochemistry programs has been precipitous and unabated. Radio and nuclear chemistry have been dropped from many undergraduate and graduate chemistry curricula. Only seven universities⁴⁸ continue to offer graduate programs in radiochemistry; in four of those, only a single faculty member remains. Fewer than six radiochemistry Ph.D.s are granted each year; forensics is only one of several possible career paths available to these graduates. Without a program to reverse the drift, these numbers will dwindle further as faculty retire and are not replaced.

The key goals of a program to increase the number of appropriately trained scientists are to concentrate efforts to train new Ph.D. scientists in technologies relevant to nuclear forensics and foster collaborations between university partners in relevant disciplines and existing staff at the national laboratories working on nuclear forensics.

To accomplish the first goal, the most promising existing university radiochemistry programs should be identified and funded over the long-term (10+ years). It is difficult to predict how many of the graduate students in these programs would apply to, and be hired by, the national labs. Demand

for graduates also exists for careers in academia, the nuclear power industry, nuclear medicine, waste management technologies, or other competing industries. Regardless, the number of Ph.D.s granted yearly in radiochemistry must be elevated above the current rate in order to yield one to three potential hires at the national labs.

The second goal is the strengthening of university-national laboratory interactions. This can be done through several tested mechanisms, such as:

- Graduate fellowships in nuclear forensics tied to service at a national laboratory.
- Post-Doctoral fellowships at the national labs in nuclear forensics.
- Summer internships for graduates and undergraduates.
- National lab support for university contracts.

International Cooperation

Role of International Cooperation

Nuclear forensic investigations carried out on intercepted nuclear materials or debris from a nuclear detonation and the subsequent interpretation of the forensic results have, of necessity, several international dimensions. Intercepts have all, so far as is known publicly, occurred outside the United States and involved materials of non-U.S. origin. A nuclear detonation could occur either in the United States or abroad but the radioactivity would be carried around the world in detectable and analyzable amounts. International capabilities have contributed to the interpretation of intercepted materials and would contribute to the interpretation of radioactive debris from a detonation. In either case, international credibility, at least among a number of key countries, is needed as a basis for international action.

The United States and Russia, the co-chairs of the Global Initiative to Combat Nuclear Terrorism¹⁹ launched in 2006 by Presidents George W. Bush and Vladimir Putin, are the owners of more than 90% of the nuclear weapons and nuclear weapon materials in the world. As such, they are in an excellent position, working cooperatively with other nuclear weapons states, to promulgate high standards and propose liability and accountability standards for all states possessing nuclear weapon materials. Those standards should pertain not only to physical security, but also to personnel security. Such measures are not only valuable of themselves but also enhance the deterrent value of existing nuclear forensics capabilities particularly in respect to “specialists” in all countries, who might otherwise believe they could escape detection. Agreement on standards could lead to an international convention on liability (similar to the Vienna Convention on Civil Liability for Nuclear Damage), in which parties would agree to assume responsibility for the consequences of theft or misuse of nuclear weapons or nuclear materials (and, as parties to the convention, would be eligible for compensation if they are the victims of theft or misuse). Such a convention could act as an incentive to improve material protection, control, and accounting.

One of the Global Initiative’s goals is to highlight the role of “non-traditional partners.” Specialized personnel in these partner countries, as well as in the Non-Proliferation Treaty (NPT) nuclear weapon states, must be deterred from active participation in terrorist activities. Involvement of non-traditional partners in cooperative efforts to prevent nuclear terrorism enhances both forensic capabilities and the ability of nuclear forensics to deter the participation of skilled individuals in nuclear terrorist acts.

Perhaps the most important aspect of international cooperation occurs in connection with the need for international databases and sample archives in order to interpret the forensics findings and assist in attributing the origin and history of materials. This is not simple, and requires a uniform commitment to transparency.

Roles of International Databases in Nuclear Forensics

Databases provide the means of comparison between intercepted nuclear materials or debris from a nuclear explosion and possible sources of the nuclear materials, such as the type and location of the reactors in which plutonium was made or the type and location of uranium enrichment or fuel fabrication facilities. Such databases are essential to the nuclear forensics mission. The comparison of data from a particular intercept or terrorist event with data from databases supports three different objectives. One is to try to identify one or a few possible matches between the intercepted sample(s) or collected debris and entries in the database. Another is to rule out other possibilities as potential matches. A third objective is to enhance the preventive effect of nuclear forensics by making clear ahead of time the existence of internationally agreed methods of analyzing and identifying nuclear materials to assist in the overall attribution process.

Sample archives consist of analyzed samples, that is, small (grams or less) amounts of plutonium, uranium, and possibly other fissile materials from identified sources; corresponding databases contain an analysis of the history and composition of the sample from its originating source as well as indexed records of nuclear material properties, production locations, and use histories. Access to the physical samples is needed to validate the database, and to allow more detailed analyses as needed. For maximum credibility and deterrent effect, it is important that the methods of analysis that correlate samples to their sources be internationally vetted and accepted. A good start has been made in that direction by the Nuclear Smuggling International Technical Working Group (ITWG)²⁰ and the EC Joint Research Center- Institute for Transuranium Elements (ITU)²¹ in Karlsruhe, Germany. An international community of experts has begun developing mutually agreed-upon techniques for performing reliable nuclear forensic analysis, and the analytic techniques are peer-reviewed and regularly benchmarked in internationally accepted tests using unfamiliar samples.

For databases to play as useful a role as possible in nuclear forensics and attribution, they must include as many analyzed samples from as many countries and multinational facilities as possible.

Current Status of International Databases

At present, international databases are not nearly extensive or usable enough to fulfill the potential utility of nuclear forensics in the event of a detonation. Several small databases similar to what we propose currently exist. One has been established by the ITU, in cooperation with the Bochvar Institute in Russia.^{22,23} The IAEA maintains a limited-scope database on safeguarded nuclear material, which is protected by confidentiality agreements with the IAEA member states. Safeguarded materials from the civilian nuclear cycle are a possible source of materials for terrorists, although they may need further processing for use in nuclear weapons. Confidentiality agreements would probably not stand in the way of a forensic investigation following a detonation, but could cause time delays. While potentially useful, therefore, those databases are incomplete and not well-designed for the event-driven rapid forensics that would be required in response to a terrorist detonation.

The U.S. government maintains databases that would be of crucial help in the case of an event. These databases have been created and are maintained by several different U.S. government agencies. Generally speaking, databases containing information pertaining to U.S. weapons programs are classified and fall beyond the scope of this document. Other databases containing information on commercial and research reactor fuel and uranium ore concentrate, while not classified per se, contain information subject to non-disclosure agreements and are not widely distributed. These databases contain a variety of information, depending on the specific focus of the database, including isotopic abundances for U and Pu; abundances of trace impurity elements; chemical/molecular form of the U/Pu; and isotopic compositions for stable isotopes, such as lead and oxygen. The DOE maintains a database to provide information about DOE-owned or -managed spent nuclear fuel. This Spent Nuclear Fuel Database²⁴ contains the following information: inventory data by site, area, and facility, physical characteristics, chemical composition of the fuel compound, cladding, and other significant constituent components, burn-up data, and source term data²⁵. A similar database, Spent Fuel Isotopic Composition Database (SFCOMPO), has been compiled

by the French.²⁶ Algorithms for interrogating the information contained in these databases are under development.

A Proposal for a Future International Database

The ideal international database would include:

- Fissile materials characteristics
- Other nuclear material information that may be relevant to tracing fissile materials
- Fissile materials production and processing information, subject to security measures to safeguard commercially protected information
- Information on fissile materials storage sites, including types and quantities of materials and site security measures, subject to security measures to safeguard both commercial and national security information.

The ideal database would be managed to allow full and prompt access in case of a nuclear emergency of any kind occurring anywhere in the world. It would be supplemented by a sample archive containing as many actual samples as possible. Vetted and accepted analytic processes to link information obtained from debris and intercepts to the database information would accompany the database.

Some of these desired attributes are likely to be achieved only incrementally and some not at all. A plan for proceeding that would maximize the likelihood of getting the most crucial information soonest should be worked out by the principal interested parties, and particularly by the nuclear weapon states. Such a plan should be based on a detailed analysis of what can be accomplished by adding various data and attributes to existing databases so that the process of establishing the desired database can be optimized. Such an analysis would likely have to be classified and is beyond the scope of this study.

There will certainly be objections, some of which are discussed below in more detail. Objections may particularly be raised regarding sharing information on nuclear material not subject to international safeguards, which includes nuclear weapons source materials. Lack of access to such data would be a major shortcoming of the database. We believe that authenticated and secured access to forensic signatures of such materials can be ensured with goodwill, international cooperation, and new technologies.

The database could be held centrally, for instance by the IAEA, which already gathers similar data in connection with

its safeguards mission. The IAEA has access to safeguarded nuclear material – but not weapons material – worldwide and could obtain authentic samples for analysis and ensure the completeness of the database. This would require a broadening of the IAEA mandate, but a broadening that would be consistent with the overall IAEA mission and would take place along lines that are already technically understood by the international community. Alternatively, the database could be distributed among several countries. This approach might ease certain intelligence sensitivities but would also entail delays in an operational situation, unless coordination among the various sites where data are stored was carefully tested in realistic exercises. Similar arguments apply to sample archives. Samples could be divided among national archives or held centrally. Sample archives exist at some laboratories and at the IAEA now, but they are not complete enough to be useful in forensics.

Obstacles to Establishing a Comprehensive International Database

The obstacles to establishing such a database may be summarized as follows:

- Commercial desires to protect sensitive data
- Problems related to classification and established government policies
- Refusals of states to cooperate
- Attempts to spoof the database

We discuss each category of obstacle briefly below, together with possible means to overcome those obstacles.

Commercial Desires To Protect Sensitive Data

Valuable information, such as the precise composition of uranium or plutonium from various sources or chemical impurities added to nuclear fuels, is in the hands of commercial providers of uranium enrichment and plutonium reprocessing services for power reactors, but for competitive reasons, that information is either private or, if shared with the IAEA, held for the sole purpose of safeguarding the facility and not otherwise disclosed. Such information might be shared with the U.S. government or other governments intent on finding the source of nuclear material either intercepted or used in a detonation, but the process has not been either agreed to or tried out under realistic exercise conditions. This kind of data could either be shared with the keepers of the described database or agreements could be

in place for access to the data under specified circumstances. In the latter case, the data would have to be described in sufficient detail to permit agreements on vetting the methods for proceeding from the data to source attribution and also to permit realistic exercises to take place.

Problems of Classification and Government Policies

While the problem with sharing information on the sources of safeguarded materials is one of preserving commercial confidentiality, the problem with un-safeguarded weapons-grade material is one of preserving classification and protecting intelligence sources and methods. Since un-safeguarded materials are likely to be the ones of greatest interest to terrorists interested in nuclear capability, and since the very governments whose cooperation is likely to be most needed are the ones that established policies to protect weapons data and intelligence, this is a problem that must eventually be resolved if the proposed international database is to be most useful. It is technically possible to include key information – including isotopic composition of source materials – that does not reveal details of how the weapons are made.

One proposal put forward by May, Davis, and Jeanloz²⁷ envisages, for the classified part of the database, information protocols that allow appropriate disclosure of sensitive data (perhaps to a small set of vetted analysts) in time of need. Message digests known as hash codes can be used to encapsulate analytical information and to interrogate the database. Hashing is often used in electronic commerce and indeed in most situations where a password is being verified to keep information secure. The advantage of hashing is that only a small fraction of the data file is encrypted, so it is less vulnerable to interception than traditional encrypted data. Provided that information in the secure database is stored in a pre-determined format, the task of comparing it to new forensic information is straightforward. Other technical solutions to this problem exist.

So far as access to actual materials samples, a mechanism similar to the “challenge inspections” agreed to, for instance, in certain arms control agreements such as the Chemical Weapons Convention (CWC)²⁸ and implemented as part of the Additional Protocol by the IAEA²⁹, could be used to make samples available under appropriate and pre-approved conditions, notably, in response to a terrorist nuclear detonation. The main issue is likely to be obtaining political agreement to allow use of classified or sensitive information whatever the technical protection method.

Motivations for Cooperation and for Refusal of States to Cooperate

A primary motivation for disclosure of information and samples to this proposed database and for participation in the associated forensic analysis would be assurance of access to or participation in attribution assessments and the consequent political or military steps. Participation, cooperation, and transparency could greatly reduce the probability that one’s own country would be mistakenly identified as the source of the material used in the attack. While cooperation in a database is not required under the Nuclear Non-Proliferation Treaty, cooperation could be made a requirement for receiving nuclear-related exports from members of the Nuclear Suppliers Group, as occurred with the Additional Protocol that imposes stricter inspection measures for nuclear energy sites under IAEA purview. As with the Additional Protocol, agreements would have to be negotiated with the recipient countries.

Obtaining agreement to participate in an expanded and more accessible database and a sample archive would take time. At an appropriate time, the proposed database/sample archive program could be made part of the program of the Global Initiative. Incorporating the database into this program would greatly enhance the value of cooperation and provide access for non-nuclear weapons states.

Another motivation is to avoid attracting automatic suspicion by refusing to cooperate, especially if most countries do cooperate. Nevertheless, states may, for a variety of reasons, refuse to cooperate or else place obstacles to implementation in the form of delays, legal and technical objections, providing partial or adulterated samples, etc. Technical cheating via provision of altered samples is often detectable, however. Detecting partial cooperation may prove difficult. Political and legal objections are more likely methods for delaying or preventing implementation.

Refusal to cooperate could stem from existing policies to protect sensitive information relevant to nuclear weapons³⁰ or commercial processes; a reluctance to share that information with particular states; or a desire to retain freedom of action regarding possible transfers of materials to third parties (e.g., in the case of a new or continuing A.Q. Khan network centering on materials rather than technologies). Refusal could also stem from a desire to reduce the danger of retaliation in the event of lost or stolen nuclear materials being intercepted or used in a nuclear device. Legitimate motivations, e.g., existing policies and commercial property

rights, can provide a cover for non-legitimate motivations. If this proposal is adopted, a major task will be for the most willing and important states to devise suitable protection for both national security and commercial information. The IAEA has experience on the commercial side, and technical means exist that can provide the desired protection.

In all, international cooperation in nuclear forensics could have a salutary effect, reminding the participants how important it is to secure nuclear materials and of the potential consequences if they don't, as well as producing useful forensics information.

Attempts to Spoof

States or terrorist organizations, for reasons that might range from protecting secrets to preventing attribution, may attempt to spoof any later investigation by mixing materials from different sources. It is difficult to make a general statement about the ease of spoofing and the ease of detecting spoofing. Some kinds of spoofing are likely to fail. For example, North Korea attempted to mix plutonium from different reprocessing campaigns and subsequently detected by international inspectors.³¹ Mixing of weapons materials with different impurities is likely to be assessed as originating from different sources. Mixing of uranium from ore with uranium from reactors will show up as uranium with a different history from the original. Depending on the type of investigation and the particular way in which nuclear forensics

fits into the general investigation, these and other spoofing attempts may or may not mislead analysts. More likely, they will result in lessening the utility of forensics to the overall investigation and possibly delaying attribution. It should be noted that any sample contributed to the database that has been deliberately altered in an attempt to spoof will itself provide clues about the originating state's capabilities and intent. In addition, because the production of fissile material is challenging, spoofing by including additional nuclear materials likely is expensive and would tend to involve more participants, thereby likely making the program more exposed to detection.

Conclusion

A comprehensive international database and sample archives are needed to take full advantage of nuclear forensics in assisting the attribution process in case of a nuclear detonation of unknown origin or in the case of interdicted nuclear materials. The more comprehensive the samples and analyses, and the more processes for ascribing samples to their sources are internationally understood and vetted, the better the database will be able to assist in attribution and do so as quickly as will be necessary. While there will be objections to establishing such a database, these can be met technically. Getting political consensus will require careful negotiations and leadership, particularly from the nuclear weapon states.³²

Exercises

Exercises to Improve Coordination among Responsible Agencies

As the awareness of the possibility of major terrorist acts grew after the initial World Trade Center bombing in 1993 and the African Embassy attacks in 1998, the U.S. government began to plan and execute a series of exercises to test the ability to respond to and recover from acts of large-scale terrorism. Generically known as TOPOFF Exercises (for TOP OFFICIALS), these exercises concentrated on issues of authority establishment; coordination among federal, state, and local governments; resource delivery; and consequence management. They were in part stimulated by event cases developed by DTRA for nuclear, biological, and chemical attacks within representative U.S. cities. The overwhelming emphasis was on minimizing casualties and providing accurate and actionable information to both first responders and affected citizens. Questions of forensics at first played a minor role if any: the focus of this series of exercises was to learn what obstacles existed to dealing promptly with the crisis.

Nuclear forensic analysis on foreign intercepts of sub-weapon quantity nuclear materials, as practiced to date, and nuclear forensic analysis as it would have to be practiced after a nuclear detonation or the intercept of a nuclear weapon or even a weapon-like quantity of nuclear material, call for very different types of exercises. Examples of the first are practiced regularly as a result of customs and police activities. The procedures and results, together with any conflicting interpretation of the forensics, need to be documented and analyzed both for their technical and operational implications. In the past, there have been lacunae in both procedures and results: the chain of custody for the evidence has not always been maintained and conflicting interpretations have not always been resolved. A review of procedures and results to date would be useful. It may also be useful to challenge the system occasionally with prepared unknowns. The present practice of classifying or holding in confidence the results of nuclear material intercepts should also be reviewed with the goal of finding a policy that would take advantage of the value of advertising successful instances of nuclear forensics and attribution.

The detonation of a nuclear weapon of significant yield in a city would be a world-changing event. Even the intercept of a nuclear weapon or a weapon-like quantity of nuclear material would be considered an emergency situation, albeit one not nearly so catastrophic. Exercises to develop and practice the skills and relationships needed for rapid production and sharing of critical information across the multiple agency and organizational boundaries involved in

the event are critical. The subsequent creation of timely technical information for a possible attribution decision, for public health and emergency response measures, and to maintain continued confidence in the government at all levels will require unprecedented coordination, cooperation, and understanding. The desire for access to the incident scene by multiple organizations with different agendas such as life saving, crime scene preservation and evidence collection, infrastructure recovery, and economic restoration may create conflicts and delays. The need for access to sensor and diagnostic information obtained by national technical means poses very different problems of access and authority, though it would usually be played out at a venue remote from the event. Finally, the preparation and shipping of samples for off-site analysis while maintaining chain-of-custody, the subsequent analysis of the materials, and the synthesis of data all pose novel problems under the emergency conditions that would be created by a nuclear detonation.

Dealing with the aggregate set of conflicting authorities, institutional needs or desires, personal or institutional political vulnerabilities, and the need to communicate accurately and effectively to the media and the public requires development of special sets of organizational and institutional skills. These skills are acquired only through practice against a wide variety of cases. The events practiced are almost never the ones that actually occur, but such practice builds a toolkit that is more adequate for the real event.

It is useful to draw a distinction between two types of exercises. The first are technical exercises in which the full gamut of sample acquisition and recovery, field and laboratory technical analysis, interpretation and synthesis, and integration with intelligence and conventional forensic data is carried out. The second are step exercises for very senior officials. Technical exercises test the operational capabilities of the program, identify its research needs and opportunities, and allow assessment of its decision-making processes. The players are the operational, technical, and analytical staff resident in the program, wherever they may sit in the government. Such an exercise may run for a week at 18 to 24 hours per day depending on staffing levels and should be coordinated with exercises to test and improve the coordination among federal, state, and local agencies responsible, such as the TOPOFF exercises.

Multiple agencies have had a role in the TOPOFF exercises to date. They have involved the Department of Justice (DOJ)/FBI, the Department of Health and Human Services (DHHS), the DOD, the DOE, and the DHS, along with appropriate regional, state, and local players, as the specific scenario requires. For the explicit post-detonation case, exercises have been created and run by a combination of the DOD, DOE, DOJ/FBI, and intelligence agencies. Robust multiple-day exercises have been run against the clock, including sample recovery and analysis, data generation and synthesis, comparison to databases, and all-agency summary conclusions. There is a classified 2007 National Technical Nuclear Forensics Presidential Decision Document that may establish clear responsibility for the creation and support of exercises.

Exercises to Improve Understanding of Dilemmas Faced by Top Decision Makers

The TOPOFF exercises cannot simulate the chaotic environment that may prevail among both public and government authorities. These exercises primarily stress the technical component of the problem. There is a need for a second kind of exercise, exercises at high levels in government that stress the integration of information, decision-making, and communication to the public for which only the highest level of the government is responsible. Recommendations regarding public health, foreign policy, or military action can only come from this level. These personnel must have a clear understanding of their responsibilities and authorities and of the timelines of such events. Silence or misunderstanding at this level or a cacophony of conflicting statements from various authority figures that are ungrounded in fact could make an already dire situation far worse. The Three Mile Island crisis was an example of such confused communication under far milder conditions. The poor federal communications and decision-making that followed the anthrax letter events are also a good example. Many of the errors in that event (e.g., communication of inaccurate medical information by a cabinet member, multiple and varying interpretations of CDC therapeutic recommendations by treating physicians, etc.) had been identified in previous exercises, but the lessons learned were not carried across the boundary of a change of administration.

From the record of TOPOFF and similar exercises, it is possible to create a group of exercises of this second kind, which are often referred to as step games. Focused on training political appointees and policy advisors, the results of the exercise are time-stepped, presenting information as it becomes available at the end of 12 to 24 hour increments. Such games test authority, resources management, communications, and decision making at the level above the technical, providing senior governmental officials training in expectations management, their responsibilities, and the sorts of decisions they will be expected to make or participate in on short time scales. To date, these have mostly focused on response activities such as consequence management, not forensics and attribution and the policy decisions that would follow. These should be included.

High-level exercises are essential to manage expectations, including the expectations of decision-makers. Exercises should be preceded or accompanied by suitable briefings to the senior personnel involved. Staff at policy decision-making levels will develop an understanding of what the technical, law enforcement, and intelligence communities supporting them can actually deliver and on what schedule such delivery is possible. Policies will need to be developed and tested for dealing with the inevitable pressure for rapid action. Assuring that no additional events occur will have the highest priority and may require cooperation, voluntary or forced, with states suspected of assisting or neglecting terrorist threats. Confrontation by either political or military means may follow, but only after confidence that additional events will not occur is established and attribution information is believed reliable. Exercises beginning with simple cases and building to hard ones are particularly useful in this regard.

There is a strong precedent for the institutionalization of technical and policy assessment to serve decision makers. During much of the Cold War, there was a standing non-governmental expert panel (the Bethe Panel) that served to integrate and synthesize technical data from foreign nuclear tests and then participate in the policy forming decisions made in response to them. The recreation of such a panel and institutionalization of it across administrations, if not generations, would be prudent. Institutionalized panels with formal procedures are in use at the National Transportation

Safety Board for transportation accident investigations and at the Centers for Disease Control and Prevention for devising responses to pandemic events. Those models are worthy of study for application to the nuclear forensics problem.

Making Best Use of Exercises

Among the most successful exercises that the government carries out are formal military war games. Given the importance of the threat of nuclear terrorism to the country, an equivalent investment in resources and rigor is appropriate for this case. War games in particular use a “White Cell” of experienced leaders who are given a complete overview of the situation to be played out and who may be allowed to intervene to change the play as it develops. To make best use of exercises calls for a permanent organization tasked to observe the exercise and to perform a formal evaluation of:

- Technical performance and shortfalls – How did the players perform?
- Concept of operation shortfalls – Are the doctrine and plan adequate?
- Research and development needed – Can instrumentation or other tools be improved?
- Technical accuracy – Did the inferred summary match the test case?
- Quality of coordination – Were authority and handoffs clear and accepted?
- Quality of integration and communication – Were summary assessments accurate and communicated accurately? Was needed associated information developed?
- Near misses or false leads – Did the players go down a wrong path or nearly do so?
- Other observations of importance – Were the quality of planning for the exercise, personnel training, and resources all adequate?

Conclusions

This chapter leads us to the following conclusions:

1. Exercising all involved agencies and laboratories as well as involved state and local institutions in nuclear detonation scenarios in the United States and abroad is essential if the full benefit of nuclear forensics and nuclear attribution efforts are to be realized.

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2. Because a number of key decisions, involving immediate actions in response to the detonation, public information policies, agency coordination, and international relations, will have to be taken by decision makers at the top of the federal government, they or some very senior representatives should be involved in suitable parts of the exercises.
 3. Senior decision-makers and others involved should be made aware of the time scales required to obtain forensic results and of the need to manage expectations in the wake of a nuclear event.
 4. The results of the exercises should be evaluated and incorporated into operating policy in a way similar to the practice of the armed forces in war games.
 5. Using the forensics applied to interdicted materials would help to train and improve the capabilities that would be needed for post-detonation forensics. In particular, running interdicted forensics against the clock and including speed as one of the measures of success of interdicted forensics would be invaluable in developing better post-detonation forensics. Even without accelerating the forensics/attribution work for interdicted material, it would be good to formally include an assessment of the choke points that slowed down the post-interdiction activity and identify what would be needed to accelerate the forensics process.
 6. A permanent organization should be established and involved in sequential exercises, so that it is possible for people to preserve and enact the lessons learned, rather than relying on archived information. Given the average rotation of cabinet and sub-cabinet officers, formal training for this unexpected responsibility is an important portion of their readiness to serve. Presidential appointees need to be made aware of and prepared for eventualities that are not obvious in their titles.
 7. An expert panel similar to the Bethe Panel of the Cold War should be re-established in order to provide an ongoing evaluation of what nuclear forensics, in conjunction with other techniques for attribution, is telling decision makers and, equally important, what is not yet known or not yet certain. The growing community of exercise supervisors could feed the re-established expert panel and provide a credible cadre of high-level people with operational and technical expertise, supporting ongoing education at high level.

The effectiveness of the exercises will be measured in the end by the level of those participating inside the U.S. government. We believe that institutionalizing exercises at senior levels in the government at the level of detail and resources comparable to DOD war gaming will prepare for both technical and policy success.

Appendix A: Biographies of the Working Group Members

Michael May is professor emeritus (research) in the Stanford University School of Engineering and a Senior Fellow with the Center for International Security and Cooperation of the Freeman-Spogli Institute for International Studies at Stanford. He is director emeritus of the Lawrence Livermore National Laboratory (LLNL). He served as a U.S. delegate to SALT 2 and on a variety of defense and energy government advisory bodies. He has received the Distinguished Public Service and Distinguished Civilian Service Medals from the Department of Defense and the Ernest Orlando Lawrence Award from the Atomic Energy Commission. He is a member of the Council on Foreign Relations and the Pacific Council on International Policy, and a Fellow of the American Physical Society (APS) and the American Association for the Advancement of Science (AAAS). His current work is on nuclear security and energy issues.

Reza Abedin-Zadeh retired from the IAEA, after 30 years of service in several senior management positions in the Department of Safeguards, in 2005. He graduated with a doctorate in nuclear physics from the University of Graz, Austria, in 1970. He had academic positions at the University of Graz and University of Tehran, Iran. At present, he is a consultant to IAEA, working in the Office of Nuclear Security in the Department of Nuclear Safety and Security. To date, he has published over 200 articles covering a wide array of issues in the fields of radiological safety, safeguards verifications, nuclear security, and the non-destructive assay of nuclear and other radioactive material.

Donald Barr joined Los Alamos National Laboratory (LANL) in 1957 after earning a doctorate in nuclear chemistry from the University of California, Berkeley. Barr served as a staff member, associate group leader, and deputy group leader of the Nuclear Chemistry Group at LANL. He later served at associate division leader and division leader of Isotope and Nuclear Chemistry, retiring from the laboratory in 1990. His research interests focused on nuclear and radiochemistry, the physics and chemistry of nuclear explosives, nuclear weapons test diagnostics, and nuclear cross sections. Barr received a National Science Foundation Fellowship in 1955, and in October 1980 was honored with the Ernest Orlando Lawrence Award for his “innovative and incisive diagnostic

methods, which assist weapons designers in understanding and interpreting different aspects of their work and lead to improved designs.”

Albert Carnesale is chancellor emeritus of the University of California, Los Angeles (UCLA), and holds professorial appointments in the School of Public Affairs and in the Henry Samueli School of Engineering and Applied Science. Carnesale’s research and teaching focus on international affairs and security, with emphasis on technological, military, and political issues associated with weapons of mass destruction. He is the author or co-author of six books and more than 100 articles. He served as chancellor of UCLA from 1997 to 2006. Prior to that, he was at Harvard University for 23 years, where he held the Lucius N. Littauer Professorship in Public Policy and Administration, and served as dean of the John F. Kennedy School of Government and as provost of the university. He holds a Ph.D. in nuclear engineering, has served in industry and government, and is a Fellow of the American Academy of Arts and Sciences and a member of the Council on Foreign Relations.

Philip E. Coyle is a senior advisor to the World Security Institute, a Washington D.C.-based national security study center. He is a recognized expert on United States and worldwide military research, development, and testing; operational military matters; and national security policy and defense spending. From September 29, 1994, through January 20, 2001, Coyle was assistant secretary of defense and director, operational test and evaluation, in the Department of Defense. In this capacity, he was the principal advisor to the secretary of defense on test and evaluation in the DOD. From 1959 to 1979, and again from 1981 to 1993, Coyle worked at LLNL. From 1987 to 1993, he served as laboratory associate director and deputy to the laboratory director. During the Carter administration, Coyle served as principal deputy assistant secretary for defense programs in the Department of Energy.

Jay Davis is a nuclear physicist retired from LLNL. His research career consisted of designing and building accelerators for applications in materials science, the biosciences and medicine, environmental research and national security. Davis was the founding director of the Center for Accelerator

Mass Spectrometry. In national security areas, he served in the NEST program, was an UNSCOM inspector in Iraq after the first Gulf War, and was founding director of the Defense Threat Reduction Agency. His undergraduate education was at the University of Texas and his graduate training in fast neutron physics was at the University of Wisconsin. A Fellow of the APS, he is a member of the National Academy of Sciences Board on Army Science and Technology and the Nuclear and Radiation Science Board. He serves on DOD's Threat Reduction Advisory Committee and is a member of the Board of Directors of the Hertz Foundation.

William Dorland received his Ph.D. in plasma physics from Princeton University, and his master's in public affairs from Princeton University's Woodrow Wilson School in 1993. He is currently an associate professor of physics at the University of Maryland, and director of the Maryland Center for Multiscale Plasma Dynamics. He has joint appointments with the Center for Scientific Computation and Mathematical Modeling and the Institute for Research in Electronics and Applied Physics. His research is focused on understanding turbulence in thermonuclear conditions and in a variety of astrophysical systems. He is a Fellow of the APS and a member of its Panel on Public Affairs, and past chair of the APS Committee on the International Freedom of Scientists.

William Dunlop received his Ph.D. in nuclear physics from the University of California, Los Angeles, in 1971. During his career at LLNL, he worked in the nuclear weapons program in numerous roles including project manager for strategic missile, defensive weapons systems, program manager for the development of the W87 warhead, program manager for earth penetrator weapons, and division leader overseeing work on thermonuclear weapons development. He led the LLNL nonproliferation and arms control program from 1990 until 2004. Dunlop was on the U.S. delegation to the Conference on Disarmament in Geneva in 1979 and in 1988 and 1989 was a member of the U.S. delegation to the Nuclear Testing Talks. From January 1994 until December 1995, he served as the technical advisor to the U.S. ambassador for negotiations on the Comprehensive Test Ban Treaty. Dunlop retired from LLNL in 2004, but continues to work part time on projects related to maritime security and nuclear forensics.

Steve Fetter is dean of the School of Public Policy at the University of Maryland, where he has been a professor since 1988. His research interests include nuclear arms control and nonproliferation, climate change, and energy policy. He is a member of the Council on Foreign Relations, a Fellow of the APS, and has served on several committees of the National Academy of Sciences. He has held positions in the Department of Defense and the Department of State, served as an advisor to many nongovernmental organizations, and has been a visiting Fellow at Stanford University, Harvard University, and the Massachusetts Institute of Technology. He has given more than 100 invited lectures and has published over 30 journal articles, over 20 chapters in edited volumes, and several books and monographs. Fetter received a Ph.D. in energy and resources from the University of California, Berkeley, and a S.B. in physics from MIT.

Alexander Glaser is on the research staff of the Program on Science and Global Security at Princeton University. Since 2006, he also works with the International Panel on Fissile Materials (IPFM). Glaser received his Ph.D. in physics in 2005 from Darmstadt University of Technology, Germany. Between 2001 and 2003, he was an SSRC/MacArthur Fellow with the Security Studies Program at the Massachusetts Institute of Technology and, in 2000 and 2001, an adviser to the German Federal Ministry of Environment and Reactor Safety. Glaser is associate editor of *Science & Global Security*.

Ian D. Hutcheon is the deputy director of the Glenn T. Seaborg Institute and associate program leader for technical nuclear forensics and scientific capability leader for chemical and isotopic signatures in the Chemical, Materials, Earth and Life Sciences Directorate at LLNL. He received a Ph.D. in physics from the University of California, Berkeley, in 1975. He spent seven years in the Enrico Fermi Institute at the University of Chicago and then was senior research associate in the Division of Geological and Planetary Science at the California Institute of Technology, until joining LLNL in 1994. His current activities focus on nuclear and biological forensics, international safeguards, and the development and application of advanced microanalytical techniques. He has authored over 130 publications in peer-reviewed journals in the areas of secondary-ion mass spectrometry, nuclear forensic analysis, and the early history of the solar system. He is a Fellow of the Meteoritical Society.

Francis Slakey received his Ph.D. in physics in 1992 from the University of Illinois, Urbana-Champaign. He is the associate director of Public Affairs for the APS where he oversees all APS legislative activities. He is also the Upjohn Professor of Science and Public Policy and the co-director of the Program on Science in the Public Interest at Georgetown University. His technical publications have received more than 500 citations. He has also written widely on science policy issues, publishing more than 50 articles for the popular press including *The New York Times*, *Washington Post*, and *Scientific American*. He has served in advisory positions for a diverse set of organizations, including the National Geographic, the Council on Foreign Relations, *Reviews of Policy Research*, and the Creative Coalition. He is a Fellow of the APS, a MacArthur Scholar, and a Lemelson Research Associate of the Smithsonian Institution.

Benn Tannenbaum received his Ph.D. in experimental particle physics from the University of New Mexico in 1997. He is currently associate program director of the Center for Science, Technology and Security Policy at the AAAS, focusing on connecting scientists with government on security matters. He has testified before the U.S. House of Representatives Committee on Homeland Security about radiation portal monitors. He serves on the APS's Panel on Public Affairs and on the board of directors of *The Triple Helix*. He served as the 2002–03 APS Congressional Science Fellow. During his fellowship, Dr. Tannenbaum worked for Representative Edward J. Markey (D-MA) on nonproliferation issues. He has authored or co-authored over 160 scientific and policy-related publications.

Appendix B: Meeting Agendas

AAAS/APS Panel on Nuclear Forensics: Meeting 1 Agenda Stanford University, Palo Alto, CA

DAY 1: July 18, 2007

8:30 – Breakfast/Introductions

9:00 – Review of Study: scope and timetable; Q&A (*May, et al.*)

9:30 – Discussion of the Department of Homeland Security's (DHS) and Domestic Nuclear Detection Office's (DNDO) missions and programs and perspective on the nuclear attribution. (*Daitch, DNDO*)

10:30 – Discussion of the Department of Defense's (DOD) and the Defense Threat Reduction Agency's (DTRA) missions. Review of how nuclear forensics fits into the overall nuclear attribution task. (*Evenson, DTRA*)

11:15 – Department of Energy's (DOE) and National Nuclear Security Administration's (NNSA) missions, programs, and perspective (*Harvey, NNSA*)

1:00 – The outlook for international cooperation against nuclear terrorism (*Grant & Curry, State; Abedin-Zadeh, IAEA*)

2:00 – Discussion of presentations: What is the government decision-making process?

3:00 – Technical overview: workforce issues (*Niemeyer, LLNL*)

3:30 – Discussion of present state of the art and of where it could go next. (*Hutcheon, Barr & Dunlop, LLNL*)

4:30 – Wrap up/closing comments

DAY 2: July 19, 2007

Executive session

AAAS/APS Panel on Nuclear Forensics: Meeting 2 Agenda American Association for the Advancement of Science, Washington, D.C.

DAY 1: November 15, 2007

8:30 – Breakfast/introductions

9:00 – Briefing I: “Models for Managing Info: ‘Bethe Group,’ National Transportation Safety Board” (*Hagengruber, LANL*)

10:15 – Discussion: Conclusions of paper

11:30 – Report overview (*May*)

12:00 – Lunch discussion with administration representatives

1:00 – Presentation of draft study (*May*)

1:45 – Congressional Q&A session

3:00 – NGO/independent experts Q&A session

4:00 – Wrap up/closing comments

DAY 2: November 16, 2007

9:00 – Briefing II: “Plutonium Isotopes, Uranium Isotopes, and Post-explosion Analysis” (*Glaser, Princeton*)

10:00 – Executive session

3:00 – Adjourn

Appendix C: Abbreviations and Acronyms

AAAS	American Association for the Advancement of Science	IAEA	International Atomic Energy Agency
APS	American Physical Society	LANL	Los Alamos National Laboratory
DOD	Department of Defense	LLNL	Lawrence Livermore National Laboratory
DOE	Department of Energy	NNSA	National Nuclear Security Administration
DOS	Department of State	NPT	Treaty on the Nonproliferation of Nuclear Weapons
DHS	Department of Homeland Security	POPA	Panel on Public Affairs (APS)
DTRA	Defense Threat Reduction Agency	SNM	Special Nuclear Material
		WMD	Weapons of Mass Destruction

Appendix D: Roles of U.S. Government and the IAEA

Roles and Capabilities of the United States Government

The United States' technical abilities in nuclear forensics are, in many ways, an outgrowth of nuclear weapons testing and material quality assurance and quality control programs. Because of this, many of the specific technical and analysis capabilities are based in the Department of Energy's (DOE) lab system. In addition, many other parts of the U.S. government play important roles. We examine each in turn.

The *Department of Homeland Security (DHS)*, through the National Technical Nuclear Forensics Center (NTNFC), is responsible for providing overall program planning.³³ It works with the Department of Energy to develop and sustain pre-detonation plans and technical capabilities, as well as to support research and development of new and improved capabilities. DHS is also responsible for conducting assessments, gap analyses, and exercises for the entire nuclear forensics effort. Finally, DHS works to ensure the development of standards for nuclear forensics.

The DHS's Domestic Nuclear Detection Office (DNDO) was created in April of 2005 to "provide a single accountable organization with dedicated responsibilities to develop the global nuclear detection architecture, and acquire, and support the deployment of the domestic detection system to detect and report attempts to import or transport a nuclear device or fissile or radiological material intended for illicit use."³⁴ As part of this effort, DNDO created the NTNFC in October 2006 to oversee and coordinate the efforts of the various partners in nuclear forensics. The NTNFC provides no technical expertise itself, but instead plays a coordinating role to ensure that the

seven agencies – the Departments of Transportation, Energy, State, and Defense, and the Nuclear Regulatory Commission, the FBI, and the Office of the Director of National Intelligence – that work on nuclear forensics function as smoothly as possible. To that end, there are only a few DNDO staff working at the NTNFC; the rest of the personnel are detailed from the participating agencies.

The *Federal Bureau of Investigations (FBI)* is the lead agency for investigating acts of terrorism in the United States and against U.S. assets abroad. It conducts and directs all aspects of nuclear and radiological forensics and can perform traditional forensics on contaminated conventional evidence. The primary participants are from the FBI Weapons of Mass Destruction Directorate and the Chem-Bio Sciences Unit (CBSU) and the Hazardous Materials Response Unit (HRMU) of the FBI Laboratory.

The *Department of Defense (DOD)* provides the capability to collect and analyze post-detonation debris. DOD maintains a variety of technologies to collect samples, including aircraft and remotely controlled robots. Further, DOD is responsible for developing and sustaining "CONOPS," or the concept of operations, for post-detonation forensics work. In addition, the DOD conducts research to improve technical and operational capabilities. Engaged components of DOD include the Defense Threat Reduction Agency [DTRA], the Air Force Technical Applications Center, the Office of the Assistant to the Secretary of Defense for Nuclear, Chemical and Biological Defense Programs (OATSD [NCB]), the Office of the Assistant Secretary of Defense for Homeland Defense, and several of the combatant commands.

The *Department of Energy* (DOE) is responsible for providing the capability to collect and analyze pre-detonation materials (both complete devices and components). DOE also supports “prompt diagnostics” at the time of detonation and short turn-around analyses. Like the DOD, the DOE conducts research to improve nuclear forensics capabilities. Participants from the DOE include the National Nuclear Security Administration, DOE Intelligence, the Deputy Undersecretary for Counterterrorism, and nuclear weapons designers, modelers, materials experts, and radio chemists at the DOE national labs.

The *Department of State* is the lead agency for international nuclear incidents and manages the Global Initiative to Combat Nuclear Terrorism.

Finally, the *intelligence community*, including the CIA, has the responsibility to contribute intelligence information to better understand the origins and pathways involved in a nuclear incident.

In addition to the support provided by DOE, several DOE labs also play critical roles in nuclear forensics. Along with police and fire departments, and public health personnel, DTRA teams, which include experts from these laboratories, would be among the first responders following a nuclear incident. The teams carry sensitive instruments for on-scene analysis, and have prompt access to well-equipped laboratories for extended radiochemical analysis. Through the Nevada Operations Office, the Department of Energy manages Joint Terrorism Operations Teams (JTOT), which include experts from these laboratories. Those teams would search for additional nuclear explosive devices.

The *Lawrence Livermore National Laboratory* (LLNL) provides scientists to perform “the chemical, isotopic, and morphological analysis of interdicted illicit nuclear or radioactive materials.”³⁵ LLNL is one of two FBI hub laboratories (the other is Savannah River National Laboratory) with accredited receipt laboratories and protocols for the analysis of nuclear and radiological materials. In addition, working with NNSA’s Office of Non-proliferation and International Security and DHS’s Domestic Nuclear Detection Office, LLNL scientists have made agreements with Tajikistan, Kyrgyzstan, and Kazakhstan to obtain and analyze isotopic and trace-element content, grain size, and microstructure of uranium produced in those nations; they intend to work with additional countries. The lab also supports the Nuclear Smuggling International Technical Working Group and is

working with the International Atomic Energy Agency (IAEA) to promote nuclear forensics.

Los Alamos National Laboratory (LANL) scientists have “studied possible designs for terrorist devices and calculated the systematics of radiochemical diagnostics for such devices.”³⁶ The Chemistry Division provides analysis for forensics, and others at the lab have studied ways to attribute the source of spent fuel in dirty bombs.

The *New Brunswick Laboratory* (NBL) serves as a repository of information about nuclear material. In particular, it “provides federal expertise for the tracking of strategic nuclear material subject to special control and accounting procedures, analysis and validation of nuclear material inventory data, nuclear certified reference materials, and measurement evaluation assessment and assistance for nuclear materials; provides technical, federal nuclear materials experts for interagency and nonproliferation activities.”³⁷

Savannah River National Laboratory (SRNL) is one of two FBI hub laboratories with accredited receipt laboratories and protocols for the analysis of nuclear and radiological materials. The Radiological Evidence Examination Facility at SRNL has specialized capabilities (hot cells) for working with highly radioactive samples. SRNL also has extensive experience with uranium and plutonium fuel reprocessing.

Oak Ridge National Laboratory (ORNL) runs a chemical and isotopic mass spectrometry group to use “ultra-trace analysis [as] applied to nuclear safeguards/nonproliferation and develop and applies advanced mass spectrometry to forensics and attribution.”³⁸

The *Idaho National Laboratory* (INL) has scientists working on identifying radioactive source histories based on trace elements. Together with Argonne National Laboratory, INL is a leader in the development of databases for nuclear and radiological materials and sources.³⁹

Sandia National Laboratories (SNL) is applying computer codes to “enable forensic analysis of post-explosion radionuclide debris.”⁴⁰

Pacific Northwest National Labs’ Radiation Detection and Analysis Laboratories work closely with the Air Force’s Technical Application Center on radiation sensors, radiochemistry, simulation and modeling of scenarios, data analysis, and instrument development.⁴¹

To avoid bureaucratic delay and confusion, these various agency roles need to be well understood and exercised regularly. The Congressionally mandated “TOPOFF” (Top

Officials) exercises have been valuable in this regard. TOPOFF exercises are “national-level, multi-agency, multi-jurisdictional, “real-time”, limited-notice WMD response exercises, designed to better prepare senior government officials to effectively respond to an actual terrorist attack involving WMD. In addition, TOPOFF involves law enforcement, emergency management first responders, and other non-governmental officials.”

Roles and Capabilities of the IAEA

The International Atomic Energy Agency (IAEA) is a major contributor and coordinator in the area of nuclear security worldwide. Based on the established international legal instruments and obligation contained in the safeguards agreements, the Convention on Physical Protection of Nuclear Material (CPPNM) and its Amendment, the International Convention for the Suppression of Acts of Nuclear Terrorism, and the relevant UN Security Council resolutions, the IAEA has established a comprehensive safeguards program and has enhanced nuclear security worldwide through assistance to member states.

Within the framework of the safeguards activities, the IAEA seeks to determine whether there are any indications of the diversion of nuclear material to non-peaceful purposes or of undeclared nuclear material or activities in the state. Within the nuclear security program, the IAEA assists national efforts to identify needs through evaluation missions; develops and disseminate guidelines and recommendations; provides capacity-building activities with international, regional, and national training courses; and the provision of physical protection, detection, and response equipment as well as assisting in removing or reducing the inventory of high-risk material such as highly-enriched uranium.

Taking into account the fact that the threat of nuclear terrorism remains undiminished, the IAEA remains the main organization for implementing and enhancing international nuclear security measures and plays a vital role in assisting member states to establish effective nuclear security regime based on prevention, detection, and response to nuclear terrorism threats.

In response to several resolutions by its General Conference, the IAEA has adopted an integrated approach to protection against nuclear terrorism. The IAEA maintains an outreach program for ensuring the universal adherence and political commitments by states to the relevant, legally binding, and non-binding international instruments and to achieve effective protection, control, and accountancy of nuclear material. The IAEA assists states in improving the physical protection of facilities and locations with nuclear material.

Related to the application of nuclear forensics, the IAEA has published within the IAEA nuclear security series a document on nuclear forensics support⁴² and has been promoting the worldwide application of nuclear forensics for identification of the origin, intended use, and route of transfer of seized nuclear and other radioactive material. The activities have been endorsed by IAEA General Conference resolutions in 2004, 2005, and 2006. The developed scheme enables all member states to receive nuclear forensics support for analysis and interpretation in forensics laboratories in a few advanced member states. It encourages international cooperation and transparency among the member states.

In order to promote research and development and foster international cooperation in the field of nuclear forensics, the IAEA has established a coordinated research project on “application of nuclear forensics in illicit trafficking of nuclear and other radioactive material.” The objective of this coordinated research project is to assist member states in strengthening their capabilities to characterize seized items while preserving forensic evidence and to utilize forensics techniques for nuclear attribution.

The IAEA maintains several databases on nuclear material characteristics at nuclear fuel cycle facilities and on safeguarded nuclear material. It has no information on weapons stockpiles or weapons materials. Currently, the safeguards database is limited to safeguards applications and it does not contain all necessary data for nuclear forensic interpretations. If agreed and requested by member states, the IAEA has the capabilities, with additional resources, to expand the database and establish the required nuclear forensics database for all safeguarded nuclear material. However, this would require a newly negotiated agreement between the IAEA and each of the participating states.

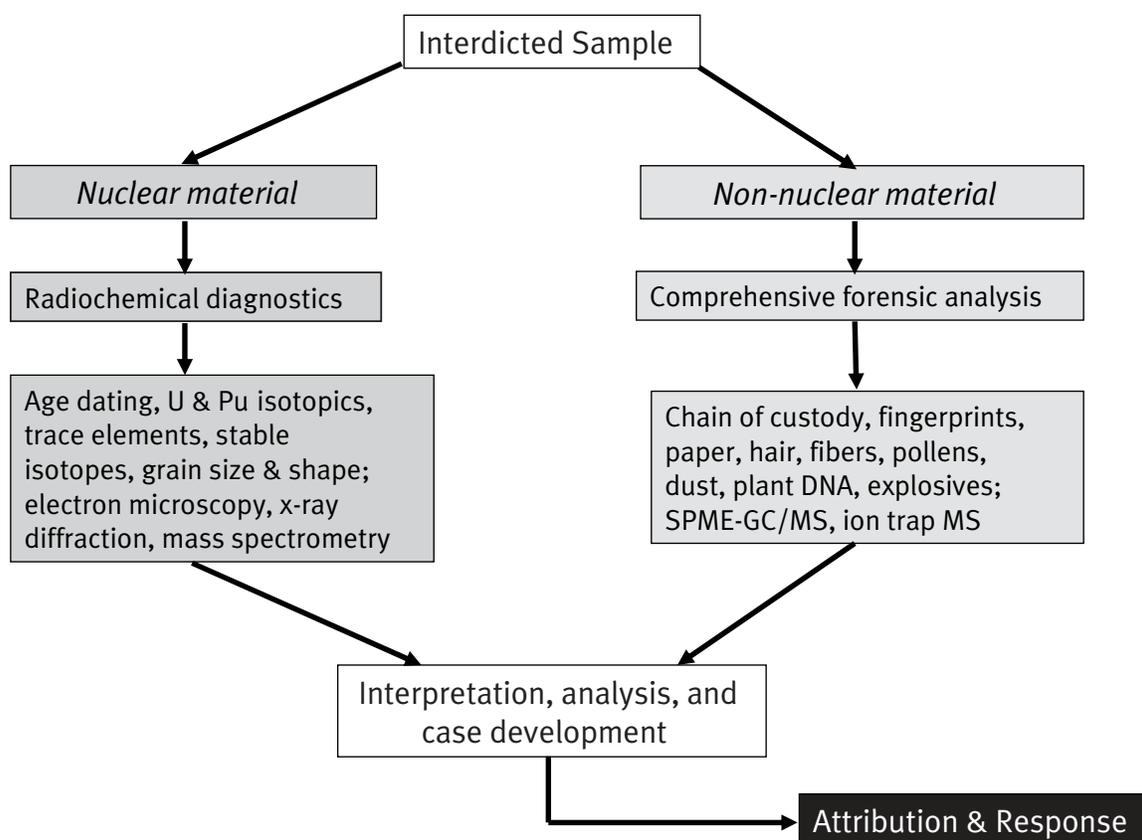
Appendix E: Signatures, Techniques, and Instrumentation

Model Action Plan and Sequencing Techniques

Basic characterization is the starting point for developing an analytical plan for both radioactive and non-radioactive samples associated with either an interdiction or following a nuclear incident. In general terms, nuclear forensic investigations follow the model action plan (MAP) originally developed by the International Technical Working Group

(ITWG) and now adopted by the IAEA; the basic structure of the MAP is shown in Fig. E.1. The MAP is designed to enable a nuclear forensic investigation to analyze all the radioactive and traditional, non-nuclear forensic evidence, in order to attribute the nuclear material, including its origin, method of production, the likelihood that more material exists, transit route, and the means and point at which legitimate control was lost.

Figure E.1: Model action plan for nuclear forensic analysis



The international nuclear forensics community has reached a general consensus on the proper sequencing of techniques to provide the most valuable information as early as possible in the attribution process. Table E.1 shows the generally

accepted sequence of analysis, broken down into techniques that should be performed within 24 hours, one week, or one month. These timelines are provided only for guidance and should not be taken as a reflection of U.S. policy.

Table E.1: Timeline for a nuclear forensic investigation of intercepted material

TECHNIQUES/METHODS	24 HOURS	1 WEEK	1 MONTH
Radiological	Estimated total activity Dose Rate (alpha, gamma, n) Surface Contamination		
Physical characterization	Visual Inspection Radiography Photography Weight Dimension Optical Microscopy Density	SEM (EDS) XRD Organics	TEM (EDS)
Traditional forensic analysis	Fingerprints, Fibers		
Isotope analysis	alpha-spectroscopy gamma-spectroscopy	Mass spectrometry (SIMS, TIMS, ICPMS)	Radiochemical separations mass spec. for trace impurities: Pb Stable isotopes
Elemental/chemical		ICP-MS XRF ICP-OES	GC/MS

Key to abbreviations:

SEM: scanning electron microscopy; TEM: transmission electron microscopy; EDS: energy dispersive x-ray spectrometry; XRD: x-ray diffraction; SIMS: secondary ion mass spectrometry; TIMS: thermal ionization mass spectrometry; ICPMS: inductively coupled, plasma source mass spectrometry; XRF: x-ray fluorescence; GC/MS: gas chromatography mass spectrometry; ICP-OES: inductively coupled plasma source optical emission spectroscopy

Tools for Sample Characterization

The nuclear forensic scientist has a wide array of analytical tools to use for detecting signatures in radioactive material. Appendix II of *Nuclear Forensics Support* provides a listing and description of many of the techniques used in nuclear forensics. These individual techniques can be sorted into two broad categories: bulk analysis 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, when the amount of material available for analysis is limited or concentrations of trace impurity or radioactive decay products (e.g., ^{230}Th) are very low, bulk analysis provides the best approach to obtain precise and accurate data on sample composition and age. The presence and concentration of trace constituents are often vitally important as signatures for manufacturing processes, for determining the time since the material was last chemically processed and whether the material has been exposed to a neutron flux.

Because bulk analysis provides an integrated compositional measurement of the sample as a whole, if the material is inhomogeneous, bulk analysis alone may obscure important signatures localized in individual components. Imaging tools should be used to produce magnified images or maps of the material confirm sample homogeneity or heterogeneity. Imaging can reveal spatial and textural heterogeneities vital to fully characterize a sample.

If imaging indicates that the sample is heterogeneous, then microanalysis tools can quantitatively or semi-quantitatively characterize the individual constituents of the bulk material. The category of microanalysis tools also includes surface analysis tools, which can detect trace surface contaminants or measure the composition of thin layers or coatings, which could be important for attribution.

Materials Signatures

Signatures can be divided into two categories: (1) empirical signatures discovered through the systematic analysis of nuclear and radiological materials and (2) predictive signatures developed from modeling, based on the chemistry and

physics of the nuclear fuel cycle and weapons manufacture.

Physical characteristics include the texture, size, and shape of solid objects and the particle size distribution of unconsolidated materials. For example, the dimensions of a nuclear fuel pellet are often unique to a given reactor type. 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 specific manufacturing processes.

Chemical characteristics include the chemical composition of the material or the association of unique molecular components. For example, uranium oxide is found in many different forms, e.g., UO_2 , U_3O_8 , or UO_3 , each of which occurs under different operating conditions. The association of some organic compounds, such as certain light kerosene oils or tributyl phosphate, with the nuclear material can indicate a reprocessing operation.

Elemental signatures include major, minor, and trace element abundances and, in the case of complex materials, an indication of the scale of chemical heterogeneity. Major elements, of course, define the identity of the nuclear material, but minor elements, such as erbium or gadolinium that serve as burnable poisons in nuclear fuel or gallium that serves as a phase stabilizer for Pu, also help define material function. Trace elements can also prove to be indicative of a process, e.g., iron and chromium residues from stainless steel tooling or calcium, manganese, or chlorine residues from a water-based cleaning process.

Isotopic signatures should be carried out on the major constituents, uranium and plutonium, as well as on fission or neutron-capture products. They can provide indisputable evidence, for instance, about whether the material has been in a nuclear reactor and can serve as a fingerprint of the type and operating conditions of the reactor. The trace (and relatively short-lived) uranium isotopes, ^{232}U , ^{233}U , and ^{236}U , are especially valuable indicators of reactor operations. The decay products from radioactive “parent” isotopes provide valuable information on the age of the material (“age” in this context means the time since the material was last

chemically processed). For example, ^{230}Th is a decay product of ^{234}U and ^{235}U is a decay product of ^{239}Pu . Stable isotopes of elements such as oxygen, strontium, and lead can also provide insight into the locations where nuclear material was fabricated or reprocessed; these isotopes are known as “geolocation” indicators.

Table E.2 lists relevant signatures in a plutonium sample and what those signatures might reveal. Table E.3 does the same for uranium signatures. It may be noted that the uranium signatures are less revealing than the plutonium signatures, although research is ongoing at the laboratories and elsewhere to increase what can be learned from uranium signatures.

Table E.2: Relevant signatures in plutonium

SIGNATURE	INFORMATION REVEALED
In-growth of daughter isotopes (^{241}Am , ^{235}U)	Chemical processing date
Pu isotope ratios	Type of Pu production reactor used: – Enrichment of U in production reactor – Neutron spectrum in production reactor
Residual isotopes	Chemical processing techniques
Concentrations of short-lived fission product progeny	Chemical yield indicators
Kr and Xe isotopic abundances	Casting time

Table E.3: Relevant signatures in uranium

SIGNATURE	INFORMATION REVEALED
Ratio of naturally occurring isotopes (^{234}U , ^{238}U , ^{235}U)	Can point to or exclude some uranium ore sources
Presence of isotopes produced by irradiation (^{232}U , ^{236}U)	Indicates uranium has been reprocessed and may point to type of reactor used
In-growth of daughter isotopes (^{230}Th , ^{231}Pa)	Chemical processing date
Kr and Xe isotopic abundances	Casting time

Chronometry

Because radioactive isotopes decay at a rate determined by the amount of the isotope in a sample and the half-life of the parent isotope, the relative amounts of decay products compared to parent isotopes can be used to determine the “age” of the material (time since the parent isotope was last chemically separated from its decay products). Consider, for example, the “4n+2” chronometric relationships among the heavy-element nuclides, so named because in each case the mass number divided by 4 leaves a remainder of 2; the decay chain is illustrated in Table E.2. The decay network begins with 87.7-y ^{238}Pu and proceeds through the in-growth of long-lived ^{234}U , ^{230}Th , and ^{226}Ra . Subsequent decays by short-lived ^{222}Rn , ^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po result in 22.3-y ^{210}Po . For samples that are more than a few weeks old, the short-lived species are not useful chronometers. If any member of the 4n+2 decay chain is purified, decay processes will immediately begin to produce descendant species; in a purified U sample, the ^{238}Pu concentration is zero and remains zero because ^{238}Pu is a decay precursor of ^{234}U and not vice versa. The time since a sample was last purified can be calculated from the ratio of any two concentrations among the decaying nuclides. An analogous approach works for the entire “4n” series of isotopes (4n, 4n+1, 4n+2, 4n+3).

A sample consisting of mixed U or Pu isotopes provides the opportunity to measure the age of the sample through as many as a dozen different chronometers. Table E.4 lists the radio-chronometers frequently applied to age-date samples containing both uranium and plutonium. If the sample was completely pure at the time of the last separation, all of the chronometers should yield the same age (within measurement uncertainties). In a Pu sample, the $^{232}\text{U}/^{236}\text{Pu}$, $^{234}\text{U}/^{238}\text{Pu}$, $^{235}\text{U}/^{239}\text{Pu}$, and $^{236}\text{U}/^{240}\text{Pu}$ chronometers generally all yield the same age (as they should, since the purification of a Pu sample from one U isotope is as effective as the purification from all of them). When this age matches those determined from $^{241}\text{Am}/^{241}\text{Pu}$ and $^{230}\text{Th}/^{238}\text{Pu}$, it is assumed that the sample was completely purified at the time of separation. However, for U.S. weapons-grade Pu, $^{241}\text{Am}/^{241}\text{Pu}$ often gives a significantly larger value for the age than do the U isotopes. The only reasonable explanation is that when the U isotopes were removed from the Pu for the last time, some Am was left in the material. Thus, at any subsequent time, there will be more ^{241}Am in the sample than can be explained by in-growth, resulting in a value for the age that is too large.

Table E.4: Radio-chronometers commonly used in nuclear forensics investigations

NUCLIDE SYSTEM	HALF-LIFE (Y)
$^{232}\text{U} - ^{228}\text{Th}$	1.4e10
$^{233}\text{U} - ^{229}\text{Th}$	3.28e4
$^{234}\text{U} - ^{226}\text{Ra}$	2.45e5
$^{234}\text{U} - ^{230}\text{Th}$	2.45e5
$^{235}\text{U} - ^{227}\text{Ac}$	7.04e8
$^{235}\text{U} - ^{231}\text{Pa}$	7.04e8
$^{236}\text{U} - ^{232}\text{Th}$	2.34e7
$^{239}\text{Pu} - ^{235}\text{U}$	2.41e4
$^{241}\text{Pu} - ^{237}\text{Np}$	14.4
$^{241}\text{Pu} - ^{241}\text{Am}$	14.4

Figure E.2: The $4n+2$ chronometric nuclides

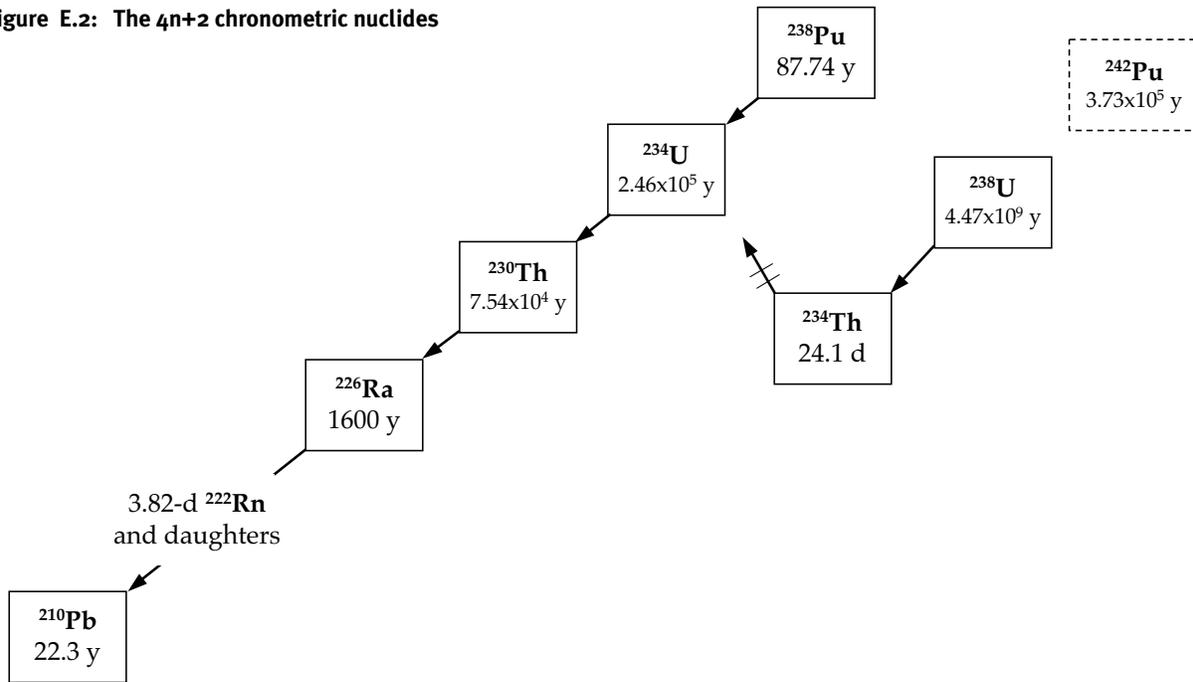


Table E.5: A guide to the analysis of post-detonation samples

ACTIVITY (ARRANGED IN ORDER OF INCREASING TIME SINCE AN EVENT)	INFORMATION GAINED
“Prompt” analysis by γ -ray spectrometry, tritium detection, satellite and seismic sensing/data	Initial “picture,” i.e., snapshot, of the device; yield
Receipt and chain of custody	Starting point for laboratory analyses
γ -ray spectrometry of bulk samples	Initial look at fuel type (U or Pu) and device sophistication
Sample processing (dissolution/ashing/particle and solids separation/isolation of non-nuclear debris)	
Whole solution assays by high-resolution gamma-ray spectrometry	Improved knowledge of fuel type (U or Pu) and device sophistication

Analysis of Post Detonation Material

The iterative analysis of post detonation samples is shown schematically in Table E.5, where the arrow represents the continuous refinement of the forensic analysis and increasing degree of confidence in the attribution assessment.

Calculations based on previous findings can lead to new measurements and possibly to the need for new samples.

While the above guide gives an idea of the sequence of events to be expected in a post-detonation analysis, the actual time elapsed between steps depends a great deal

on the specifics of the situation, including such things as degree of preparation, locale, logistical availability of personnel, equipment and transport, and ease of access. For

that reason, it is not possible to go beyond the general time dimensions given in Table E.1.

Table E.5: A guide to the analysis of post-detonation samples (continued)

ACTIVITY (ARRANGED IN ORDER OF INCREASING TIME SINCE AN EVENT)	INFORMATION GAINED
High resolution α -particle and γ -ray spectrometry of individual isotopes/elements	Device design, fuel materials, original isotopics, fuel mass
Particle analysis by SEM/electron microprobe/mass spectrometry	
Gas analysis	Burn-up, fuel origin
Non-nuclear (collateral) forensics	Pathways traveled by materials and individuals
Interpretation and all-source fusion for attribution assessment	Origin, comparison with known designs

Appendix F: Signatures of Plutonium and Uranium

This appendix gives an overview of isotopic signatures that can be expected for weapon-grade compositions of plutonium and uranium. The purpose of this analysis is to quantify the range of isotopic variations and, ultimately, to understand the relative importance of *predictive* versus *empirical* signatures. For nuclear forensics, empirical signatures are preferred over predictive signatures, but predictive signatures, which can be obtained with theoretical approaches or computer simulations, assume greater value in the absence of empirical signatures. In practice, the results of predictive signatures are used to guide or set priorities for measurements on samples.

The results presented below are primarily based on computer modeling of common reactor types for plutonium production and of the main enrichment processes for HEU production. We do not discuss the age of the material or the time since last purification as indicators, assuming that

these factors have already been considered (by chronometric methods) without resolving ambiguities regarding the origins of the material.

Signatures of Plutonium Compositions

Plutonium isotopics are primarily determined by the burnup [and type] of the uranium fuel in which it was originally produced. In general, the isotopics also depend on the reactor type and the operating history of the reactor. Therefore, even if two plutonium samples are similar in one respect, for example, the same ^{239}Pu content, their origin may still be identified based on an analysis of selected isotope ratios. Plutonium isotopics also change significantly with the age of the material, primarily due to the decay of ^{241}Pu , which has a half-life of only 14.4 years. The resulting buildup of ^{241}Am is a good indicator to determine the time that has elapsed since the material was last purified.

Table F.1: Selected reactor types used for plutonium production

	GRAPHITE MODERATED		HEAVY-WATER MODERATED		DRIVER FUEL WITH EXTERNAL DU TARGETS
	H ₂ O COOLED	CO ₂ COOLED	H ₂ O COOLED	D ₂ O COOLED	
Prominent examples	Hanford	Calder Hall	Cirus (NRX)	Dimona	Savannah River
United States	X				X
Russia	X				
U.K.		X			
France		X			X
China	X				
Israel				X	
India			X	X	
Pakistan			X		
North Korea		X			

Plutonium Production Reactor Types

Plutonium is produced in nuclear reactors, when ²³⁸U absorbs a neutron creating ²³⁹U, which decays into Np and, ultimately, to ²³⁸Pu. Other plutonium isotopes are primarily produced via subsequent neutron absorptions in ²³⁹Pu. Virtually any reactor type can be used for the production of weapon-grade plutonium by limiting the burnup of the uranium fuel. Reactor designs that permit continuous refueling are preferred for dedicated production reactors in order to facilitate frequent discharge and reloading of fuel elements for extraction of the plutonium. Table F.1 lists the main reactor types that have been or are being used for dedicated plutonium production.

Plutonium buildup is maximized in natural-uranium-fueled reactors. These reactors cannot use ordinary water to moderate (i.e., slow down) neutrons, because of parasitic neutron absorption in hydrogen. Instead, high-purity graphite or heavy water has to be used with natural uranium fuel. As shown in the table, graphite-moderated designs have played the dominant role in the case of the Non-Proliferation Treaty (NPT) nuclear weapon states. In particular, the light-water-cooled reactors used in Russia and China were reportedly virtually identical to the original U.S. reactors operated at the Hanford site. Heavy-water-moderated natural uranium

reactors were built in Israel, India, and Pakistan. In addition, the United States and France have also built heavy-water reactors, in which enriched driver fuel and depleted uranium targets are used.⁴³

For this report, we have carried out neutronics calculations for three most important types of production reactors. These are an early design of the graphite-moderated and light-water-cooled reactor used in the United States (“Hanford-type”); the graphite-moderated and gas-cooled reactor used in the United Kingdom (“Calder-Hall-type”) and more recently also in North Korea; and the heavy-water-moderated and light-water-cooled reactor, originally developed in Canada for civilian purposes but later used in India and Pakistan for military plutonium production (“NRX-type”).⁴⁴ Given that the neutron spectrum is very thermal and the diameter of the uranium rods rather similar for all designs (3.0-3.4 cm), we do not expect large differences in the isotopics of the plutonium built up in the fuel.

Plutonium Signatures

A manifold of isotopic ratios are available to characterize plutonium compositions and samples.⁴⁵ We have analyzed the evolution of plutonium ratios for the production reactors illustrated above, which represent the most important test cases for nuclear forensic analysis. All simulations have

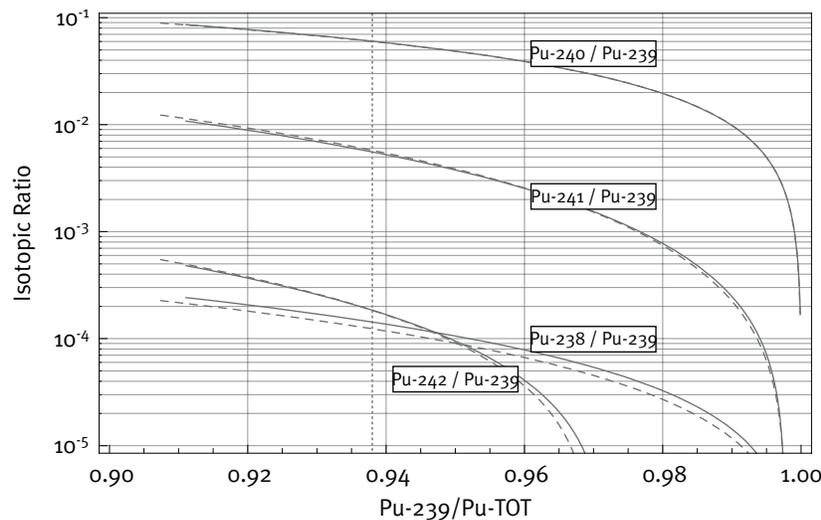


Figure F.1: Isotopic ratios for various plutonium isotopes as a function of Pu-239 content. The compositions of Hanford-type plutonium (solid line) and Calder-Hall-type plutonium (dashed line) are shown. Ratios are remarkably similar, even for increasing burnup. The isotopic ratios of NRX-type plutonium cannot be discerned in this graph as they overlap with those of the Hanford-type. Results are based on MCODE simulations. The power density in the fuel was 40 W/cc in all cases.

been carried out with the computer code MCODE, which is based on ORIGEN2 coupled with MCNP for spectrum-averaged cross-section generation and other purposes.⁴⁶ Figure F.1 shows the main results and the remarkable degree of similarity of compositions, even for increasing fuel burnup and, thus, decreasing Pu-239 fraction in the material.

Figure F.1 shows isotopic correlations for two selected ratios: $^{242}\text{Pu}/^{240}\text{Pu}$ and $^{238}\text{Pu}/^{239}\text{Pu}$, which have been identified as one of the most characteristic signature combinations.⁴⁷ Specifically, the $^{238}\text{Pu}/^{239}\text{Pu}$ ratio is an indicator of the hardness of the neutron spectrum, whereas the $^{242}\text{Pu}/^{240}\text{Pu}$ ratio is a measure of exposure or burnup. The data shown is based on mass-spectroscopic analyses of plutonium samples from diverse origins. Most of these samples, however, correspond to high-burnup fuels and may be less relevant for a forensic analysis, in which weapon-grade plutonium might be intercepted or recovered.

To assess the capability of nuclear forensic analysis in this situation, we compared plutonium compositions that are identical in one important aspect, making an analysis more challenging, but also more meaningful. These compositions are characterized by a selected reference value of 93.8% for the isotope ^{239}Pu . Again, Figure F.1 illustrates the main results.

The data show that it is possible to distinguish with a high level of confidence weapon-grade plutonium compositions from different basic reactor types. These include fast-breeder reactors, light-water reactors using low-enriched fuel, and reactors fueled with natural uranium. It is, however, extremely difficult to distinguish among plutonium compositions that

were generated in dedicated production reactors fueled with natural uranium. Whereas, the Calder-Hall-type plutonium can be identified, the isotopic compositions produced in the Hanford-type and the NRX-type reactors are virtually identical. A nuclear forensic analysis based on predictive signatures, i.e., without access to actual samples, could well remain inconclusive in this case. An analysis based on samples is likely to be more conclusive because these would reveal unique features of the material caused by *a priori* unknown specifications, e.g., the target burnup set by the operator, or other details of the production process.

Signatures of Uranium Compositions

Uranium is the source material for the production of both plutonium in nuclear reactors and highly enriched uranium using isotope separation techniques. Three potential sources for relevant uranium signatures are considered here: variations in the isotopics of original uranium ore, history of the uranium used for the enrichment process (natural vs. reprocessed uranium), and different enrichment technologies used for the production of the weapon-grade uranium.

Variations in the Isotopics of Natural Uranium

Only the isotopes ^{234}U , ^{235}U , and ^{238}U occur naturally in relevant concentrations. Variations in the composition of the ore have been widely reported. They are due to isotopic fractionation, nuclear reactions, or anthropogenic contamination.⁴⁸ An effort is now underway to characterize uranium ores worldwide. The overall objective – or hope – of this effort is to make it eventually possible to identify the source

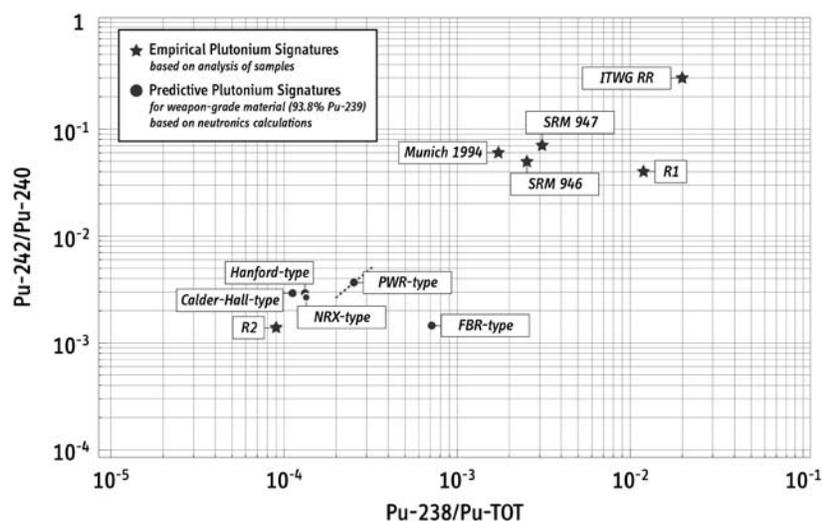


Figure F.2: Isotopic ratios for selected plutonium compositions. Data points obtained for actual plutonium samples are shown as stars. Most of them, however, correspond to high-burnup fuels. Weapon-grade plutonium compositions are based on neutronics calculations for typical operating conditions and are shown as circles. Some reactor types are easy to distinguish, e.g., light-water from fast-neutron reactors, but dedicated production reactors are not. Sample data from reference in Endnote 47.

of intercepted natural uranium samples (ore or refined products).

^{234}U exists in natural uranium, despite its short half-life of “only” 230,000 years, due to the decay of ^{238}U into ^{234}Th , which itself quickly decays into ^{234}U via $^{234\text{m}}\text{Pa}$. The equilibrium concentration of ^{234}U (about 0.005%) is determined by the ratio of the half-lives of ^{234}U and ^{238}U . However, as a result of chemical and mineralogical processes that can occur in the host matrix of the ore, the concentration of ^{234}U is *not* necessarily constant for arbitrary geological locations. ^{234}U variations, which are typically on the order of $\pm 10\%$,⁴⁹ are significant and relevant for forensic purposes. Even for ores from the same region, the ^{234}U content can vary as much as for ores from other regions.

In summary, the potential of uranium ore-signatures for nuclear forensic analysis is the subject of ongoing research. Under favorable circumstances, the ^{234}U content in natural uranium can point towards particular mines or regions, or exclude others. However, once the uranium is processed either by irradiation in a nuclear reactor or by enrichment, this signature would most likely be lost.

Enrichment of Natural vs. Reprocessed Uranium

Due to uranium ore constraints, nuclear weapon states have in some cases used a “dual track” approach to fissile material production: uranium is first used in a plutonium production reactor, in which the ^{235}U is only slightly depleted from 0.7% to about 0.6%. The plutonium *and* the uranium are

then extracted from the spent fuel, and the reprocessed uranium is later used as feed-material for HEU production. In fact, most of the Russian and U.S. fissile material stockpile was produced with this method, which maximizes production rates under ore supply constraints. Pakistan may be pursuing a similar strategy today.

The presence of non-naturally occurring uranium isotopes in enriched uranium, in particular the presence of ^{236}U , is a clear indicator that the uranium had been previously irradiated.

Another unique signature of reprocessed uranium are traces of ^{232}U ; its concentration in reprocessed uranium, however, is strongly dependent on a factor that is unrelated to reactor irradiation. After purification of the natural uranium, a given period of time elapses before the fuel is loaded into a reactor and irradiated to produce plutonium. During that period, some of the ^{235}U decays into ^{231}Pa via the short-lived isotope ^{231}Th . When exposed to a neutron flux, ^{231}Pa is transmuted into ^{232}Pa , which quickly decays into ^{232}U . This effect significantly increases the ^{232}U buildup during irradiation of natural uranium fuel, and must be considered for an in-depth forensic analysis. In the following example, we assume a typical value of one year between purification and irradiation.

Table F.2 summarizes the uranium isotopics for two types of production reactors: a graphite-moderated design of the Hanford-type and a heavy-water-moderated design of the NRX-type. To accentuate differences in the isotopics, we

Table F.2: Atom fraction of uranium recovered from production reactor at target burnup. The time elapsed between last purification and beginning of irradiation was assumed to be one year, which is equivalent to an initial ^{231}Pa content of about 1 ppm of U-235. Note that the power density of the Hanford-type reactor is only 20 W/cc compared to 80 W/cc for the NRX-type reactor.

	HANFORD-TYPE	NRX-TYPE	RATIO
^{232}U	2.03×10^{-12}	1.20×10^{-12}	1.684
^{233}U	3.58×10^{-11}	3.77×10^{-11}	0.949
^{234}U	5.29×10^{-05}	5.29×10^{-05}	1.000
^{235}U	6.01×10^{-03}	5.90×10^{-03}	1.019
^{236}U	1.86×10^{-04}	1.99×10^{-04}	0.932
^{237}U	9.94×10^{-01}	9.94×10^{-01}	1.000

Table F.3: Atom fractions of weapon-grade uranium using natural uranium (left) and uranium recovered from two types of production reactors (right). The target enrichment level is 93 at% of ^{235}U . Results are based on MSTAR calculations, which are most representative for the gaseous diffusion process.

	HEU (CLEAN)	HANFORD-TYPE	NRX-TYPE	RATIO
^{232}U	–	5.48×10^{-8} at%	3.34×10^{-8} at%	1.643
^{233}U	–	8.86×10^{-7} at%	9.58×10^{-7} at%	0.925
^{234}U	0.93 at%	.12 at%	1.15 at%	0.977
^{235}U	93.00 at%	3.00 at%	93.00 at%	1.000
^{236}U	–	1.26 at%	1.36 at%	0.923
^{238}U	6.07 at%	4.62 at%	4.49 at%	1.029

assume that the Hanford-type reactor is operated at a lower power density of 20 W/cc compared to 80 W/cc for the NRX-type reactor.⁵⁰

In both cases, the ^{236}U content in the reprocessed uranium reaches about 3% of the ^{235}U content, equivalent to about 0.02% of the total uranium. In the present example, the ^{232}U content in the uranium is the most significant difference between the two compositions. The higher ^{232}U content is a result of the longer in-core period of the fuel in the Hanford reactor, operating at a much lower power density in this test case. As the ^{235}U decays during irradiation, ^{231}Pa is building up and facilitates ^{232}U production.

For subsequent enrichment of the material, we assume that two candidate compositions of reprocessed uranium display some characteristic signature, as the reference materials listed in Table F.2 do.⁵¹ These two materials will be used as the feed-stock for weapon-grade uranium production characterized by a reference value of 93 at% ^{235}U . Results are obtained with the MSTAR-IAEA Enrichment Code, which models multi-isotope enrichment using the matched-abundance-ratio approach.⁵² The results are summarized in Table F.3 and are most representative for a gaseous diffusion process.⁵³ Remarkably, signatures that were present in the material prior to enrichment are preserved in the

enrichment process – an important finding for assessing the effectiveness of uranium-isotope signatures in nuclear forensics, if details of the production history of the material are known or can be estimated. For reference purposes, HEU produced from natural uranium is also included here.

Signatures of the Enrichment Process: Gas Centrifuge vs. Gaseous Diffusion

Different enrichment processes have been used historically to produce highly enriched uranium for weapon purposes. The most relevant ones are the gaseous diffusion process and the gas centrifuge. The two exploit different physical principles to separate isotopes of different molecular weight. It could therefore be expected that highly enriched uranium might carry an isotopic signature that is unique to the enrichment process used to produce the material. Unfortunately, as the discussion below shows, this is generally not the case.

As already discussed, significant additional information has to be available to calculate predictive signatures (using computer models) for enriched uranium produced from reprocessed uranium. In particular, the ^{232}U content in HEU critically depends not only on the mode of operation of the production reactor in which the uranium was originally irradiated, but also on the non-reactor-related history, namely the length of storage periods before and after irradiation, i.e., all events that occur before actual enrichment of the uranium. Furthermore, the enrichment process itself permits larger flexibility than the production of plutonium.⁵⁴ Even though HEU may be enriched in a single cascade, countries have sometimes used several interconnected smaller cascades for HEU production.⁵⁵ In addition, multiple feed and withdrawal points are possible and typical. All these features go beyond traditional discussions of cascade theory.

Finally, U-isotope signatures introduced by a specific enrichment process (gaseous diffusion vs. gas centrifuge) are weak. Even though the absolute value of the separation factors, and therefore the number of stages required to produce weapon-grade uranium, is drastically different for the two main processes, effective differences in the concentrations of the trace uranium isotopes (^{232}U , ^{234}U , and ^{236}U) are extremely small due to interstage-mixing of these isotopes in a cascade optimized for enrichment of ^{235}U .⁵⁶ As a net result of this effect, potential signatures of particular enrichment processes are largely washed out.

Characterizing the performance of gas centrifuges is particularly challenging. Not only does the basic design information of the machine have to be known, but also the way the centrifuge is operated. A typical machine may accept a range of feed rates and still operate at or near optimum separative power. Accordingly, the separation factor of a centrifuge increases if the flow-rate of UF_6 is reduced. In other words, the separation factor of a gas centrifuge is not determined by the design itself, but also depends on the selected feed rate. The selected set of parameters for operation of the centrifuge then determines the shape of the enrichment cascade.

In summary, essentially complete knowledge of the enrichment technologies employed, of the cascade design, and of the mode of operation is required in order to make meaningful (quantitative) statements about expected HEU signatures. We therefore conclude that predictive signatures for highly enriched uranium have greatest value when used in concert with other nuclear forensic techniques.

Conclusion

Nuclear forensic analysis uses sophisticated techniques to determine the isotopics of nuclear materials with remarkable accuracy. Based on such an analysis, it is possible, for instance, to determine the age of a material or the time that has elapsed since it was last purified. While valuable, these indicators may, however, not be sufficient to identify the origin of a sample. Ideally, one would seek forensic signatures or combinations of signatures that are unique for a specific production facility.

Historically, only few reactor types have been used to produce weapon-grade plutonium. Moreover, nearly identical designs were sometimes used by more than one country. As a result, isotopic signatures of plutonium isotopics are weak identifiers. While the type of reactor used to produce weapon-grade plutonium can generally be distinguished, considerable information would have to be available to identify a particular facility based on predictive signatures, i.e., based on computer modeling alone.

The situation is even more complex in the case of highly enriched uranium due to a greater degree of flexibility in the HEU production process. Here, it may even be difficult to identify the particular enrichment process that was used in the production of a given HEU sample with purely theoretical approaches. Still, some important observations are possible

without additional knowledge about the origin of a sample. Beyond its age, it is straightforward to determine whether or not an HEU sample was produced from reprocessed uranium, which would point to a parallel plutonium production program and narrow down the potential origin significantly. At the same time, however, new uncertainties are introduced because additional factors related to the history of the uranium have to be considered for a complete assessment.

Pre-explosion nuclear forensics strongly benefits from “collateral” forensic indicators such as non-nuclear impurities or organic trace materials. A post-explosion analysis, however, would have to rely largely on the isotopics of the nuclear material used in the explosive device or weapon.

Based on the analysis above, the value of predictive signatures for this purpose is limited in this case. Instead, nuclear forensic analysis would – whenever possible – have to rely on empirical signatures obtained from actual samples to perform its task with confidence. The fact that countries generally produced weapon materials under strictly controlled and dissimilar operating conditions has created differences in material properties that nuclear forensics seeks to exploit. We finally note that there is considerable experience with post-explosion forensic analysis in some nuclear weapon states, where nuclear-weapon-test data have been available to benchmark and validate computational models with both known pre- and post-explosion isotopics.

Appendix G: Endnotes

¹ We use ‘nuclear materials’ to mean “fissile materials, their products, precursors and associated materials.”

² The IAEA Illicit Tracking Database (<http://www-ns.iaea.org/security/itdb.htm>) details these incidents.

³ The “age” of a plutonium sample is the time since the last chemical separation of the plutonium from which the sample was taken. It is measured by the relative abundance to plutonium of its radioactive daughters.

⁴ Matthew Bunn, *Securing the Bomb 2007* (Cambridge, Mass., and Washington, D.C.: Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, September 2007).

⁵ Peter Zimmerman and Jeffrey Lewis, “The Bomb in the Backyard,” *Foreign Policy*, November/December 2006.

⁶ Andrew H. Kydd and Barbara F. Walter, “The Strategies of Terrorism,” *International Security* 31, 1 (Summer 2006): 49-80.

⁷ These include: the Convention on the Physical Protection of Nuclear Material; the Convention on the Suppression of Acts of Nuclear Terrorism; Security Council resolutions 1373 and 1540.

⁸ See <http://cns.miis.edu/pubs/week/070126.htm>.

⁹ *Discouraging Terrorism: Some Implications of 9/11*, Washington, D.C.: National Academy Press, 2002. Martha Crenshaw, “Coercive Diplomacy and the Response to Terrorism,” *The United States and Coercive Diplomacy*, edited by Robert J. Art and Patrick M. Cronin. Washington: United States Institute of Peace Press, 2003. Michael Miller, “Nuclear Attribution as Deterrence,” *The Nonproliferation Review*, Volume 14, Issue 1, March 2007, pages 33-60.

¹⁰ Robert F. Trager and Dessislava P. Zagorcheva, “Detering Terrorism: It Can Be Done,” *International Security* 30, 3 (Winter 2005-06): 87-123. Michael Levi, *On Nuclear Terrorism*, Harvard University Press (November 30, 2007)

¹¹ Ashton B. Carter, Michael M. May, and William J. Perry, “The Day After: Action Following a Nuclear Blast in a U.S. City” *The Washington Quarterly*, 30:4 pp. 19–32, Autumn 2007. A more extended version can be obtained at http://www.belfercenter.org/publication/2140/day_after.html.

¹² This is a total figure, which has been obtained by putting together information from a variety of sources. One of the authors (Hutcheon) can attest to the validity of the data. For more details about the NAP, see <https://www-gs.llnl.gov/rn.html>

¹³ For more details see <http://www-ns.iaea.org/security/itdb.htm>.

¹⁴ The United States, Russia, China, United Kingdom, France, India, and North Korea have all detonated plutonium-based nuclear weapons. It is unclear if Pakistan's weapons program has successfully detonated such a weapon.

¹⁵ According to "Fissile Material: Stockpiles Still Growing" (Albright and Kramer, *Bulletin of the Atomic Scientists*, November/December 2004, page 15), Belgium, Germany, Italy, Japan, the Netherlands, and Switzerland each have over one ton of separated civil plutonium.

¹⁶ The number depends on how narrowly nuclear forensics is defined.

¹⁷ Office of Nuclear Energy, Science and Technology, DOE, July 2004. Also see "U.S. Workforce and Educational Facilities' Readiness to Meet the Future Challenges of Nuclear Energy," APS POPA report, March, 2008.

¹⁸ The U.S. universities providing graduate programs in radiochemistry and/or nuclear chemistry are Washington State University; University of California, Berkeley; University of Nevada, Las Vegas; Auburn University; Clemson University; Florida State University; and Oregon State University.

¹⁹ See <http://www.whitehouse.gov/news/releases/2006/07/20060715-3.html>.

²⁰ More information is available at http://projects.jrc.cec.eu.int/show.gx?Object.object_id=PROJECTS000000000045C5E.

²¹ More information is available at <http://itu.jrc.cec.eu.int/>.

²² J. Dolgov, Y. K. Bibilashvili, N. A. Chorokhov, A. Schubert, G. Janssen, K. Mayer and L. Koch. Installation of a database for identification of nuclear material of unknown origin at VNIINM Moscow; 21st ESARDA Symposium, 1999, Sevilla, Spain, Report EUR 18963 EN.

²³ A. Schubert, G. Janssen, L. Koch, P. Peerani, Y. K. Bibilashvili, N. A. Chorokhov and J. Dolgov. A software package for nuclear analysis guidance by a relational database. ANS

International Conference on the Physics of Nuclear Science and Technology, 1998, New York, USA.

²⁴ Available online at http://nsnfp.inel.gov/factsheets/spe_fuel-data-r1.pdf.

²⁵ Available online at <http://nsnfp.inel.gov/snfData.asp>.

²⁶ SFCOMPO was originally developed at the JAERI Department of Fuel Cycle Safety Research's Fuel Cycle Safety Evaluation Laboratory. SFCOMPO provides isotopic composition data via the Internet [Ref 3 and 4]. It archives measured isotopic composition data and the values of their ratios, which are required for the validation of burn-up codes. See <http://www.nea.fr/sfcompo/>.

²⁷ "Preparing for the Worst," Michael May, Jay Davis, and Raymond Jeanloz, *Nature*, 26 October 2006.

²⁸ See http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=426069 for an abstract of what challenge inspections do under the CWC and further references.

²⁹ See "Model Protocol Additional To The Agreement(s) Between State(s) And The International Atomic Energy Agency For The Application Of Safeguards," IAEA. September 1997 www.iaea.org/Publications/Documents/Infcircs/1997/infcirc540c.pdf.

Also http://www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html for latest status and Theodore Hirsch, "The IAEA Additional Protocol: What It Is and Why It Matters" *The Non-Proliferation Review*, Volume 11, No. 3, 2004, for a discussion.

³⁰ As an example, Russia, unlike the United States, regards the isotopic composition of weapons-grade plutonium as classified.

³¹ See <http://www.iaea.org/NewsCenter/Focus/laeaDprk/dprk.pdf>. Also "Solving the North Korean Nuclear Puzzle," David Albright, Kevin O'Neill editors, ISIS Report (2000) pp. 120-121.

³² A start on this has been made. See the National Defense Authorization Act For Fiscal Year 2008, P.L. 110-181, Sections 4307-4308.

³³ The material that follows is adapted from a presentation given by DND Assistant Director William Daitch to this panel on July 17, 2007.

³⁴ National Security Presidential Directive 43 / Homeland Security Presidential Directive 14, accessed on the Federation of American Scientists website.

³⁵ See http://www.cmls.llnl.gov/?url=science_and_technology-chemistry-nuclear_forensics. See also Kenton J. Moody, Ian D. Hutcheon, and Patrick M. Grant, "Nuclear Forensic Analysis" (CRC - Feb 28, 2005) for a comprehensive review of the state of the art.

³⁶ See www.lanl.gov/orgs/t/publications/nuclear_weapons_highlights_2006/Nuclear%20Physics/Hayes.pdf.

³⁷ See <http://www.nbl.doe.gov/htm/goals.htm>.

³⁸ See http://www.ornl.gov/sci/csd/Research_areas/cims_group.html.

³⁹ See <http://www.inl.gov/featurestories/2007-07-25.shtml>.

⁴⁰ See www.sandia.gov/ASC/pubs_pres/PIMeeting/2007/kusnezov/DKato7PIMtg.ppt.

⁴¹ See <http://homeland-security.pnl.gov/rnc.stm>.

⁴² *Nuclear Forensics Support Technical Guidance*, publication #1241, IAEA Nuclear Security Series No. 2 (2006).

⁴³ Weapon-grade plutonium can also be obtained from the blanket of fast neutron (breeder) reactors. Reportedly, France pursued this option to a limited extent with its Phénix reactor in the 1970s and 1980s. D. Albright, F. Berkhout and W. Walker, *Plutonium and Highly Enriched Uranium 1996*, Oxford University Press, 1997, p. 73. India may use a similar strategy once its Prototype Fast Breeder Reactor (PFBR) is operational. For an assessment of this option, see A. Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science & Global Security*, Vol. 15, No. 2, 2007, pp. 85-105.

⁴⁴ The following main references have been used to develop the reactor models: for the Hanford (B) reactor, H. Toffer and S. P. Roblyer, *Hanford Site Production Reactor Data*

Pertinent to Actinide Burning, WHC-SA-1816-FP, Westinghouse Hanford Company, U.S. Department of Energy, June 1993; for the Calder Hall reactor, B. D. Murphy, *ORIGEN-ARP Cross-Section Libraries for Magnox, Advanced Gas-Cooled, and VVER Reactor Designs*, Oak Ridge National Laboratory, ORNL/TM-2003/263, February 2004; for the NRX reactor, D. G. Hurst and A. G. Ward, "Canadian Research Reactors," pp. 1-48 in R. A. Charpie, D. J. Hughes, D. J. Littler, and M. Trocheris (eds.), *Progress in Nuclear Energy, Series II, Reactors*, Vol. I. Pergamon Press, London, 1956.

⁴⁵ For more detailed discussions, see Moody, I. A. Hutcheon, and P. M. Grant, *Nuclear Forensic Analysis*, Taylor & Francis, CRC, Boca Raton, 2005; M. Wallenius, *Origin Determination of Reactor Produced Plutonium by Mass Spectrometric Techniques: Application to Nuclear Science and Safeguards*, Ph.D. Thesis, University of Helsinki, 2001.

⁴⁶ Z. Xu, P. Hejzlar, M. J. Driscoll, and M. S. Kazimi. "An Improved MCNP-ORIGEN Depletion Program (MCOE) and its Verification for High Burnup Applications," *PHYSOR 2002*, Seoul (Korea), October 7-10, 2002.

⁴⁷ K. Mayer, M. Wallenius, and I. Ray, "Nuclear Forensics—A Methodology Providing Clues on the Origin of Illicitly Trafficked Nuclear Materials," *The Analyst*, The Royal Society of Chemistry, 130 (2005), pp. 433-441.

⁴⁸ S. Richter, A. Alonso, W. De Bolle, R. Wellum, P. D. P. Taylor, "Isotopic 'Fingerprints' for Natural Uranium Ore Samples," *International Journal of Mass Spectrometry*, 193 (1999), pp. 9-14.

⁴⁹ Richter et al., *op. cit.*

⁵⁰ These values are per cubic centimeter in the fuel and are consistent with historic operating data, but graphite-moderated reactors can be operated at higher power densities that are comparable to those obtained in heavy-water production reactors. In fact, the power level of the Hanford B reactor was increased significantly over the years: from 250 MW to eventually 2210 MW thermal. For details, see *Plutonium: The First 50 Years: United States Plutonium Production, Acquisition and Utilization from 1944 through 1994*, U.S. Department of Energy, DOE/DP-0137, 1996, www.ipfmlibrary.org/does96.pdf.

⁵¹ Here, we do not correct for isotopic shifts that would occur during an additional storage period of the spent fuel, primarily due to the decay of U-232 (half-life 68.9 years).

⁵² D. F. Starr, *MSTAR-IAEA Enrichment Code User Guide*, K/NSP-386, U.S. Department of Energy, June 1996. All calculations presented here were carried out by Prof. Houston Wood, University of Virginia, based on input data specified by the author.

⁵³ Independently of the simulated enrichment process, MSTAR uses a standard expression to calculate the separation factors for uranium isotopes other than U-235. This approximation is most accurate for the gaseous diffusion process.

⁵⁴ In general, operating conditions of a nuclear reactor are quite stable over time, and nominal or average values for power density, neutron flux level, etc. can be used to determine predictive signatures for plutonium based on neutronics calculations.

⁵⁵ For example, the United States has documented the general architecture of its HEU production process. The Paducah plant was used to enrich uranium to 0.9-1.1%. This material was then either shipped to Oak Ridge and enriched

to 93% for weapon-use, or to Portsmouth and enriched to 97-98% for naval-reactor use. *Highly Enriched Uranium: Striking a Balance; A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 Through September 30, 1996*, U.S. Department of Energy, 2001, Rev. 1, www.ipfmlibrary.org/doe01.pdf; see, in particular, Figure 2.2 (Integrated Operation of the Gaseous Diffusion Plant).

⁵⁶ In an enrichment cascade designed for HEU production, about 50% of the U-235 originally contained in the feed material is extracted at the top of the cascade as product. The separation factors for the isotopes U-232 and U-234 are higher (compared to the factor for U-235), but the cascade is not optimized for their enrichment and significant mixing therefore occurs between stages. As MSTAR analyses show, only about 80% of the U-232 present in the feed are therefore extracted at the top of the cascade, even though there are sufficient stages in the cascade to extract almost all U-232.