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## Strengthening the Foundations of Proliferation Assessment Tools

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### **Abstract**

Robust and reliable quantitative proliferation assessment tools have the potential to contribute significantly to a strengthened nonproliferation regime and to the future deployment of nuclear fuel cycle technologies. Efforts to quantify proliferation resistance have thus far met with limited success due to the inherent subjectivity of the problem and interdependencies between attributes that lead to proliferation resistance. We suggest that these limitations flow substantially from weaknesses in the foundations of existing methodologies – the initial data inputs. In most existing methodologies, little consideration has been given to the utilization of varying types of inputs – particularly the mixing of subjective and objective data – or to identifying, understanding, and untangling relationships and dependencies between inputs. To address these concerns, a model set of inputs is suggested that could potentially be employed in multiple approaches. We present an input classification scheme and the initial results of testing for relationships between these inputs. We will discuss how classifying and testing the relationship between these inputs can help strengthen tools to assess the proliferation risk of nuclear fuel cycle processes, systems, and facilities.



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## 1.0 Introduction

Although not a new concept, methodologies for evaluating the proliferation risk or resistance of nuclear energy systems have increased in number and prominence in the last several years. Although many different measurement approaches have been considered and substantial work has gone into development and refinement, most agree that challenges still remain.

An evaluation of the most prominent tools suggests that technical assessment tools are most effective when used to consider technical questions and must be used judiciously when high-level, policy questions are at stake. Furthermore, what is learned during the process of methodology application is more relevant than any final number purporting to represent a conclusion. The greatest contribution these tools can make is providing a structured method for evaluation; a “checklist” of key features which must be considered.

To perform this checklist function credibly and reliably, assessment tools should be structured in such a way that they are auditable, transparent, and flexible. This will allow these tools to account for a range of potential users and circumstances. Methodologies differ significantly in the degree to which they meet these criteria, largely based on what information is considered, how that information is obtained, and how it is used.

This observation led us to focus our efforts not on the development of new methodologies or the modification of existing methodologies, but rather on the foundations of the basic data inputs.

Our goal is to produce a limited set of basic inputs which rely as little as possible on subjective judgment and which exclude internal interdependencies to the greatest degree possible. Where objective quantitative evaluation is impossible subjectivity is necessary and where dependencies are impossible to eliminate, we attempt to define the effect of each on aggregation schemes.

We have developed a set of inputs and attributes which contribute to the achievement of this goal. In this paper, we present the current draft of our full list of inputs and attributes and a discussion of each. We consider the list to be a work in progress and anticipate that further consideration by experts will be necessary to continue its refinement. To this end, we also demonstrate the approach we have developed to testing this list of inputs and attributes across four criteria:

- 1) Can numbers be associated with each input?
- 2) Does the set cover all important elements?
- 3) How would the required information be obtained? and
- 4) How do relationships between the inputs affect results?

If successful, we believe this strengthened foundation can help to ensure that proliferation risk or resistance assessment tools are reliable guides for policy-makers and technology developers in efforts to make civilian nuclear energy systems the least attractive path to the development of nuclear weapons.

## 2.0 Definition and Assumptions

The demand from policy-makers for assessment tools, the diversity of approaches, and their increasing complexity, can, at times, cause confusion – especially for the uninitiated. One of our primary motivations in the work described below will be to contribute to the increased usability of these tools. Clearly and carefully defining terms and stating assumptions is a critical first step toward that goal.

In the most general sense, these tools are intended to help a variety of stakeholders evaluate how the features and characteristics of any nuclear process, facility, system – to include reactors – or activity intended for civilian use, could impede or aid the pursuit of non-civilian capabilities.

There is an active and ongoing debate between those who refer to the assessment tools developed for this purpose as *proliferation resistance* assessment tools and those who refer to them as *proliferation risk* assessment tools. Because we believe our work is relevant to either approach, we take no position on that debate in this paper. While not dismissing potential deeper differences between the two terms, for the purpose of this paper we use them interchangeably and imply only a difference in orientation with *resistance* evaluating how the features of a system impede proliferation and *risk* evaluating how the features of a system – or the lack thereof – might make proliferation more likely. In most cases, we use the more general term “assessment tools” to encompass both approaches.

We have adopted a narrow definition of the term “proliferation” in the context of these assessment tools to include only those activities undertaken by a state to pursue a nuclear weapons capability using civilian nuclear technology under their control. Although a successful effort by any actor, non-state or otherwise, to *steal* nuclear material or technology may result in a nuclear weapon, it is a sufficiently distinct type of threat deserving separate consideration. Evaluating the performance of features to address theft-type threats may require a different approach (most notably one which considers physical protection characteristics), as technology features and characteristics which aid or impede host state-type threats may have not always have a consistent relationship to theft-type threats.

It is our strong view that the evaluation of technology features or characteristics must always be placed in the context of a state’s nuclear energy system – all the civilian nuclear energy activities including the use of reactors to generate electricity. (In this paper, we use the term “nuclear energy system” instead of “nuclear fuel cycle” to emphasize the inclusion of reactors.)

We further believe that assessment tools are most valuable when used to evaluate nuclear energy systems or activities *under International Atomic Energy Agency (IAEA) safeguards*, as a wide range of information about nuclear energy systems outside of the international safeguards system will likely be much more difficult to obtain. It may be possible to make a high-level assessment of a facility or activity not under safeguards but this is not the task to which assessment tools are *best suited*.

It must, however, be noted that the specifics of an IAEA safeguards approach to a specific facility and the data acquired are confidential between the Agency and the Host, and generally not available to outside parties. For this reason, elements of assessment tools which evaluate the performance of the safeguards system will not typically be accessible.

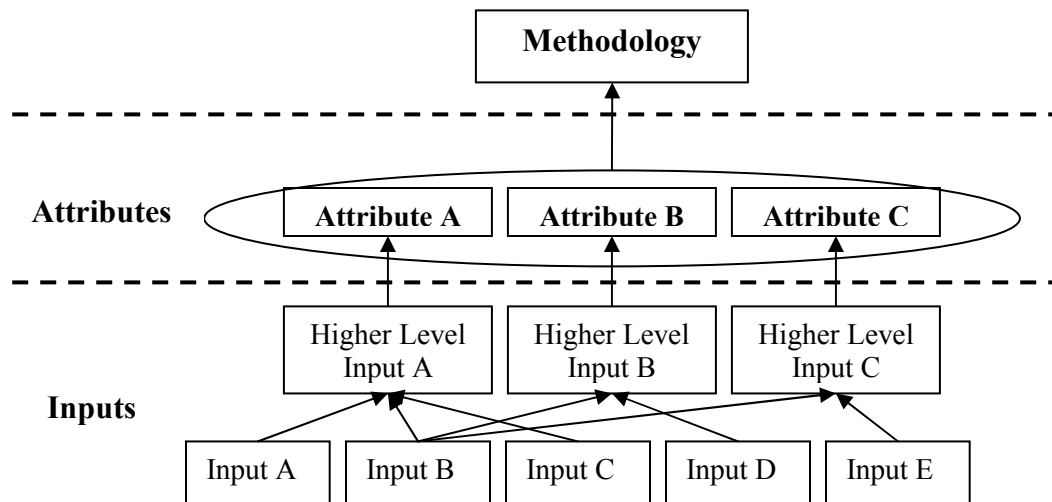
All assessment tools evaluate technology features or characteristics in some fashion and then attempt to aggregate those evaluations. The features and characteristics being assessed are referred to using a variety of terms including “indicators”, “measures”, “attributes”, and “metrics”. In our work, we have adopted the following nomenclature:

- *Inputs* are discrete elements of a system, the most basic of which can be directly measured. To account for the possibility that some circumstance may not grant access to this level of data, in many cases, a hierarchy of inputs may be employed. Inputs are specific measurable or definable characteristics of the system and scenario under consideration.
- *Attributes* are derived from the combination of one or more inputs and are directly relevant to proliferation assessment.



- *Methodology* refers to the process by which attributes and inputs are combined to draw analytic conclusions about a nuclear energy system.

Figure 1 gives a conceptual overview of how these terms apply to the general architecture of proliferation assessment methodologies.



**Figure 1.** Elements of proliferation assessment methodologies

### 3.0 Roles and Limitation of Assessment

With the increased interest in proliferation risk and resistance methodologies has come a desire to use these assessments for a variety of purposes. These purposes can be grouped into four general categories, the first two of which are primarily policy-focused and the last two of which are primarily technically-focused:

1. International Policy Considerations: Evaluations of the effect the acquisition of a particular nuclear energy system has on a given state's ability to develop a weapons capability while under IAEA safeguards.
2. Domestic Policy Considerations: Internal choices about the adoption of any given nuclear technology. In most cases, the primary concern of domestic policy will relate to theft-type threats and the performance of physical protection measures. However, in some cases a state may wish to implement systems which impede host-state diversion as a confidence building measure or as an example for others.
3. Technical Design and Evaluation Tasks: Design and assessment of fuel cycle and safeguards technologies; cost/benefit evaluations.
4. Technical Analysis Capabilities: Improved ability to understand how system features impact nonproliferation goals.

Assessment tools become more effective as you move down this list. As a general matter, tools for conducting technical evaluations are best suited to make technical decisions. The more prominent political and policy considerations become, the more careful analysts must be when making claims about technical considerations. Particularly, for international policy decisions, the results of evaluating a particular technical system may be less relevant in comparison to the weight of political factors.

That said, the degree to which technical features mitigate or contribute to proliferation risk may be *one* of the factors considered in making nonproliferation-related policy decisions. While technical features will never be sufficient to stop a determined proliferator, they can make the civilian nuclear energy system the least attractive path for a state and help to build confidence among neighboring states that civilian facilities are not a cover for military programs. Trusted assessment tools can support these policy objectives.

Finally, it must also be noted that technical evaluations of proliferation risk or resistance are only *one* factor in overall technical evaluations of nuclear systems. Factors such as security, safety, and operational performance are also of critical importance, as is an understanding of how the achievement of each of these technical goals affects the other.

A careful understanding of the roles and limitations of assessment tools is important for two reasons. First, if applied to evaluations for which they are ill-suited, these tools will inevitably perform badly and cause policy-makers to lose confidence in their ability to help us make even the narrow evaluations for which they are well-suited. Second, well-defined goals can guide work to strengthen these tools.

## 4.0 Desirable Characteristics of Technical Assessment Tools

The focus on tools which can credibly and reliably help users evaluate how technical features affect proliferation and the role they play in other systems considerations suggests that well-developed tools should be<sup>1</sup>:

1. *Auditable*: Assessment tools should readily allow others to review the results of their application and lend themselves to criticism and contestation.
2. *Transparent*: Users and reviewers should be able to easily determine *what* data was used, *how* it was obtained, and how each element or input affects the results. The use of expert judgment to obtain data should be explicit and its effect on the overall results determinable. Similarly, the existence of relationships between data inputs which may unintentionally weight or discount particular elements, should be identifiable and their effects understood.
3. *Flexible*: Assessment tools need to be flexible in three primary ways. First, they should allow for sensitivity analysis to evaluate the importance of the presence or absence of individual inputs. Second, they should be applicable to any nuclear process, facility, or activity and they should allow for the assessment of sets of technologies and activities. Evaluations of specific technologies in the absence of the context of a state's nuclear energy system in which they are deployed offer only limited, and in some cases, misleading information. Finally, assessment tools should be applicable to multiple users. They should allow users to make evaluations of particular areas of interest and to apply tools even without access to full information. This flexibility, however, must be complemented with the ability to evaluate what is being missed when limited interest or information result in the performance of partial assessments.

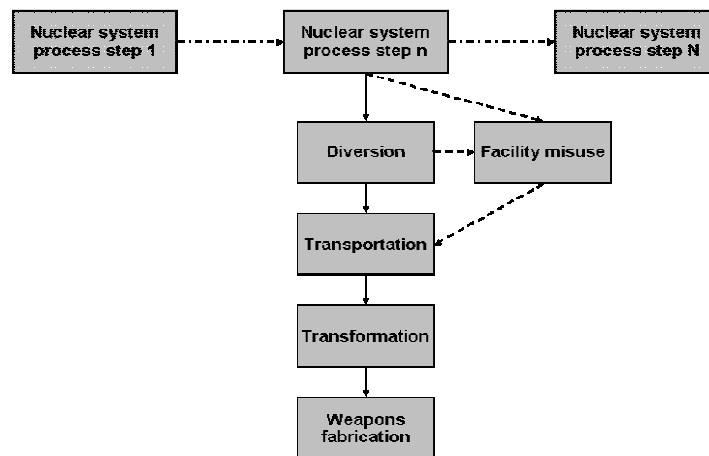
A close examination of these desirable characteristics reinforces the value of focusing on the foundations of assessment tools – the basic inputs and attributes. Understanding *which* features matter, *how* they matter individually, and how they affect other features is a prerequisite to continually improving systems. To do this, assessment tools must help us ensure we are considering all the important elements.

## 5.0 Attribute and Input Development

To support the goal of strengthened assessment tool foundations, we developed a draft set of model inputs and attributes applicable to multiple assessment approaches which can facilitate the achievement of the desirable characteristics discussed above. This set of inputs and attributes was developed by attempting to subdivide the pathway to a nuclear weapon, beginning in a safeguarded civilian facility, into ever-smaller pieces until we reached inputs which could not be divided further and were, in as many cases as possible, directly measurable.

### 5.1 Stages of Proliferation

In our first subdivision, we followed the Simplified Approach for Proliferation Resistance Assessment of nuclear systems (SAPRA) methodology<sup>2</sup> and divided the proliferation pathway into stages: diversion, facility misuse, transportation, transformation, and weapons fabrication (Fig. 2). The “facility misuse” stage is an optional stage which, depending on the context being assessed and the methodological approach used, may be omitted.



**Figure 2.** Stages of proliferation.

The definitions of each stage are as follows:

- Diversion: Covertly removing from a safeguards-controlled area, at least one significant quantity (SQ) of IAEA declared nuclear material from the declared inventory of any given fuel cycle process step (to include those in reactors) during an activity taking place under international safeguards.<sup>3</sup>
- Facility Misuse: The use of a civilian, safeguarded facility to produce at least one SQ of undeclared nuclear material. This stage does not occur in all proliferation pathways. In some cases the stage involves the covert insertion of undeclared material into a facility, while in other cases the material may already be present. The stage always involves use of a safeguarded facility in manner inconsistent with its declared purpose and undeclared removal of material (not necessarily identical to that material illicitly introduced) from the safeguarded facility.
- Transportation: The process of transporting diverted material (typically from a safeguarded facility to another facility).
- Transformation: Conversion of the diverted material to a weapons-usable metallic form in an un-safeguarded facility.
- Weapons Fabrication: The process of designing and building a weapon with the transformed material.

## **5.2 Attributes and Inputs for Each Stage**

Our second level of subdivision was to develop a set of attributes within each stage using expert consensus. We considered two questions for each stage: 1) What factors make the activity described by the stage difficult to accomplish? and 2) What factors make the activity described by the stage difficult to accomplish without being detected? We sought to use the fewest number of attributes possible which still covered all major factors and allowed for the consideration of the broadest range of proliferation pathways.

Once the attributes for each stage were developed, we subdivided these attributes by considering what data was necessary to characterize the attribute. In some cases, the necessary data – or input – was a basic input (e.g., mass). In other cases, the necessary input could only be assessed through the consolidation or analytical treatment of more basic inputs. Where the latter was the case, we sought to further subdivide until we reached the most basic level of inputs possible. As with the development of attributes, we sought to use the fewest number of inputs possible while ensuring that we were able to fully characterize each attribute.

Throughout the research, we repeatedly revisited and reevaluated our attribute and input list through the consideration of hypothetical scenarios. While the list below is the product of significant consideration and evaluation, we do not believe it is complete. In Section 6, we demonstrate through testing procedures, several areas in which the list needs to be strengthened. We seek review by outside experts to help us to further refine this list.

In the section that follows, we define the attributes and inputs developed and describe the considerations behind each element.

### **5.2.1 Diversion Stage**

A state seeking to develop a nuclear weapon faces three principle challenges: 1) the technical difficulty of removing material from the source system; 2) the difficulty of handling the material once it is removed from the source system; and 3) the difficulty of avoiding detection of the diversion. These three obstacles are represented through five attributes (Figure 3). One seeks to measure the difficulty of handling the material, another measures the difficulty of conducting modifications to access the material, and three address avoiding safeguards systems.

As noted above, we developed our diversion attributes and inputs specifically for facilities and activities that are under IAEA safeguards. We recognize that in many cases, the information necessary to evaluate the safeguards system will not be available to most users. We nonetheless felt it important to leave open the possibility of evaluating safeguards effectiveness for those users with sufficient information and interest. Where it is impossible or inappropriate to make these evaluations, the relevant attributes (“Difficulty of evading detection by the accounting system”, “Difficulty of evading detection by the material control system”, and “Difficulty of evading detection of the facility modifications for the purposes of diverting nuclear material”) may be characterized by accepted or assumed levels of probability.

#### **5.2.1.1 Attribute: Material Handling Difficulty during Diversion**

There are a number of factors which would make nuclear material difficult to handle even for the owner of a nuclear facility, most are direct functions of the composition and form of the material being diverted or the process from which it is being diverted. These factors include the material’s mass, bulk, heating rate, radiation dose rate and the hazard it presents to any humans nearby. We identified eight inputs relevant to this attribute.

5.2.1.1.1 Input: Mass/SQ of nuclear material (kg/SQ)

This input assumes that increased mass makes the act of diversion more difficult. It considers the mass of the entire diverted object or quantity of solution which contains the fissile material of interest. Items or solutions that have a higher concentration of fissile material (and thus, a lower mass/SQ) will be more attractive to a proliferator since a lower total mass would need to be diverted and handled to acquire a useable significant quantity. Significant quantities are defined by the IAEA for each type of fissile material.<sup>4</sup> The use of SQs allows the user to normalize the input for all materials. As the value of this input increases, the proliferator will need to take more time and/or use more equipment to move the amount of material needed for a nuclear weapon, thus increasing the material handling difficulty.

**Table 1.** Inputs for the diversion stage.

<b>DIVERSION</b>	
<ul style="list-style-type: none"> <li>• <b>1.1 Material handling difficulty during diversion</b> <ul style="list-style-type: none"> <li>1.1.1 <i>Mass/SQ of nuclear material</i></li> <li>1.1.2 <i>Volume/SQ of nuclear material</i></li> <li>1.1.3 <i>Number of items/SQ</i></li> <li>1.1.4 <i>Material form (solid, liquid, powder, gas)</i></li> <li>1.1.5 <i>Radiation level in terms of dose</i></li> <li>1.1.6 <i>Chemical reactivity</i></li> <li>1.1.7 <i>Heat load</i></li> <li>1.1.8 <i>Process Temperature</i></li> </ul> </li>   <li>• <b>1.2 Difficulty of evading detection by the accounting system</b> <ul style="list-style-type: none"> <li>1.2.1 <i>Uncertainty in accountancy measurements</i></li> <li>1.2.2 <i>Expected vs. actual MUF</i></li> <li>1.2.3 <i>Frequency of accounting record comparisons and verifications</i></li> <li>1.2.4 <i>Amount of material available</i></li> </ul> </li>   <li>• <b>1.3 Difficulty of evading detection by the material control system</b> <ul style="list-style-type: none"> <li>1.3.1 <i>Probability of detection based on vulnerability analysis of material control system in place (requires the development of standards and an evaluation of how facilities compare)</i></li> </ul> </li>   <li>• <b>1.4 Difficulty of conducting undeclared facility modifications for the purpose of diverting nuclear material</b> <ul style="list-style-type: none"> <li>1.4.1 <i>Is there enough physical space and access to actually make the modifications?</i></li> <li>1.4.2 <i>Number of people needed to perform modifications</i></li> <li>1.4.3 <i>Requirement for use of remote handling tools</i></li> <li>1.4.4 <i>Requirement for specialized tools</i></li> <li>1.4.5 <i>Requirement to stop process to make modifications</i></li> <li>1.4.6 <i>Risk of modification (safety)</i></li> <li>1.4.7 <i>Risk of penetrating containment</i></li> </ul> </li>   <li>• <b>1.5 Difficulty of evading detection of the facility modifications for the purposes of diverting nuclear material</b> <ul style="list-style-type: none"> <li>1.5.1 <i>Probability of detection based on vulnerability analysis of design verification system [to include factors such as percentage of facility or process step under effective IAEA surveillance and frequency of inspection (number/year, IAEA criteria)]</i></li> </ul> </li> </ul>	

5.2.1.1.2 Input: Volume/SQ of nuclear material (m<sup>3</sup>/SQ)

As with mass/SQ, this input assumes that increased volume makes the act of diversion more difficult. The volume per SQ of nuclear material considers the volume of the diverted item or solution. For solutions, greater volume will necessitate more time and more containers to achieve a diversion of one SQ. For solid

objects, great volume could require the use of larger cranes and over-sized vehicles. In both cases, the difficulty of handling the material increases as the volume per SQ increases. For example, one SQ of weapons grade metallic Pu or U represents a volume small enough to be carried by hand and thus limited handling difficulty. By contrast, natural uranium ore might have a volume in excess of 2,000 m<sup>3</sup>/SQ. Again, the use of SQs normalizes the input so that it can be applied uniformly to all fissile materials.

#### *5.2.1.1.3 Input: Number of items/SQ*

The greater the number of items that the proliferator must divert to obtain one SQ of fissile material, the greater will be the difficulty of handling the material. This is based on the assumption that handling a greater number of items is more difficult than handling fewer, if for no other reason than because the diversion task will have to be repeated. For example, obtaining one SQ of plutonium from the spent fuel (with a standard irradiation) from a pressurized water reactor (PWR) would require the diversion of only two fuel assemblies whereas it would take about 150,000 fuel pebbles from a pebble bed reactor to achieve the same diversion. The latter would be more difficult to handle than the former.

#### *5.2.1.1.4 Input: Material form (solid, powder, liquid, gas)*

This input assumes that, all other things being equal, solids are easier to handle than powders, powders easier to handle than liquids, and liquids easier to handle than gases. Barring considerations such as heat and radiation, a solid object will likely require no container. A powder would require some form of container, probably with a lid to keep the material from dispersing. Liquid would require an impermeable container or a tank. Gas is considered the most difficult because it would likely require a tank that could be pressurized as well as a sealed transfer mechanism.

#### *5.2.1.1.5 Input: Radiation level in terms of dose (Sv/hour/SQ)*

This input considers the acute biological effects of whole-body radiation dose to the proliferator. High dose rate materials would be hazardous to handle and may require the use of expensive and unique equipment. Extremely high dose rate materials would also provide a danger to the physical well-being of the proliferator especially if acute effects incapacitated the proliferator in a short time period. Thus, radiation has a direct effect on the difficulty of handling a diverted material, with difficulty increasing as with dose rates rise. As in previous inputs SQs are used to normalize this input over all fissile materials

#### *5.2.1.1.6 Input: Chemical reactivity (rate of reaction)*

The chemical reactivity of the diverted material with common substances like air, water, steels, and plastics can complicate the handling of the diverted material. Reactions that occur quickly will have a greater impact on handling difficulty than those that occur slowly. If the material has rapid reactions with air, then it must be kept in an inert atmosphere as it is removed from a system. If it reacts readily with water, that atmosphere will need to be dry. These create significant handling difficulties. Rapid reactions with steels or plastics will severely limit the options the proliferator has for container materials, creating moderate difficulties. Finally, if the material has slow reactions (i.e. corrosion, etc.) with steels and plastics, it will limit the amount of time available for transport in such containers, a smaller difficulty. Material handling difficulty increases with the number of these chemical reaction issues that exist.

#### *5.2.1.1.7 Input: Heat load (thermal Watts per cubic centimeter)*

This input considers the heat load of the diverted material itself. It is a measure of the rate at which the material itself generates heat (such as from the decay of radioactive isotopes). If this heat load is high enough, it will need to be mitigated with some kind of heat removal system which must be applied during diversion. Also, increasing the heat load will create a need for increasingly complex or large heat removal equipment.

#### 5.2.1.1.8 *Input: Process temperature (degrees Celsius)*

This input considers the temperature of the system from which the material is being diverted. In general, wherever nuclear material is intended to be handled by workers on a regular basis, it exists in a system that is relatively cool. However, if the proliferator chooses to divert material from some other, unusual location, the system temperature may be higher. If it is hot enough, it may begin to limit the tools that can be used and the amount of time that people can spend working on the diversion. For that reason, handling difficulty will increase with temperature.

#### 5.2.1.2 Attribute: Difficulty of Evading Detection by the Accountancy System

Detection through the accounting system is provided through international inspection activities. These activities are used to confirm the adequacy and veracity of the State System of Material Accounting and Control (SSAC). Each state under IAEA safeguards must implement an SSAC. This system, based upon discrete Material Balance Areas (MBA), requires a state to keep track of existing inventory as well as incoming, outgoing, produced and destroyed nuclear materials. Declarations of periodic inventories are provided to international inspectors, based upon material measurements that confirm that any record imbalances (material unaccounted for, or MUF) meet the required safeguards criteria and are within measurement uncertainties. Inspectors perform periodic evaluations of facilities and confirm inventories and facility records through confirmatory measurements to detect if any material is missing. Four inputs can be used to gauge the strength of this accountancy system.

##### 5.2.1.2.1 *Input: Uncertainty in accounting measurements (SQs/year)*

The uncertainty in the accountancy measurements is obtained by multiplying the measurement uncertainty value (a percentage) by the number of SQs of fissile material processed through the facility in or held in inventory during an inventory period. The inventory period is an IAEA requirement that depends on material type.<sup>5</sup> As uncertainty in the accountancy system declines, protracted diversions become more difficult (decreases in uncertainty may also make abrupt diversion more difficult, though the input is better suited for protracted diversions).

The accountancy measurement uncertainty will depend on a number of factors including the type of material, the matrix of the material, the measurement method used, and the sampling plan. The measurement uncertainty should include both random and systematic components. For hypothetical systems or if actual uncertainties for an existing system are not known, then the IAEA Initial Target Values (ITV) could be used. The assumption is that if this value is greater than one SQ, then the proliferator could have diverted enough material for one weapon without causing a statistically meaningful change in value for the accountancy system measurements. As this input value decreases, it causes greater difficulty for the proliferator to divert material without being detected.

##### 5.2.1.2.2 *Input: Expected vs. actual MUF (SQs)*

Any facility will have a certain amount of MUF due to hold-up in pipes, fuel rods that have fallen underneath the racks of a spent fuel pool, etc. These things become part of the facility's inventory record and may be verified through periodic measurement of the material on-site or may be estimated. Consistently large differences may suggest that the accountancy system is less able to detect material diversion. To avoid scenarios in which this input inadvertently penalizes large facilities, the user may choose to evaluate individual MBAs instead of entire facilities.

This input will be particularly difficult to use. In addition to the fact that the "actual MUF" will be only be available to a small group of users, "expected MUF" may also be very difficult to estimate.

#### 5.2.1.2.3 *Input: Frequency of accounting record comparisons and verifications (number per unit time)*

This input assumes that if it were possible to evaluate inventories constantly in real time, diversion could be more readily detected. Lower frequency accounting gives proliferators more time between measurements to divert a quantity of nuclear material and fabricate a weapon before the absence of the material is detected.

#### 5.2.1.2.4 *Input: Amount of material available*

The amount of material available (the process throughput and the inventory of the facility) input does not itself directly impact the difficulty of evading the accounting system, but when coupled with the accounting system uncertainty (in percentage), it is a factor in assessing the overall uncertainty in the accounting system in terms of mass of material.

### 5.2.1.3 Attribute: Difficulty of Evading Detection by the Material Control System

The third attribute considered in the diversion stage is the difficulty of evading detection by the material control system. This attribute measures the effectiveness and efficiency (timeliness) of the available systems and procedures for monitoring and controlling the integrity of safeguards-relevant data and accountancy systems (continuity of knowledge) and the physical containment of a facility to detect the undeclared insertion or undeclared movement of material. The measures include containment and surveillance systems (C/S). We identified a single input relevant to this attribute.

#### 5.2.1.3.1 *Input: Probability of detection based on vulnerability analysis of material control system in place (requires the development of standards and an evaluation of how facilities compare)*

The material control portion of the safeguards system is based on containment and surveillance and is meant to detect the unauthorized movement of nuclear materials. Tools in use for this include video surveillance, radiation monitors, seals, and RFID tags. The effectiveness of material control and, thus, the difficulty of removing material undetected, is a function of the vulnerability of the system in place. Evaluating the probability that the control system will detect unauthorized movement requires the development of standards and an assessment of how facilities compare. This would require a detailed vulnerability assessment for the material in a facility. For many hypothetical cases, there may not be sufficient information to generate this assessment. In these cases, it is suggested that this input be ignored.

### 5.2.1.4 Attribute: Difficulty of Conducting Undeclared Facility Modifications for the Purpose of Diverting Nuclear Material

This attribute evaluates the difficulty of conducting undeclared modifications of a civilian nuclear facility for the purpose of covertly removing nuclear material from the normal process stream. Undeclared facility modification means altering the design, structure and/or equipment of an existing safeguarded facility for the purpose of diverting nuclear material. The identified inputs only seek to evaluate “reasonable” modifications which would not compromise the structural integrity of the facility or permanently compromise the ability of the facility to continue operations. An example of reasonable facility modifications might be the installation of new valves and piping in a centrifuge enrichment facility to covertly divert an amount of UF<sub>6</sub> gas. Another example would be constructing additional facility penetrations to bypass the material control system. There are seven inputs used to characterize this attribute.

#### 5.2.1.4.1 *Input: Is there enough physical space and access to actually make the modifications?*

This input considers whether there is enough physical space or access to perform the modifications. For example, a proliferator may want to add an additional penetration through a wall to allow for removal of a large container of nuclear material; however, the wall may have structural supports or large permanent equipment in place that inhibits penetrations of that size.



*5.2.1.4.2 Input: Number of person-years needed to perform modifications*

This input accounts for the number of person-years of effort required to perform the modification. The larger the effort required to perform the modification, the more difficulty the modification is to complete.

*5.2.1.4.3 Input: Requirement for use of remote handling tools*

Some modifications may need to be made inside of high radiation environments or other highly hazardous environments that would necessitate the use of remote handling. The use of remote handling tools increases the difficulty of performing the modifications because of the specialized equipment and expertise needed. Also, certain operations are more difficult to perform remotely and may limit the types of modifications that can be made.

*5.2.1.4.4 Input: Requirement for specialized tools*

Some modifications may require the use of specialized tools. Specialized tools are those that are difficult to acquire, difficult to transport to the facility, or require specialized training to use. The need for this equipment will add increased complexity to the operation of performing the modifications.

*5.2.1.4.5 Input: Requirement to stop process to make modifications*

Some modifications may require that regular operations be interrupted. Disrupting normal facility operations will add increased operational complexity to the modifications. This input is intended to capture these increased complexities *not to capture the increased probability of the modifications being detected.*

*5.2.1.4.6 Input: Risk of modification (safety)*

This input is intended to reflect the increased risk to the safety of the facility personnel due to the modification construction and performing the diversion while the modification is in place.

*5.2.1.4.7 Input: Risk of penetrating containment*

This input is intended to reflect the increased risk to the structural and operational integrity of the facility due to the construction of the modifications and the act of performing the diversion with those modifications.

**5.2.1.5 Attribute: Difficulty of Evading Detection of the Facility Modifications for the Purposes of Diverting Nuclear Material**

This attribute evaluates the difficulty of evading detection while conducting undeclared modifications to a civilian nuclear facility for the purpose of covertly removing nuclear material from the normal process stream. This addresses whether or not the proliferator is likely to be detected while the modifications necessary to divert the material are being conducted or are in place. We identified a single input relevant to this attribute.

*5.2.1.5.1 Input: Probability of detection based on vulnerability analysis of design verification system [to include factors such as percentage of facility or process step under effective IAEA surveillance and frequency of inspection (number/year, IAEA criteria)]*

This input captures the ability of the international community to detect the facility modifications made for the purpose of diverting nuclear material. Part of the routine inspections for a facility may include design verification and this input is in part intended to reflect the difficulty for the proliferator in evading detection from that inspection. This will involve a detailed vulnerability assessment of the modification in the facility which also includes the characteristics of the inspection regime. The frequency of inspections will be determined by the safeguards criteria (see reference 5).

## 5.2.2 Transportation Stage

The transportation stage presents two obstacles to the proliferator: material handling difficulties and the risk of detection. However, these must be considered differently from the same obstacles in the diversion stage. During transport, the analyst must consider the difficulties in handling the nuclear material as well as the *container* in which the material is being moved. This will likely add significantly to the mass and bulk that must be considered and could create new difficulties such as a need for active heat removal. Also, the methods available to detect transportation are different from those in the safeguards systems at the source facility. These barriers can be addressed with two attributes.

**Table 2.** Inputs for the Transportation stage.

<b>TRANSPORTATION</b>	
•	<b>2.1 Difficulty of handling material during transportation</b>
	2.1.1 <i>Mass/SQ</i>
	2.1.2 <i>Volume/SQ</i>
	2.1.3 <i>Material form (solid, liquid, powder, gas)</i>
	2.1.4 <i>Radiation level in terms of dose</i>
	2.1.5 <i>Heat load</i>
	2.1.6 <i>Chemical reactivity with common substances</i>
	2.1.7 <i>Chemical toxicity – immediate</i>
	2.1.8 <i>Chemical toxicity - time-weighted averaged</i>
•	<b>2.2 Difficulty of evading detection during transport</b>
	2.2.1 <i>Mass of material and transportation container</i>
	2.2.2 <i>Volume of material and transportation container</i>
	2.2.3 <i>Heat load of material</i>
	2.2.4 <i>Radiation signature from transportation container</i>
	2.2.5 <i>Host country size/land area</i>
	2.2.6 <i>Number of declared nuclear facilities</i>
	2.2.7 <i>Number of IAEA satellite images of host country analyzed per unit time</i>

### 5.2.2.1 Attribute: Difficulty of Handling Material during Transportation

This attribute considers the physical transportation of a single unit of material from the diversion site to the transformation site. A single unit of material could include examples such as: a single fuel assembly, a can of oxide powder, a 55 gallon drum of plutonium nitrate solution containers, a UF<sub>6</sub> gas cylinder. The transportation could be via any of a number of modes including motor vehicles, railcars, marine vehicles, aircraft, pedestrian transport, etc. Factors critical to the assessment of this attribute will include mass, bulk or volume, specialized container requirements for transportation due to material phase (solid, liquid, or gas), the biological hazard associated with the radiation field from the material, required shielding associated with the radiation field from the material, chemical reactivity (including corrosiveness, flammability, volatility, explosiveness, etc.), and the biological hazard associated with the chemical form of the material (inhalation toxicity, ingestion hazards, or damage through the skin).

The material handling difficulties in transporting nuclear material are similar to those in the diversion stage, but there are key differences. The mass and volume of the material must be considered again, but for transportation there is likely a sizeable container that must also be considered. Detectability remains an issue, but the means of detection here are different. Also, the personnel involved in this stage of proliferation will likely be spending more time in close proximity to the material than in the diversion stage, so health and safety hazards must be considered.

#### 5.2.2.1.1 *Input: Mass/SQ*

The mass per SQ of nuclear material is the mass of both the diverted item(s) and the transport container. The containment considered must be sufficient to carry at least one SQ of weapons-usable material. Greater mass causes greater handling difficulties as hoisting equipment and more heavy-duty transport vehicles become necessary, so there is a direct relationship between this input and the material handling attribute.

#### 5.2.2.1.2 *Input: Volume/ SQ*

The volume of material per SQ is similar to the volume input in the diversion stage, except that it must now include the volume of the transport container as well. Greater volume causes greater handling difficulties as larger vehicles and more complex rigging become necessary for transport. This could even limit the available routes of movement, especially over land as some roads are too small to accommodate large trucks.

#### 5.2.2.1.3 *Input: Material form (solid, liquid, powder, gas)*

The form of the diverted material, solid, powder, liquid or gas dictates the necessity for the use of special containers. This generally does not apply to solids, but liquids and gases would require tanks and/or high-pressure bottles which would likely be difficult to transport in an ordinary vehicle.

#### 5.2.2.1.4 *Input: Radiation level in terms of dose (Sv/hour)*

The radiation level is in terms of dose of the unshielded material, not the radiation signature on the outside of the transport container. This input will dictate what that container needs to be made of in order to protect nearby people (truck driver, barge pilot, etc.) from exposure. Greater radiation coming from the materials will create greater handling difficulties by necessitating shielding (requiring knowledge of shield physics and increasing the mass being transported) or regulated exposure time for individuals conducting the transport. This input will be a measure of the exposure rate at a distance of one meter from the source, in units of Sv/hr.

#### 5.2.2.1.5 *Input: Heat load (Watts/SQ)*

The heat load of the material is identical to the heat load input included in the diversion stage. Many nuclear materials generate heat and require active cooling to prevent damage and material release. The greater this heat load, the greater the complexity of the portable cooling system that will be needed for transport. This input will be measured in thermal Watts emitted per SQ of material.

#### 5.2.2.1.6 *Input: Chemical reactivity with common substances*

The chemical reactivity of the diverted material with common substances like water, air, steels and plastics is identical to the chemical reactivity input in the diversion stage.

#### 5.2.2.1.7 *Input: Chemical toxicity - immediate*

The immediate chemical toxicity (hazard to humans) is much like the radiation dose input above, if the material is chemically toxic to humans, measures must be taken to protect those conducting the transport. The greater those measures, the greater the difficulty in handling the material. This consideration is separated into two inputs because chemical toxicity can be measured in two distinctly different ways. One is the Immediately Dangerous to Life and Health (IDLH) concentration of a material, as established by the US Center for Disease Control (CDC). This deals with a substance's ability to rapidly incapacitate an individual. The lower the IDLH concentration is for a material, the more difficult it will be to handle safely.

#### 5.2.2.1.8 *Input: Chemical toxicity – time-weighted average*

Another way to measure toxicity is a Time-Weighted Average (TWA) concentration limit which, if exceeded, would pose health risks. TWA toxicity deals with long-term health effects and would not be exceeded if the transportation stage is short. However, if the transport takes a very long time, the TWA limits will result in personnel risk and its accompanying difficulties.

#### 5.2.2.2 *Attribute: Difficulty of Evading Detection during Transportation*

This attribute considers the likelihood that the transportation of material within its transportation package can be detected by a concerned third party. It will depend on the characteristics of the material being moved and the presence and effectiveness of monitoring systems that are not under the control of the diverting party. These monitoring systems could include multi-national environmental sampling (i.e., searching for effluents from the material), border monitors (i.e., searching for radiation signatures from the material), satellite or aerial detection (i.e., searching for the visual, infrared, or multi-spectral signature from the material or its container), or physical inspection.

##### 5.2.2.2.1 *Input: Mass of material and transportation container (kg)*

If the material and its container are very massive, then they will require a large vehicle to move which can be more easily detected. This will require the analyst to include specifications of the transportation container in the scenario definition. For example, the analyst could specify that the container is a standard spent nuclear fuel transport cask for truck or rail transport. For the mass input, the measured quantity is the combined mass of the diverted material and transport container.

##### 5.2.2.2.2 *Input: Volume of material and transportation container (m<sup>3</sup>)*

The volume of the container being transported (or the volume of the material if no container is used) will impact the difficulty of transportation. If the container is very large, then it will require a large vehicle to move which can be more easily detected. This will require the analyst to include specifications of the transportation container in the scenario definition. For the volume input, the measured quantity is the volume of the outer boundary of the container (or of the diverted material if no container is used).

##### 5.2.2.2.3 *Input: Heat load of material*

The heat load of the material is the same input described in the first transportation attribute. It is used here to account for the fact that heat is a signature of nuclear material that can be detected remotely. As the heating rate increases, the transport vehicle will show up more easily on infrared images and make it more difficult to move the material undetected.

##### 5.2.2.2.4 *Input: Radiation signature from transportation container*

The diverted material may be transported within the range of a detector system which may be sensitive to the radiation signature outside the transportation container. This input is intended to capture the increased difficulty of evading the detection systems when the radiation signature from the transportation container increases. This involves a calculation that includes the radiation emitted from the material as well as the shielding effect of the container which may include shielding materials (note the mass and volume of these shielding materials must be included in the inputs above).

##### 5.2.2.2.5 *Input: Host country size/land area (km<sup>2</sup>)*

This input addresses the difficulty of detecting the movement of diverted material within the proliferating state(s). Larger areas make detection less likely. It should be noted that this should be measured in square kilometers of host country including both land and waterways, since transport could occur over either.

#### 5.2.2.2.6 *Input: Number of declared nuclear facilities*

This input is meant to capture the difficulty of determining which activities within a country of interest are legitimate and which are not. If a country were to successfully divert material out of a safeguarded plant and into a transportation system that regularly supports legitimate nuclear cargo detection will be less likely than if the movement of nuclear material represented an anomaly.

#### 5.2.2.2.7 *Input: Number of IAEA satellite images of host country analyzed per unit time*

Though a transport is observable, it will not be detected unless someone is looking for it. The number of satellite images of the host country analyzed by the IAEA per unit time gives an indication of the level of scrutiny that a country is under by the international community (imagery from national technical means (NTM) is not considered here). Greater scrutiny results in a greater chance of detection. Therefore, the higher this rate is, the more difficult it will be for the proliferator to avoid detection.

This data will either be unavailable or inaccessible to most parties other than the IAEA. However, it was determined that there is value in leaving the input in for the sake of being able to evaluate the conditions under which a state could undertake certain activities. For example, this could be used to show that a certain number of analyzed images would sufficiently reduce the proliferation risk of a certain process, facility or system in a particular state.

### 5.2.3 *Transformation Stage*

Material transformation will require facilities, equipment and knowledge that may not be consistent with a state's civilian nuclear industry. The extent of this new infrastructure development will depend greatly on what material was diverted and how much work must be done to convert it to a weapons-usable metal. For example, if the diverted material is reactor-grade uranium in a fuel bundle, it will first have to be chemically separated, then converted to UF<sub>6</sub> gas, then re-enriched to weapons-grade and converted back to metal. However, if the diverted fuel was HEU metal reactor fuel, it would only need to be chemically separated from the fuel matrix to be used in a weapon. We identified four attributes to assess these considerations (Figure 5).

#### 5.2.3.1 *Attribute: Facilities and Equipment needed to Process Diverted Materials*

This attribute considers the difficulty inherent in converting a diverted material into a weapons-usable form indicated by the type and quantity of equipment and facilities needed to perform the conversion. It does not consider facilities and equipment which might be acquired to evade detection. For example, low enriched uranium in the form of UF<sub>6</sub> gas would require an enrichment facility to enrich the material to a high enrichment and a chemical conversion facility to convert the UF<sub>6</sub> gas to a metallic form. Alternatively, facilities or equipment would not be required to process metallic plutonium. This attribute assumes that any transformation activity requires the construction of a facility in which to conduct transformation.

The extent of facilities and equipment needed to process diverted material serves as a barrier to proliferation: the more facilities and equipment needed, the higher the barrier. This can be assessed by determining what needs to be done to the diverted material and what facilities are needed to complete that work and can be captured with three inputs.

##### 5.2.3.1.1 *Input: Cost of facilities and equipment required for transformation*

The need for facilities and equipment for transformation can vary widely from almost nothing to an entire enrichment or reprocessing plant. This will be a major indicator of the feasibility of a particular proliferation path. The input units are in dollars or other appropriate currency.

5.2.3.1.2 *Input: Number of different types of export controlled equipment/materials*

The number of different types of export-controlled equipment and materials that the proliferator would need to conduct the transformation the material is an indication of the technical level of the process. The presence of export controls will make a piece of equipment/material more difficult to obtain. This input only considers the difficulty of acquiring the first of a kind of technology/material. The difficulty associated with replication of that technology should be considered in country-specific capability assessments, not within this input.

**Table 3.** Inputs for the Transformation stage.

<b>TRANSFORMATION</b>	
<ul style="list-style-type: none"> <li>• <b>3.1 Facilities and equipment needed to process diverted materials</b> <ul style="list-style-type: none"> <li>3.1.1 <i>Cost of facilities and equipment required for transformation</i></li> <li>3.1.2 <i>Number of different types of export controlled equipment/materials</i></li> <li>3.1.3 <i>Minimum electrical requirement</i></li> </ul> </li>   <li>• <b>3.2 Knowledge, skills and workforce needed to process diverted materials</b> <ul style="list-style-type: none"> <li>3.2.1 <i>Highly trained technical experts needed to transform the material</i></li> <li>3.2.2 <i>Advanced degreed scientists and engineers needed to transform the material</i></li> <li>3.2.3 <i>Technicians needed to transform the material</i></li> <li>3.2.4 <i>Labor workers needed to transform the material</i></li> </ul> </li>   <li>• <b>3.3 Difficulty of evading detection of transformation activities</b> <ul style="list-style-type: none"> <li>3.3.1 <i>Is the Additional Protocol in force in this state?</i></li> <li>3.3.2 <i>Frequency of environmental sampling measurements</i></li> <li>3.3.3 <i>Isotopic signatures</i></li> <li>3.3.4 <i>Sensitivity of equipment (used by inspectors) to detect and measure signatures associated with a range of types of processes used for transformation (e.g., aqueous or pyro-processing for a reprocessing facility; centrifuges or calutrons for an enrichment facility)</i></li> <li>3.3.5 <i>Facility size</i></li> <li>3.3.6 <i>Heat load</i></li> <li>3.3.7 <i>Sonic load</i></li> <li>3.3.8 <i>Radiation load</i></li> <li>3.3.9 <i>Volume of non-naturally occurring gases emitted</i></li> <li>3.3.10 <i>Undiluted volume of liquid emissions</i></li> </ul> </li> </ul>	

5.2.3.1.3 *Input: Minimum electrical requirement (kw)*

The electrical requirement of the material conversion process is an indication of the total work required for the transformation. Large electrical requirements call for generation resources and it would make covert operation of a transformation facility more difficult. This input will be a measure of the electricity demand of the transformation facility or facilities.

5.2.3.2 **Attribute: Knowledge, Skills and Workforce Needed to Process Diverted Material**

This attribute considers the difficulty inherent to converting a diverted material into a weapons-usable form indicated by the level of knowledge and skills needed to perform the conversion and the manual labor. The required areas of expertise could include radiation shielding, radiation detection, chemical separation/enrichment, chemical conversion, and metallurgical skills depending on the degree of transformation necessary to process the diverted material to a weapons-useable form.

#### 5.2.3.2.1 *Input: Highly trained technical experts*

These will be specialists that cannot easily obtain the required skills and knowledge at a typical college or university. Example skill sets are actinide chemistry, remote material handling, waste handling and disposition and plutonium metallurgy. The units may be number of individuals or person-years depending upon the analysis.

#### 5.2.3.2.2 *Input: Advanced degreed scientist and engineers*

Scientists and engineers may be needed for process design and control. Typical disciplines are nuclear engineering, physics, chemistry, and metallurgy. The units may be number of individuals or person-years depending upon the analysis.

#### 5.2.3.2.3 *Input: Technicians*

Electrical, mechanical or chemical technicians may be required for assembling and operating equipment. The units may be number of individuals or person-years depending upon the analysis.

#### 5.2.3.2.4 *Input: Labor workers*

Laborers may be needed for construction and installation of equipment. The units may be number of individuals or person-years depending upon the analysis.

### 5.2.3.3 Attribute: Difficulty of Evading Detection of Transformation Activities

If the proliferator is able to obtain or build all the necessary equipment and facilities and assemble an adequate work force, the work must still be performed without being detected. This attribute is a measure of the extent to which the operation of a clandestine transformation facility can be remotely detected. Detectable signatures of such a facility may include: the presence of radioactive material in the environment; heat generation; liquid or gaseous chemical releases; presence of specific infrastructures for electricity or water supplies. The primary factor in detectability of these signatures is the type of process being conducted.

#### 5.2.3.3.1 *Input: Is the Additional Protocol in force in this state?*

The Additional Protocol, an optional addendum to a state's safeguards agreement, allows the IAEA to conduct unannounced inspections of declared and undeclared sites. If the Additional Protocol is in place, the probability of detection of transformation activities will increase. This is a binary input which indicates whether a state has brought the Additional Protocol into force.

#### 5.2.3.3.2 *Input: Frequency of environmental sampling measurements*

The next two inputs are repeated from the detection attribute in the transportation stage: the frequency with which environmental samples are taken and the number of declared nuclear facilities. Environmental samples will alert inspectors to covert nuclear activity if they detect unexpected radioactive signatures. Signatures in an unexpected location would indicate a covert processing facility. Unexpected isotopic signatures at a declared facility would indicate that undeclared activities are being undertaken somewhere on site where inspectors do not routinely go. The greater the frequency of these environmental samples, the more likely detection will occur.

#### 5.2.3.3.3 *Input: Isotopic signatures*

The isotopic signature of the various compounds and processes used in transformation could be picked up by environmental samples or radiation monitors. There are specific signatures that will serve as concrete evidence that nuclear material is being transformed for non-peaceful purposes. The more of these there are in a proliferator's transformation process, the harder it will be to conceal them all and avoid detection. The material may be leaving the site either airborne as a gas or aerosol, or via a waterway. The input

could be expressed as a concentration of each detectable species leaving the site, both airborne and waterborne.

*5.2.3.3.4 Input: Sensitivity of equipment (used by inspectors) to detect and measure signatures associated with a range of types of processes used for transformation*

This is a difficult input to characterize. Assessments will need to account for the overall quality of the available detection system.

*5.2.3.3.5 Input: Facility size*

Facility size reflects the ability of the international community to spot a nuclear facility on overhead imagery. The larger a facility, the more difficult it will be to hide. Size alone, however, is not a sufficient indicator. Distinctive shapes – such as cooling towers for a reactor – and other signatures will be necessary to supplement this input.

*5.2.3.3.6 Input: Heat load (Watts)*

The heat load at a facility is the heat generated at a transformation facility that must be dissipated and could be detected with infrared scans. The difficulty of evading detection will increase with increasing heat loads.

*5.2.3.3.7 Input: Sonic load*

The sonic load of a facility, including noise level in decibels and the frequency of the sound is especially revealing with centrifuge enrichment plants which give off characteristic vibrations that can be identified. While sonic emissions can be reduced, they may still contribute to detection.

*5.2.3.3.8 Input: Radiation load (Sv/hr)*

The greater the radiation field for the entire process, the more shielding that will be required to contain and conceal it. Shielding will be expensive and bulky and thus increase the likelihood of detection.

*5.2.3.3.9 Input: Volume of non-naturally occurring gases emitted*

The final two inputs for this attribute have to do with the gaseous and liquid wastes that a transformation facility releases to the environment. Any substance that is not naturally-occurring in the surrounding environment can show up in environmental samples if its concentration is above detection thresholds. The more of these emissions a facility makes, the higher those concentrations will be, increasing the chance of detection. This and the next input are independent from the isotopic emissions discussed in section 5.2.3.3.3.

*5.2.3.3.10 Input: Undiluted volume of liquid emissions*

This attribute addresses the gaseous wastes that a transformation facility releases into the environment. Higher emissions from a facility result in an increased chance of detection.

## **5.2.4 Weapon Fabrication Stage**

The fabrication of a weapon presents a different set of obstacles to the proliferator than the material transformation stage. The risk that fabrication activities will be detected is very low and can, therefore, be neglected as a consideration. Once the material is in a weapons-usable form detectable signatures such as the radiation field have all but disappeared and the activities of weapon construction (design, casting, machining and assembly) are easily concealable in any building. The primary challenges against which success must be assessed come from the technical challenge of creating a functional weapon. These challenges can be characterized with three attributes.



**Table 4.** Inputs for the Weapon Fabrication stage.

<b>WEAPON FABRICATION</b>	
•	<b>4.1 Difficulty associated with design</b>
4.1.1	<i>Spontaneous fission neutron production rate of weapons material</i>
4.1.2	<i>Radiation exposure at one meter</i>
4.1.3	<i>Heating rate of weapons material</i>
4.1.4	<i>Can ballistic assembly methods be used?</i>
4.1.5	<i>Phase stability of weapons material</i>
•	<b>4.2 Handling difficulties</b>
4.2.1	<i>Radiation level in terms of dose</i>
4.2.2	<i>Chemical reactivity with common substances</i>
4.2.3	<i>Radiotoxicity</i>
•	<b>4.3 Knowledge and skills needed to design and fabricate</b>
4.3.1	<i>Knowledge and skill level for material/weapon type alternatives (direct input from a priori calculations)</i>

#### 5.2.4.1 Attribute: Difficulty Associated with Design

This attribute considers the difficulty associated with designing and assembling a device that will produce a nuclear yield from the material obtained. The primary factors of concern are the spontaneous fission rate, heating rate, radiation field, and chemical reactivity of the material. This attribute will answer questions such as whether a simple weapon design will suffice or if greater complexity and precision are required, whether the material can be easily fabricated into the needed shape or if its material properties will cause problems.

##### 5.2.4.1.1 Input: *Spontaneous fission neutron production rate of weapons material (n/s/SQ)*

Neutron emissions within the core will reduce the weapon's ability to produce a nuclear yield because they have the ability to initiate the fission reaction too early and cause a "fizzle" before maximum compression is achieved. The greater the neutron production rate is, the higher the probability of pre-initiation and the more difficult the weapon design will be. This value will determine the value of input 5.2.4.1.4.

##### 5.2.4.1.2 Input: *Radiation exposure at one meter (Roentgens/hour)*

The radiation exposure rate in air at a distance of one meter from the un-shielded weapon core will have a detrimental impact on the non-nuclear components of the weapon, causing radiation damage and charge deposition in the materials. This will have to be mitigated by careful selection of materials for those components, or by shielding them from the radiation. Either way, the difficulty will be directly proportional to the exposure rate.

##### 5.2.4.1.3 Input: *Heating rate of weapons material (Watts/SQ)*

Heat will have an impact on weapon components and must be dissipated for the weapon to remain functional. The greater the heating rate, the greater the effort required to dissipate it and hence, the greater the design difficulty.

##### 5.2.4.1.4 Input: *Can ballistic assembly methods be used?*

The input asks whether the weapon can function using ballistic (gun-type) assembly methods. If the answer is "yes", the design will be easier because no special shaping of the explosive will be required. If

the answer is “no”, the difficulty of designing the weapon is greatly increased by adding the need for explosive lenses and very high-precision electronic timing for the detonators.

#### 5.2.4.2 Attribute: Handling Difficulties

The second attribute is material handling difficulty during weapon fabrication. This attribute is a function of the chemical and radiological properties of the fissile material. If the material emits a high radiation field, then it could require shielding to protect the weapon assemblers and users. If the material is highly radiotoxic, meaning that it presents a great ingestion or inhalation hazard to humans, then breathing apparatuses and anti-contamination measures will be needed. Finally, if the fissile material is reactive with common substances such as air, then the weapon may need to be assembled in an inert atmosphere.

##### 5.2.4.2.1 Input: Radiation level in terms of dose (Sv/hr)

The radiation emitted by the material will cause greater handling difficulties by necessitating shielding (requiring knowledge of shield physics and possibly interfering with those constructing the weapon) or regulated exposure time. Higher dose rates will translate to a greater difficulty of working with the material.

##### 5.2.4.2.2 Input: Chemical reactivity with common substances

The chemical reactivity of the weapons material with common substances like water, air or plastics is identical to the chemical reactivity inputs used in previous stages. The need to keep air away from the material will increase difficulty.

##### 5.2.4.2.3 Input: Radiotoxicity

Radiotoxicity is the ingestion/inhalation hazard the material poses to humans. While the external radiation dose from the material may be low,  $\alpha$  radiation poses a deadly threat to the internal organs if any small particles of the material are inhaled or ingested. In order to protect themselves, workers will have to use vacuum hoods and/or respirators and use tight contamination controls, all of which will increase the difficulty of handling the material.

#### 5.2.4.3 Attribute: Knowledge and Skills needed to Design and Fabricate

The final attribute in the weapon fabrication stage is a quantification of the knowledge and skills needed to design and fabricate the weapon. This attribute considers the difficulty in obtaining a nuclear yield from the material in hand as well as the difficulty of physically working with the material as indicated by the level of knowledge and skills needed to fabricate the weapon. This could include hydrodynamics, nuclear physics, neutronics, metallurgy, electronics or high explosives skills.

##### 5.2.4.3.1 Input: Knowledge and skill level for material/weapon type alternatives

The knowledge and skills needed to design and fabricate a nuclear weapon are highly dependent on what type of weapon is desired. This, in turn, depends on the material available, any size or weight constraints, and many other factors. This will need to be assessed as a direct input from *a priori* calculations for alternative weapon types. These calculations will need to be based on several factors.

### 5.2.5 Facility Misuse Stage

The facility misuse stage assumes the use of an existing safeguarded nuclear facility for undeclared production of material. For example, the diverter might try to modify the space outside the pressure vessel on a PWR to allow for irradiation of natural uranium targets. There are five attributes used to characterize this stage.

**Table 5.** Inputs for the Facility Misuse stage (part 1).

<b>FACILITY MISUSE (PART 1)</b>	
•	<b>5.1 Difficulty of conducting facility misuse</b>
	5.1.1 <i>Mass/SQ of imported nuclear material</i>
	5.1.2 <i>Mass/SQ of exported nuclear material</i>
	5.1.3 <i>Volume/SQ of imported nuclear material</i>
	5.1.4 <i>Volume/SQ of exported nuclear material</i>
	5.1.5 <i>Number of imported items/SQ</i>
	5.1.6 <i>Number of exported items/SQ</i>
	5.1.7 <i>Imported material form (solid, liquid, powder, gas)</i>
	5.1.8 <i>Exported material form (solid, liquid, powder, gas)</i>
	5.1.9 <i>Radiation level of imported materials in terms of dose</i>
	5.1.10 <i>Radiation level of exported materials in terms of dose</i>
	5.1.11 <i>Chemical reactivity of imported material</i>
	5.1.12 <i>Chemical reactivity of exported material</i>
	5.1.13 <i>Temperature - point of material introduction</i>
	5.1.14 <i>Temperature - point of material extraction</i>
	5.1.15 <i>Heat load of imported material</i>
	5.1.16 <i>Heat load of exported material</i>
	5.1.17 <i>Throughput capacity of facility available for facility misuse</i>
	5.1.18 <i>Percentage of normal process impacted</i>
	5.1.19 <i>Extent of deviation from normal facility process</i>
	5.1.20 <i>Physical barriers to facility misuse</i>
	5.1.21 <i>Technical barriers to facility misuse</i>
•	<b>5.2 Difficulty of evading detection of facility misuse</b>
	5.2.1 <i>Number of people required to conduct facility misuse</i>
	5.2.2 <i>Frequency of environmental sampling measurements</i>
	5.2.3 <i>Normal heat load</i>
	5.2.4 <i>Abnormal heat load as a result of facility misuse</i>
	5.2.5 <i>Sensitivity of detectors available to measure heat load</i>
	5.2.6 <i>Normal radiation load</i>
	5.2.7 <i>Abnormal radiation load as a result of facility misuse</i>
	5.2.8 <i>Sensitivity of detectors available to measure radiation load</i>
	5.2.9 <i>Normal material flow rates</i>
	5.2.10 <i>Abnormal material flow rates during facility misuse</i>
	5.2.11 <i>Sensitivity of detectors available to measure material flow rates</i>
	5.2.12 <i>Normal volume of non-naturally occurring gasses in facility</i>
	5.2.13 <i>Abnormal volume of non-naturally occurring gasses in facility</i>
	5.2.14 <i>Sensitivity of detectors available to measure volume of non-naturally occurring gasses in facility</i>
	5.2.15 <i>Normal volume of non-naturally occurring gasses emitted</i>
	5.2.16 <i>Abnormal volume of non-naturally occurring gasses emitted</i>
	5.2.17 <i>Sensitivity of detectors available to measure volume of non-naturally occurring gasses emitted</i>
	5.2.18 <i>Normal characteristics (mass, volume, concentration) of liquid waste in facility</i>
	5.2.19 <i>Abnormal characteristics (mass, volume, concentration) of liquid waste in facility</i>
	5.2.20 <i>Sensitivity of detectors available to measure characteristics (mass, volume, concentration) of liquid waste in facility</i>
	5.2.21 <i>Normal characteristics (mass, volume, concentration) of liquid emissions</i>
	5.2.22 <i>Abnormal characteristics (mass, volume, concentration) of liquid emissions</i>
	5.2.23 <i>Sensitivity of detectors available to measure characteristics (mass, volume, concentration) of liquid emissions</i>
	5.2.24 <i>Deviation of utilities consumption from normal</i>
	5.2.25 <i>Deviation of use of consumables (e.g., nitric acid) from normal</i>

**Table 6.** Inputs for the Facility Misuse stage (part 2).

<b>FACILITY MISUSE (PART 2)</b>	
<ul style="list-style-type: none"> <li>• <b>5.3</b>     <b>Difficulty of making modifications to facility for the purpose of facility misuse</b></li> </ul>	<ul style="list-style-type: none"> <li>5.3.1     <i>Is there enough physical space and access to actually make modifications?</i></li> <li>5.3.2     <i>Number of people needed to perform modifications</i></li> <li>5.3.3     <i>Requirement for use of remote handling tools</i></li> <li>5.3.4     <i>Requirement for specialized tools</i></li> <li>5.3.5     <i>Requirement to stop process to make modifications</i></li> <li>5.3.6     <i>Risk of modification (safety)</i></li> </ul>
<ul style="list-style-type: none"> <li>• <b>5.4</b>     <b>Difficulty of evading detection of modifications to the facility for facility misuse</b></li> </ul>	<ul style="list-style-type: none"> <li>5.4.1     <i>Probability of detection based on vulnerability analysis of design verification system [to include factors such as percentage of facility or process step under effective IAEA surveillance and frequency of inspection (number/year, IAEA criteria)]</i></li> </ul>
<ul style="list-style-type: none"> <li>• <b>5.5</b>     <b>Knowledge, skills and workforce needed to for facility misuse</b></li> </ul>	<ul style="list-style-type: none"> <li>5.5.1     <i>Highly trained technical experts needed for facility misuse</i></li> <li>5.5.2     <i>Advanced degreed scientists and engineers needed for facility misuse</i></li> <li>5.5.3     <i>Technicians needed for facility misuse</i></li> <li>5.5.4     <i>Labor workers needed for facility misuse</i></li> </ul>

#### 5.2.5.1 Attribute: Difficulty of conducting facility misuse

This attribute considers the difficulties associated with handling, importing, and exporting the material to be used during facility misuse as well as the actual conduct of facility misuse. The attribute has different interpretation depending on the material transformation needed and whether the material in question must be covertly introduced or is already in place. Because of the varying interpretations, not all inputs will be applicable for each scenario.

In some instances the material characteristics will change during and as a result of the unauthorized activity. Therefore, in cases where material has been covertly introduced, this attribute requires separate evaluations of the material characteristics both at the point it is inserted into the facility and when it is removed. This attribute only evaluates the handling and management of material within a safeguarded area. This attribute does not consider any modifications to the plant which may be needed to conduct facility misuse.

##### 5.2.5.1.1 Input: *Mass/SQ of imported nuclear material*

This input captures the difficulty associated with moving material *into* a facility based on its mass.

##### 5.2.5.1.2 Input: *Mass/SQ of exported nuclear material*

This input captures the difficulties associated with moving material out of the facility being misused based on its mass.

##### 5.2.5.1.3 Input: *Volume/SQ of imported nuclear material*

This input captures the difficulties associated with moving material *into* a facility based on its volume.

##### 5.2.5.1.4 Input: *Volume/SQ of exported nuclear material*

This input captures the difficulties associated with moving material out of the facility being misused based on its volume.

*5.2.5.1.5 Input: Number of imported items/SQ*

This input captures the difficulties that stem from having to successfully bring multiple items into a facility with the intent to misuse that facility.

*5.2.5.1.6 Input: Number of exported items/SQ*

This input captures the difficulties that stem from having to successfully remove multiple items from a facility following misuse.

*5.2.5.1.7 Input: Imported material form (solid, liquid, powder, gas)*

As in Section 5.2.1.1.4, this input assumes that solids are easier to handle than powers, powders easier to handle than liquids, and liquids easier than gases. This input considers how material form affects the difficulty of importing material into a facility.

*5.2.5.1.8 Input: Exported material form (solid, liquid, powder, gas)*

This input considers how material form affects the difficulty of removing material from a facility.

*5.2.5.1.9 Input: Radiation level of imported materials in terms of dose*

This input parallels the input described in Section 5.2.1.1.5. The radiation fields that workers will be exposed to as material enters the facility will affect how the material is handled, whether workers must be replaced, whether additional shielding introduced, etc.

*5.2.5.1.10 Input: Radiation level of exported materials in terms of dose*

The radiation fields that workers will be exposed to as material exits the facility will affect how the material is handled, whether workers must be replaced, whether additional shielding introduced, etc.

*5.2.5.1.11 Input: Chemical reactivity of imported material*

This input parallels the input described in Section 5.2.1.1.6. It captures the hazards of the material entering the facility being misused.

*5.2.5.1.12 Input: Chemical reactivity of exported material*

This input captures the hazards of the material as it exits the facility being misused.

*5.2.5.1.13 Input: Temperature - point of material introduction*

The hazards associated with the temperature of the facility at the point the material enters will affect what precautions must be taken to ensure vital personnel and equipment remain useable.

*5.2.5.1.14 Input: Temperature - point of material extraction*

The hazards associated with the temperature of the facility at the point the material exits the facility will affect what precautions must be taken to ensure vital personnel and equipment remain useable.

*5.2.5.1.15 Input; Heat load of imported material*

Heat generation of the material as it is introduced into the facility being misused creates difficulties.

*5.2.5.1.16 Input: Heat load of exported material*

Heat generation of the material as it is extracted from the facility being misused creates difficulties.

*5.2.5.1.17 Input: Throughput capacity of facility available for facility misuse*

To misuse a civilian facility without affecting normal operations the facility must have excess capacity. This capacity could simply be true excess, or excess initiated through a fake accident/shutdown or other scenario.

*5.2.5.1.18 Input: Percentage of normal process impacted*

This is a measure of the impact of the misuse of the facility compared to normal operations.

*5.2.5.1.19 Input: Extent of deviation from normal facility process*

If misuse of a facility involves a process different from that which the facility was originally designed creates difficulties, dangers, and additional costs.

*5.2.5.1.20 Input: Physical barriers to facility misuse*

There are many types of physical obstructions, such as containment barriers.

*5.2.5.1.21 Input: Technical barriers to facility misuse*

This input captures the technical dimensions associated with facility misuse. All facilities are designed to be run a certain way. Technical needs associated with deviations from normal processes (as opposed to physical needs covered in the input above) will impose difficulties.

**5.2.5.2 Attribute: Difficulty of evading detection of facility misuse**

This attribute assesses the likelihood that facility misuse will be detected. Detectable signatures may include an increase in the presence of radioactive material in the environment; heat generation; liquid or gaseous chemical releases; increased demands for electricity or water supplies. Note: quantification of this parameter relies entirely on outside inspectors monitoring for appropriate signatures.

*5.2.5.2.1 Input: Number of people required to conduct facility misuse*

The need for additional personnel to conduct facility misuse will increase the likelihood of detection.

*5.2.5.2.2 Input: Frequency of environmental sampling measurements*

Increasing the frequency of environmental sampling will increase detection probabilities.

*5.2.5.2.3 Input: Normal heat load*

This input is necessary to assess the following two inputs.

*5.2.5.2.4 Input: Abnormal heat load as a result of facility misuse*

Greater changes in heat load will increase the likelihood of detection.

*5.2.5.2.5 Input: Sensitivity of detectors available to measure heat load*

Increased sensitivity of detectors will increase the likelihood of detecting abnormal heat load.

*5.2.5.2.6 Input: Normal radiation load*

This input is necessary to assess the following two inputs.

*5.2.5.2.7 Input: Abnormal radiation load as a result of facility misuse*

Greater changes in radiation load will increase the likelihood of detection.

5.2.5.2.8 *Input: Sensitivity of detectors available to measure radiation load*

Increased sensitivity of detectors will increase the likelihood of detecting abnormal radiation load.

5.2.5.2.9 *Input: Normal material flow rates*

This input is necessary to assess the following two inputs.

5.2.5.2.10 *Input: Abnormal material flow rates during facility misuse*

Larger changes in material flow rates will increase the likelihood of detection.

5.2.5.2.11 *Input: Sensitivity of detectors available to measure material flow rates*

Increased sensitivity of detectors will increase the likelihood of detecting abnormal material flow rates.

5.2.5.2.12 *Input: Normal volume of non-naturally occurring gasses in facility*

This input is necessary to assess the following two inputs.

5.2.5.2.13 *Input: Abnormal volume of non-naturally occurring gasses in facility*

Greater changes in the volume of non-naturally occurring gasses *in the facility* will increase the likelihood of detection.

5.2.5.2.14 *Input: Sensitivity of detectors available to measure volume of non-naturally occurring gasses in facility*

Increased sensitivity of detectors will increase the likelihood of detecting changes in the volume of non-naturally occurring gases in the facility.

5.2.5.2.15 *Input: Normal volume of non-naturally occurring gasses emitted*

This input is necessary to assess the following two inputs.

5.2.5.2.16 *Input: Abnormal volume of non-naturally occurring gasses emitted*

Greater changes in the volume of non-naturally occurring gasses *emitted from the facility* will increase the likelihood of detection.

5.2.5.2.17 *Input: Sensitivity of detectors available to measure volume of non-naturally occurring gasses emitted*

Increased sensitivity of detectors will increase the likelihood of detecting changes in the volume of non-naturally occurring gases emitted from the facility.

5.2.5.2.18 *Input: Normal characteristics (mass, volume, concentration) of liquid waste in facility*

This input is necessary to assess the following two inputs.

5.2.5.2.19 *Input: Abnormal characteristics (mass, volume, concentration) of liquid waste in facility*

Larger changes in the characteristics of liquid waste in the facility will increase the likelihood of detection.

5.2.5.2.20 *Input: Sensitivity of detectors available to measure characteristics (mass, volume, concentration) of liquid waste in facility*

Increased sensitivity of detectors will increase the likelihood of detecting changes in the characteristics of liquid waste in the facility.

*5.2.5.2.21 Input: Normal characteristics (mass, volume, concentration) of liquid emissions*

This input is necessary to assess the following two inputs.

*5.2.5.2.22 Input: Abnormal characteristics (mass, volume, concentration) of liquid emissions*

Larger changes in the characteristics of liquid waste emitted from the facility will increase the likelihood of detection.

*5.2.5.2.23 Input: Sensitivity of detectors available to measure characteristics (mass, volume, concentration) of liquid emissions*

Increased sensitivity of detectors will increase the likelihood of detecting changes in the characteristics of liquid waste emitted from the facility.

*5.2.5.2.24 Input: Deviation of utilities consumption from normal*

Detection probabilities increase as the need for the additional use of utilities to conduct facility misuse increases.

*5.2.5.2.25 Input: Deviation of use of consumables (e.g., nitric acid) from normal*

Detection probabilities increase as the need for the additional consumption of materials to conduct facility misuse increases.

**5.2.5.3 Attribute: Difficulty of making modifications to facility for the purpose of facility misuse**

This attribute considers the physical challenges associated with modifying a facility for the purpose of misusing it. It does not consider the skill level of workers needed to make the modification (this is covered in the “Knowledge and Skills” attribute below). This attribute has different interpretations depending on the civilian facility being modified. For the misuse of a reactor, modification may mean inserting fertile material into the shielding or under-irradiating fuel in an online fueled reactor through continuous loading and unloading. For an enrichment facility, it may mean the addition of pipes to loop material through the enrichment facility multiple times. Because of the varying interpretations, not all inputs will have value for each scenario.

*5.2.5.3.1 Input: Is there enough physical space and access to actually make modifications?*

This input considers whether there is enough physical space or access to perform the modifications necessary.

*5.2.5.3.2 Input: Number of people needed to perform modifications*

This input accounts for the number of person-years of effort required to perform the modification. The scale of the required effort is assumed to vary directly with the difficulty of the modification..

*5.2.5.3.3 Input: Requirement for use of remote handling tools*

The requirement to acquire and use sophisticated and/or expensive remote handling tools designed for various hazardous environments, especially if they are inconsistent normal facility operations, imposes difficulties.

*5.2.5.3.4 Input: Requirement for specialized tools*

The requirement to acquire and use specialized tools, especially if they are inconsistent normal facility operations, imposes difficulties.



5.2.5.3.5 *Input: Requirement to stop process to make modifications*

The need to shut down civilian facilities to conduct modifications, especially those with a primarily commercial purpose, is an obstacle to modification.

5.2.5.3.6 *Input: Risk of modification (safety)*

Modifications may create safety concerns which require mitigation.

5.2.5.4 **Attribute: Difficulty of evading detection of modifications to the facility for facility misuse**

This attribute considers the likelihood of detecting modifications to safeguarded facilities for the purpose of misusing the facility. It considers the facility design and the ease with which any modifications can be detected. Factors which affect the assessment of this attribute include the reliability of measurement sensors, time gap between modification and available measurements, and the potential disguise of modifications under justified operation plans.

5.2.5.4.1 *Input: Probability of detection based on vulnerability analysis of design verification system [to include factors such as percentage of facility or process step under effective IAEA surveillance and frequency of inspection (number/year, IAEA criteria)]*

This input captures the ability of inspectors to detect the facility modifications through design verification activities. Assessing this input will require a detailed vulnerability assessment of the modification in the facility and the characteristics of the inspection regime. The frequency of inspections will be determined by the safeguards criteria as discussed in section 5.2.1.2.3.

5.2.5.5 **Attribute: Knowledge, Skills and Workforce Needed to Process Diverted Material**

This attribute assesses the difficulty of performing facility misuse or modifying a facility for the purposes of facility misuse based on the level of knowledge and skills required. This attribute should take into consideration necessary knowledge needed to perform the facility misuse in a covert manner as well as what knowledge is needed to make the modifications to the facility. The attribute assumes that the necessary knowledge and skill already exist to operate the facility according to its original purpose.

5.2.5.5.1 *Input: Highly trained technical experts*

These will be specialists that cannot easily obtain the required skills and knowledge at a typical college or university. Example skill sets are actinide chemistry, remote material handling, waste handling and disposition and plutonium metallurgy. The units may be number of individuals or person-years depending upon the analysis.

5.2.5.5.2 *Input: Advanced degreed scientist and engineers*

Scientists and engineers may be needed for process design and control. Typical disciplines are nuclear engineering, physics, chemistry, and metallurgy. The units may be number of individuals or person-years depending upon the analysis.

5.2.5.5.3 *Input: Technicians*

Electrical, mechanical or chemical technicians may be required for assembling and operating equipment. The units may be number of individuals or person-years depending upon the analysis.

5.2.5.5.4 *Input: Labor workers*

Labor workers may be needed for construction and installation of equipment. The units may be number of individuals or person-years depending upon the analysis.

### 5.2.6 Time and Cost Factors

Parameters notably absent in the attribute and input lists (with the exception of Section 5.2.3.1.1) are time and cost. These are clearly important variables and ignoring them would call the validity of any proliferation assessment analysis into question. To meet the objective laid out for the definitions of the input variables it was necessary to leave treatment of these variables to the analytical method. Constraints on time and cost available to the proliferator may be implied or explicitly stated in the scenario description that sets out the scenario to be analyzed. Some of the more complex attributes and inputs that may require extensive analysis, such as probability of detection, may lead to results that provide detection probabilities as functions of both cost and time.

## 6.0 Demonstration of Test and Evaluation Approach

Once the attribute definitions and input descriptions were developed, we began several phases of testing to evaluate and refine the lists. An initial evaluation of the completeness of the list was conducted by applying the list to high-level scenarios covering a variety of facilities and approaches to host-state diversion-based proliferation. We then adopted a more rigorous approach to testing the attribute and input list against the audit-ability, transparency, and flexibility performance standards described in Section 4, with the goal of using results to refine and revise the attribute and input list. To conduct these tests, we first developed graphical representations of the attribute and input list. We then evaluated multiple detailed scenarios or “case studies” across all relevant stages of proliferation. The following section offers an example of this testing process.

As already noted, we view the list of attributes and inputs to be a work in progress. Further testing will contribute to the refinement of the list, as will further refinement and application of the testing procedures themselves.

### 6.1 Input Mapping

Once the attribute and input lists had been developed for each stage, we created graphic representations or “input maps” based on the architecture shown in Figure 2. In addition to being another way to show the attribute and input lists, these input maps set the stage for additional evaluation of the lists. Figure 3 shows a map of the Diversion stage attribute, “Difficulty of handling material during diversion”.

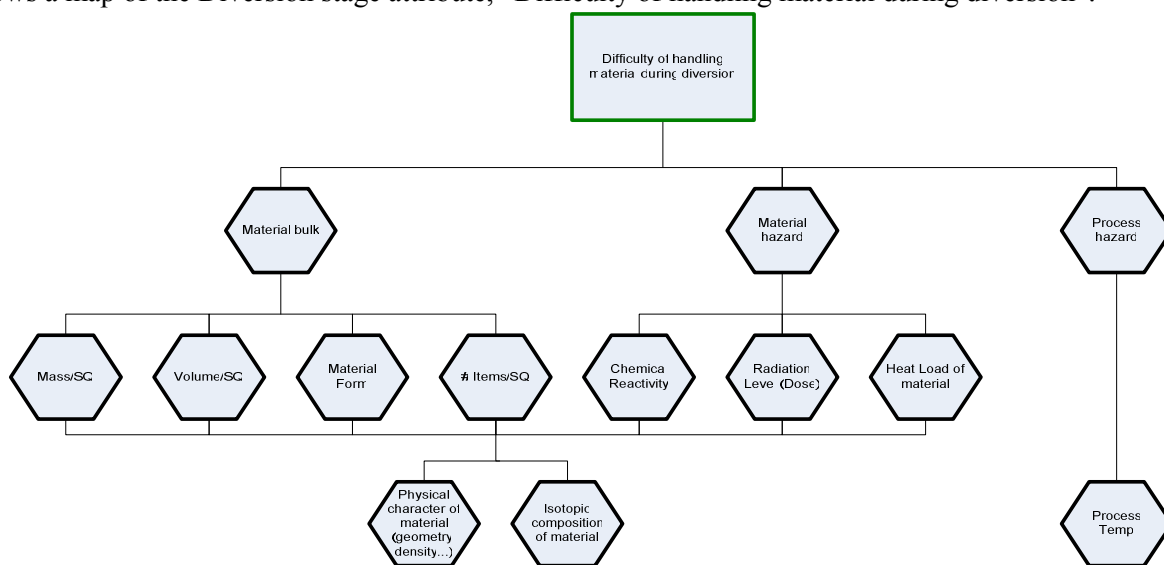


Figure 3. Map of inputs associated with the “Difficulty of handling material during diversion” attribute.

## 6.2 Testing and Assessment Using Case Studies

To evaluate the degree to which the attribute and input lists fulfilled the desired characteristics discussed in Section 4, we applied the lists to several detailed, hypothetical proliferation case studies. To obtain valid results from this method, case studies must follow a standardized approach and include substantial detail.

In the sections that follow, we provide detailed examples of the case study evaluation method for two case studies. For the sake of brevity, in the first, we show only an evaluation of the diversion stage. In the second, we show only an evaluation of the facility misuse stage. Nonetheless, both examples offer sufficient insight into the process to allow for a review of the testing procedure and to guide future researchers in the testing of additional case studies across all stages of proliferation.

For each case study, we give a brief description of the scenario and then demonstrate the testing of the attribute and input list for one stage against four characteristics which flow from our determination of proper assessment tool roles and desirable characteristics identified above:

1. Quantifiability – the ability to associate a number on each input
2. Completeness – an assessment of whether the input and attribute set accounts for all proliferation-relevant factors
3. Subjectivity – where is subjective judgment required to obtain a number for each input
4. Independence – the existence of relationships and dependencies between inputs and attributes

### 6.2.1 Case Study One

#### 6.2.1.1 Case Definition

In this example case study, the host state diverts 2,174 kg of UF<sub>6</sub> (which is equivalent to 75 kg of LEU enriched to 5 percent U235 – a “significant quantity” as defined by the IAEA) over a protracted period. These shipments arrive at the facility from a multi-national fuel supplier and are processed by the host state to produce LEU fuel for its power reactors. The host state will then enrich the material diverted to high-enriched uranium and convert it to metal in a covert facility and fabricate a nuclear weapon.

#### 6.2.1.2 Quantification of Diversion Stage

We evaluated the ability to associate a number with each diversion input and found three types of results.

1. *Input numbers could be calculated or obtained through direct measurement (assuming sufficient access).*
  - Mass/SQ of nuclear material: 2,174 kg of UF<sub>6</sub> (per SQ of finished product)
  - Volume/SQ of nuclear material: 1.04 m<sup>3</sup> (in solid form)
  - Number of items/SQ: 84 canisters (assuming that 1.14 percent is diverted from each canister)
  - Radiation level in terms of dose: 2.0 mSv/hour/SQ
  - Process temperature: 100 degrees C (temperature of material in gaseous form)
  - Heat load of material: 0.2 Watt/cc
  - Amount of material available: 600,000 kg of UF<sub>6</sub>
  - Number of people needed to perform modifications: 1

In some cases, the calculations relied on data from external sources. Since there are multiple data sources (e.g., material characteristics), consistent quantification of inputs will require the consistent use of the same sources. To this end, a series of “look-up” reference tables would have considerable value and should be developed to increase transparency and the ability to audit assessment tools.

The figures above are intended to illustrate that, for the given case study, it is possible to associate a number with an input. These particular numbers, however, are consistent with a scenario in which all the material is removed at a single point in time – an “abrupt” diversion – rather than the protracted diversion imagined in the case study above. The difference will significantly affect both the number and its relevance. We are still working to develop an approach to quantification during protracted diversion.

2. *Input numbers had to be assumed due to lack of data (often due to the confidentiality of IAEA safeguards data or commercial confidentiality)*

- Uncertainty in accountancy measurements: The scenario description gives an average measurement uncertainty of 0.14 percent. This is applied to the weight of the material and container (635 kg). Thus for a container containing 1500 kg LEU, the measurement uncertainty is about 3 kg.
- Expected vs. Actual MUF: This input requires plant operational data and thus will never be available for hypothetical cases. The case assumption is that expected MUF is 3 percent of the throughput. As such, the amount diverted is 1/3 of that value. If system losses and holdup are minimized, the actual MUF may be less than the expected.
- Frequency of accounting record comparisons and verifications: Once per year
- Probability of detection based on vulnerability analysis of material control system in place: Full incoming containers will have a mechanical seal to assure that it has not been tampered with during shipment. No additional material control would be expected until it arrives at the conversion facility, so probability of detection is zero.
- Probability of detection based on vulnerability analysis of design verification system: Inspections will occur nominally once a year. It is expected that the modifications will take place soon after an inspection. They should be modest enough (relatively minor plumbing) that they can be reversed before another inspection. So, again, the probability of detection is zero.

3. *Input numbers were associated with qualitative processes (e.g., yes = 1)*

- Chemical reactivity: High (highly toxic, highly corrosive)
- Material Form – solid, powder, liquid, gas: Gas
- Is there enough physical space and access to actually make the modifications: Yes
- Requirement for use of remote handling tools: No
- Requirement for specialized tools: No
- Requirement to stop process to make modifications: No
- Risk of modification (safety): Minimal
- Risk of penetrating containment: Not applicable

Given the details of the case study under consideration and the resulting inputs, without employing any formal assessment, it is clear that the inputs that most directly impact the proliferation risk are the details of the safeguards system. The quantity being diverted is small compared to the total throughput so that the expected MUF, probably dominated by material holdup, may mask the diverted material. It was assumed that there were no material control measures in place capable of detecting this diversion scenario.

### 6.2.1.3 Evaluation of Completeness

For this limited case study, the input parameters seemed to be sufficient to form a basis for analysis. Some, of course, are not applicable to this scenario, but that is to be expected because our inputs are meant to have a wide enough scope to cover all potential scenarios. The parameters most likely to dominate the analysis are the mass diverted and the characteristics of the safeguards system. Radiation and heat loads are small and do not contribute to the difficulty of the task or the ease of detection for this scenario.

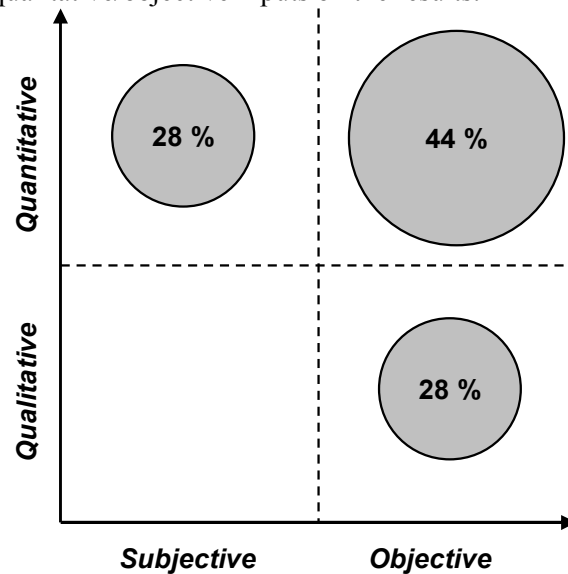
Confidence in completeness can only come through detailed examination of multiple case studies and application of the input list to determine whether it is sufficient to cover all characteristics. The developer can maximize the utility of a single case study by imagining excursions or variations from that case and repeating the query. In addition, we encourage review of this list by the expert community and solicit additional case studies and comments.

#### 6.2.1.4 Evaluation of Subjectivity

We classified each input from the diversion stage based on whether it could be evaluated objectively or subjectively and whether measurement could be done quantitatively or qualitatively. Examples of each are as follows:

- Objectively quantitative: Mass/SQ of nuclear material
- Objectively qualitative: Material form
- Subjectively quantitative: Number of people needed to perform modification
- Subjectively qualitative: Risk of modification

In the diversion stage, we identified no inputs as being obtainable via subjective judgment and only expressible through qualitative terms. More than 40 percent were objectively quantifiable (Fig. 4). Additional evaluation and case studies will be required to determine the effect of the quantitative/subjective and qualitative/objective inputs on the results.



**Figure 4.** Characterization of diversion inputs evaluated in Case Study One.

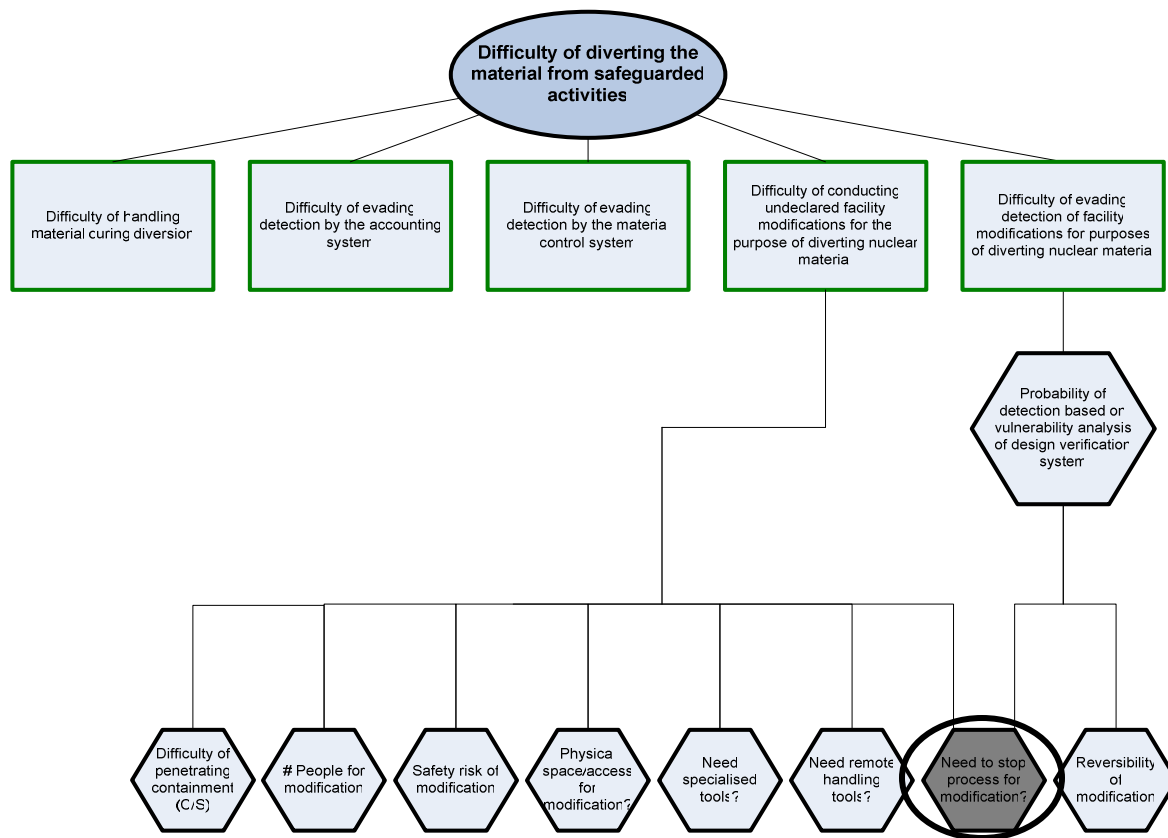
#### 6.2.1.5 Evaluation of Independence

Inter-relationships between inputs and attributes *may* result in a particular element being inappropriately counted multiple times during aggregation thereby giving it more influence on the analysis that it deserves. Initial analysis conducted for this paper suggests that inputs may be inter-related in two ways: (1) repeated use and (2) physical or conceptual dependency. The existence of inter-relationships, especially of the first type, do not necessarily adversely affect analysis. To determine where they do, testing is required. Testing helps the analyst identify where relationships may exist in a rigorous manner. Once a potential relationship is identified, however, the analyst must review the nature of the relationship to determine whether it is indeed problematic.

To identify relationships between inputs, we created maps (such as that shown in Figures 3 and 5) showing how basic inputs combined to form higher level inputs and how those, in turn combined to form attributes. Relationships can be visually identified in the maps where any single input contributes to multiple attributes (Figure 5). Because we limited our evaluation scope in this paper, the relationships were relatively easy to identify and few in number. When the analysis is expanded to include additional stages and other scenarios, formalized statistical techniques, such as orthogonal sampling<sup>6</sup> can complement the visual map analysis by identifying where relationships may exist. When complex aggregation methods are employed, statistics tests may also be able to identify the magnitude of the relationship.

The relationship shown in Figure 5 was the only relationship we were able to identify in the diversion stage at this time. The input “Need to stop process for modification?” is being used by the attributes “Difficulty of conducting undeclared facility modifications for the purposes of diverting nuclear material” and “Difficulty of evading detection of the facility modifications for the purposes of diverting nuclear material”. In this case, the similar nature of the attributes created the need for an identical input. However, because the input contributes to each attribute in a different manner, this relationship was deemed not to have an adverse effect, but does indicate the need for a further refinement of this input. In more detailed analytic projects, formal statistical testing may have been necessary to identify the relationship highlighted in this example.

The other stages have more interdependencies than the diversion stage. Further, when a scenario is evaluated across all stages, inter-stage independencies may be identified.



**Figure 5.** Identification of input contributing to multiple attributes in the diversion stage.

## 6.2.2 Case Study Two

### 6.2.2.1 Case Definition

In this example case study, the host state diverts 665,856 low-enriched uranium (LEU) fuel pellets, from a fuel fabrication facility and uses them to fabricate eight (8) PWR fuel assemblies. The state then covertly introduces these eight LEU fuel assemblies into a safeguarded PWR in place of declared LEU fuel assemblies (thus *misusing* the PWR). After irradiating 5 GWd/MTU, the undeclared fuel assemblies are removed and the original declared fuel assemblies re-introduced. The partially irradiated undeclared fuel assemblies are then transported to a covert reprocessing facility where the Pu is separated, converted to metallic form, and fabricated into an implosion device.

### 6.2.2.2 Quantification of Facility Misuse Stage

We evaluated the ability to associate a number with each diversion input and found three types of results.

*1. Input numbers could be calculated or obtained through direct measurement (assuming sufficient access)*

- Mass/SQ of imported nuclear material (mass): 5,263kg of material per SQ (~657.9kg/assembly \* 8 assemblies)
- Mass/SQ of exported nuclear material (mass): 5,263kg of material per SQ
- Volume/SQ of imported nuclear material (volume): 1.44m<sup>3</sup> (~0.18m<sup>3</sup>/assembly \* 8 assemblies)
- Volume/SQ of exported nuclear material (volume): 1.44 m<sup>3</sup>
- Number of imported items/SQ (count): 8 fuel assemblies
- Number of exported items/SQ (count): 8 fuel assemblies
- Radiation level of imported material in terms of dose (Sv/hr): 0.0 Sv/hr
- Radiation level of exported material in terms of dose (Sv/hr): 10 Sv/hr (contact) per assembly
- Temperature – point of material introduction: 80°C
- Temperature – point of material extraction: 80°C
- Heat load of imported material (Thermal watts): Ambient
- Heat load of exported material (Thermal watts): 300kW
- Frequency of environmental sampling measurements: weekly
- Normal heat load vs. Abnormal heat load as a result of undeclared production and detector sensitivity: N/A
- Normal radiation load vs. Abnormal radiation load as a result of undeclared production and detector sensitivity: N/A
- Normal flow rate vs. Abnormal flow rate as a result of undeclared production and detector sensitivity: N/A
- Normal volume of non-naturally occurring gases vs. Abnormal volume of non-naturally occurring gases in facility or emitted as a result of undeclared production and detector sensitivity: N/A
- Normal characteristics of liquid waste or emissions vs. Abnormal characteristics of liquid waste or emissions as a result of undeclared production and detector sensitivity: N/A
- Deviation of utilities consumption from normal: N/A
- Deviation of use of consumables (e.g., nitric acid) from normal: N/A

*2. Input numbers had to be assumed due to lack of data (often due to the confidentiality of IAEA safeguards data or commercial confidentiality)*

- Throughput capacity of facility available for undeclared production: 60 fuel assemblies per outage
- Percentage of normal process impacted: 15 percent
- Extent of deviation from normal facility process: minimal
- Physical barriers to undeclared production: very difficult

- Technical barrier to undeclared production: easy
- Probability of detection based on vulnerability analysis of design verification system [to include factors such as percentage of facility or process step under effective IAEA surveillance and frequency of inspection (number/year, IAEA criteria)]: Inspections will occur nominally every 12 to 18 months. It is expected that modifications will take place soon after an inspection and that work will be completed prior to the next inspection. Thus the probability of detection is zero.

3. *Input numbers were associated with qualitative processes (e.g., yes = 1)*

- Imported Material Form: solid
- Exported Material Form: solid
- Chemical reactivity of imported material: low
- Chemical reactivity of exported material: low (if properly cooled)
- Number of people required to conduct facility misuse: 50 people
- Is there enough physical space and access to actually make the modifications: yes
- Number of people needed to perform modifications: 100 people
- Requirement for use of remote handling tools: possible
- Requirement for specialized tools: extensive
- Requirement to stop process to make modifications: no
- Risk of modification (safety): minimal
- Highly trained technical experts need for facility misuse: 0 people
- Advanced degreed scientists and engineers needed for facility misuse: 2 people
- Technicians needed for facility misuse: 5 people
- Labor workers needed for facility misuse: 20 people

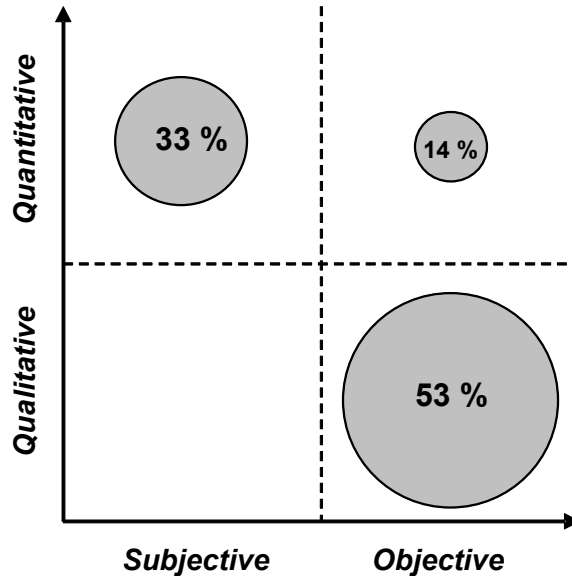
### 6.2.2.3 Evaluation of Completeness

For this limited case study, the input parameters seemed to be sufficient to form a basis for analysis. Some, of course, are not applicable to this scenario, but that is to be expected because our inputs are meant to have a wide enough scope to cover all potential scenarios. The parameter most likely to dominate the analysis is the “extent of modifications to the facility necessary”. The deviation of the plant processes from normal are small and do not contribute to the difficulty of the task or the ease of detection for this scenario.

### 6.2.2.4 Evaluation of Subjectivity

In the facility misuse stage, we identified no inputs as being obtainable via subjective judgment and only expressible through qualitative terms. Approximately 9 percent were objectively quantifiable (Fig. 6); however, more than 50 percent were qualitative objective. Additional evaluation and case studies will be required to determine the effect of the quantitative/subjective and qualitative/objective inputs on the results.





**Figure 6.** Characterization of facility misuse inputs

## 7.0 CONSIDERATIONS ASSOCIATED WITH FURTHER EVALUATION AND TESTING

While the preceding example of our approach to testing our attributes and inputs did provide a number of insights, the limited scope of the example has limitations. Further testing across all stages of proliferation, evaluating alternative case studies, and likely employing more complex aggregation methods is necessary before conclusions can be reliably reached. A number of additional issues are likely to arise in the course of full-scope testing, while others may fade. In fact, even this interplay will offer insights into the attribute and input list.

The primary effect the extension of testing across all stages of proliferation is likely to reveal additional relationships between inputs and attributes. Some of the inputs may point in opposing directions in different stages. For example, a given isotopic composition may make material accountancy more difficult – thereby making it easier to divert the material – but make the fabrication of a weapon more difficult.

The inclusion of additional case studies is likely to raise new issues through the introduction of diverse facilities and activities. Testing may reveal problems across all four testing areas, but particularly in quantification and completeness.

## 8.0 CONCLUSION

This research begins from the premise that well-developed proliferation risk and resistance assessment tools have the potential to contribute to nuclear system and safeguards technology development activities. The use of tools which are credible and reliable can help to guide the efficient allocation of resources toward ends which strengthen the nonproliferation regime. Analysis early in the design cycle can also avoid mistakes that are costly to remedy after construction.

Our evaluation of the most effective uses of these assessment tools and their desired characteristics point strongly toward devoting significant attention to the foundations of these tools – the individual data inputs upon which all assessments are built. These data inputs are critical to building assessment tools which are auditable, transparent, and flexible.

These goals are best achieved through the development of a common set of inputs and attributes that, even in the absence of a methodological framework, can contribute to nonproliferation efforts by providing technical experts and policy-makers alike a “checklist” of critical technical factors that, together with political considerations, must be evaluated to understand how any specific technology or activity in a given state may impact proliferation. This can help to identify weak points in a facility or nuclear system with regard to safeguards provisions or potential locations and process steps where diversion of materials could occur.

This paper documented the list of attributes and inputs developed to date and demonstrated our approach to testing the list for the ability to associate numbers with inputs, the completeness of the set, the method of obtaining information, and the relationships between data inputs. While additional testing will be required to reach conclusions which can be used to revise the list, these examples suggest that this draft set of inputs and attributes substantially – though not completely – fulfils the performance targets developed.

While additional refinement may be necessary, this work will further the goal of developing credible and reliable assessment tools which can contribute to the ability to develop nuclear technologies that efficiently and effectively make civilian nuclear energy systems the least attractive path to nuclear weapons development.

## 9.0 REFERENCES

- <sup>1</sup> C.M. MENDEZ et. al., “Strengthening the Foundation of Proliferation Risk Assessment Methodologies,” Proceedings 47<sup>th</sup> INMM Annual Meeting, Nashville, Tennessee, July 2006.
- <sup>2</sup> D. GRENECHE et. al., “Simplified Approach for Proliferation Resistance Assessment of Nuclear Systems – Final Report, French Working Group on Proliferation Resistance and Physical Protection,” 2007.
- <sup>3</sup> An SQ is defined by the IAEA as “the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded”. Values have been assigned to fissile materials that may be used in a weapon, e.g. 8 kg for plutonium. See IAEA Safeguards Glossary, 2001.
- <sup>4</sup> See IAEA Safeguards Glossary, 2001. A SQ of Pu and 233U is 8 kg; highly enriched uranium (HEU – uranium with  $\geq 20\%$  235U) 235U is 25 kg; 235U for low-enriched uranium (LEU, uranium with  $< 20\%$  235U) is 75 kg; natural uranium (NatU, uranium with 0.72% 235U) is 10 MT; Th and depleted uranium (DepU, uranium with  $< 0.72\%$  235U) is 20 MT.
- <sup>5</sup> Specific safeguards criteria required by the IAEA are defined based upon the material characteristics and the type of operation. In general, the requirement is that the diversion of a significant quantity be detected within a time period that is a function of material category. The categories and timeliness criteria are as follows: One month for un-irradiated direct use (not requiring enrichment); Three months for irradiated direct use; and Twelve months for indirect use (requiring enrichment).
- <sup>6</sup> R.L. IMAN et al., “An Approach to Sensitivity Analysis of Computer Models, Part 1. Introduction, Input Variable Selection and Preliminary Variable Assessment,” J. Quality Technology, Vol. 13(3), pp. 174–183 (1981).

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