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Pacific Northwest National Laboratory
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Guidelines for the Performance of Nonproliferation Assessments

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Executive Summary

The National Nuclear Security Administration (NNSA) established a Nonproliferation Assessment Methodology (NPAM) Working Group, comprised of representatives from the Department of Energy (DOE) laboratories and academia, to develop guidelines for the practical application of Nonproliferation Assessment Methodologies (NPAM). The purpose of these methodologies is to address questions and issues related to the proliferation of nuclear weapons and weapons-useable nuclear materials and related technologies, as input to policy analysis. This document presents the guidelines developed by the Working Group.

Study Conclusions

The guidelines effort has advanced the process of developing integrated methodologies to address nonproliferation issues. The guidelines build upon earlier work to take the next step towards achieving a hierarchy of methodologies that can be employed with confidence, and that will be credible to a wide range of nonproliferation analysts, policy makers, and stakeholders.

The guidelines identify three general categories of analytical methods that appear to have excellent potential for use in nonproliferation studies: attribute analysis, scenario analysis and two-sided methods. Attribute analyses evaluate the effectiveness of proliferation barriers, scenario analyses assess the pathways through those barriers, and the two-sided approaches explore the human interplay between adversaries. The three assessment approach categories are complementary in addressing the spectrum of nonproliferation issues that may be examined by NNSA and others.

No fully-mature, integrated methods have been developed to assess proliferation risk or proliferation resistance. Two promising approaches, described in this report, have been partially developed to perform integrated assessments. Multi-Attribute Utility (MAU) Barrier Analysis, an attribute analysis method, and Risk-Informed Proliferation Analysis (RIPA), a scenario analysis method, require additional development effort before they can be used routinely. Although wargames are widely used in other fields, there are only limited examples of their use in examining nonproliferation issues.

A significant challenge to the development and application of integrated assessment methodologies is the selection of appropriate metrics. These guidelines present a hierarchy of metrics that can be used to convey the results of an assessment. Large amounts of information are generated in a nonproliferation assessment that must be presented to the policy maker. Some aggregation of results must be made in the analysis to make the results understandable, presenting a challenge for any of the methods that have been surveyed. The aggregation of metrics must be done in a manner that minimizes loss of information, minimizes interdependencies, is traceable and provides useable information to the policy-makers. Detailed results should be documented to enable the policy maker to be able to trace higher-level results

back to lower-level causes. The application studies discussed previously will provide an opportunity to further develop approaches to the aggregation of metrics.

If an analysis uses or produces classified or sensitive information, the aggregation methods must also generate results that minimize the loss of information while providing appropriate protection of the classified and sensitive information. In general, methods by which to compile informative, unclassified summaries of the analysis are valuable in increasing the range of policy makers and stakeholders who can use the results.

Content of Guidelines Document

This document provides guidelines that can be used by the analyst in undertaking a nonproliferation assessment. Figure ES-1 provides a flow diagram for the process. Some of the stages of the process involve iteration or parallel development. The guidelines section of the document provides a brief description of each step in the process and provides pointers to other sections of the document that address approaches and options in more depth.

Two general categories of methods have historically been used in nonproliferation assessments: attribute analysis and scenario analysis. In the attribute analysis approach, the analyst identifies characteristics of the system being analyzed that would make the system more or less likely to allow proliferation. MAU theory is the best-known form of attribute analysis. In the scenario analysis approach, the analyst identifies and models specific scenarios leading to proliferation. Probabilistic risk analysis is an example of a scenario analysis approach. A study does not have to adopt one or the other approach. The two categories of methods are often used in combination.

Two-sided methods, another category of methods described in this document, are particularly interesting for nonproliferation assessment because they examine the interplay between adversaries with opposing objectives. Each of these methods has a role in nonproliferation assessment. The methods are complementary, in that they have different areas of strength, and mutually supporting, in that more than one type of method may be used in a particular study.

One of the purposes of these guidelines is to provide a toolbox of methods that are available to the analyst in undertaking nonproliferation assessments. The following bulleted-list of methods is described in the guidelines. Some of these methods, such as MAU theory, could form the basis for an integrated methodology of nonproliferation assessment. Other types of methods, such as the first four bulleted items in the list, have very broad applicability in support of nonproliferation studies. These are referred to as analysis tools.

- Logic diagrams - fault trees, event trees, influence diagrams, master logic diagrams are tools for the visualization and/or quantification of the relationships between systems and events.
- Expert elicitation – structured techniques for obtaining expert judgment while minimizing bias.

- Uncertainty analysis, sensitivity studies, and importance measures – methods used to place the results in the context of analysis uncertainties and to indicate which factors contribute most significantly to the results.
- Dynamic modeling – models that describe the time dependence of processes, usually by the solution of differential equations.
- MAU theory - a means of assessing and aggregating widely different characteristics of a system in a common set of units.
- Probabilistic methods – approaches to the analysis of stochastic or variable processes. Probabilistic risk analysis, as used for reactor safety analyses, involves a formalized combination of event tree and fault tree logic diagrams.
- Analytic Hierarchy Procedure – an attribute analysis method, which involves the use of pair-wise comparisons to assess the relative importance of different attributes to the next higher level in a hierarchy of attributes.
- Fuzzy sets and possibility theory – an alternative means of treating imprecise and uncertain processes in which possibilities are assessed, rather than probabilities.
- Two-sided methods – approaches that examine the interplay between adversaries with opposite objectives.

Because of the complexity of nonproliferation assessments, the problem must be decomposed into manageable elements. The guidelines describe approaches that have been taken to the decomposition of nonproliferation studies in the past. These approaches to the subdivision of the analysis include definition of a finite set of threats, definition of barriers to proliferation, development of metrics, and segmentation of the system being evaluated.

The spectrum of potential threats of nuclear proliferation is complex and ranges from small terrorist cells to industrialized countries with advanced nuclear fuel cycles. Adding to this complexity, the potential objectives of these threats are highly multidimensional. Detailed objectives of particular proliferants are difficult to ascertain with any degree of certainty and even more difficult to predict. As a result, evaluating the overall global proliferation resistance of possible fuel cycles on a country-by-country basis is probably impractical (although estimating specific proliferation risk for a particular country may be more tractable). These guidelines discuss three categories of proliferant: subnational, non-industrialized state, and developed state. These three categories are further subdivided into a total of eight threats depending on the aspirations of the proliferant regarding number of weapons sought, weapon yield, weapon reliability, and delivery vehicle.

After the objectives of the study have been clearly defined, the analyst must determine the metrics or measures (high level metrics) that will be used to characterize the proliferation resistance of the alternatives being evaluated. The guidelines review metrics that have been used in previous studies. A general hierarchy of metrics is developed to show how lower level metrics can be related to the high level measures that will be used by the decision maker to decide which are the preferred alternatives. Nonproliferation assessments generally attempt to measure the proliferation resistance of a particular alternative or the proliferation risk of a certain action or proposition. It is important to distinguish between the two types of assessment because they rely on different measures. Proliferation resistance is the degree of difficulty that a nuclear material, facility, process, or activity poses to the acquisition of one or more nuclear weapons.

Proliferation risk is the likelihood of a nation or subnational group obtaining nuclear weapons within a given time period.

Proliferation resistance can apply to an entire nuclear complex as well as to particular elements of a nuclear complex (a commercial fuel cycle, a facility, transportation of nuclear material, etc.). Proliferation risk, on the other hand, can apply to actions or activities not necessarily part of a physical nuclear complex. Acquisition of specific technologies or skills, industrial capabilities, etc., can bear on the risk of proliferation. If the intent of the assessment is focused on the relative merits of fuel cycle systems, proliferation resistance is probably the preferred top-level measure.

The system under evaluation is typically either an element of a fuel cycle system or of a nuclear weapons infrastructure. For the purpose of analysis, the system is segmented into elements. An element could consist of all operations internal to a building, a process line, or a transportation activity. The nonproliferation assessment is performed at the element level. The aggregation of results across different elements of the system to obtain a measure of the proliferation resistance or risk of the entire system is a complex issue requiring further examination.

Two integrated methodologies are described in some detail in the appendices. The Risk-Informed Proliferation Analysis (RIPA) Methodology is a scenario analysis approach that uses influence diagrams. The Technological Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems (TOPS) Barrier Analysis Method is an attribute analysis approach. Both of these integrated methodologies are in the developmental stage.

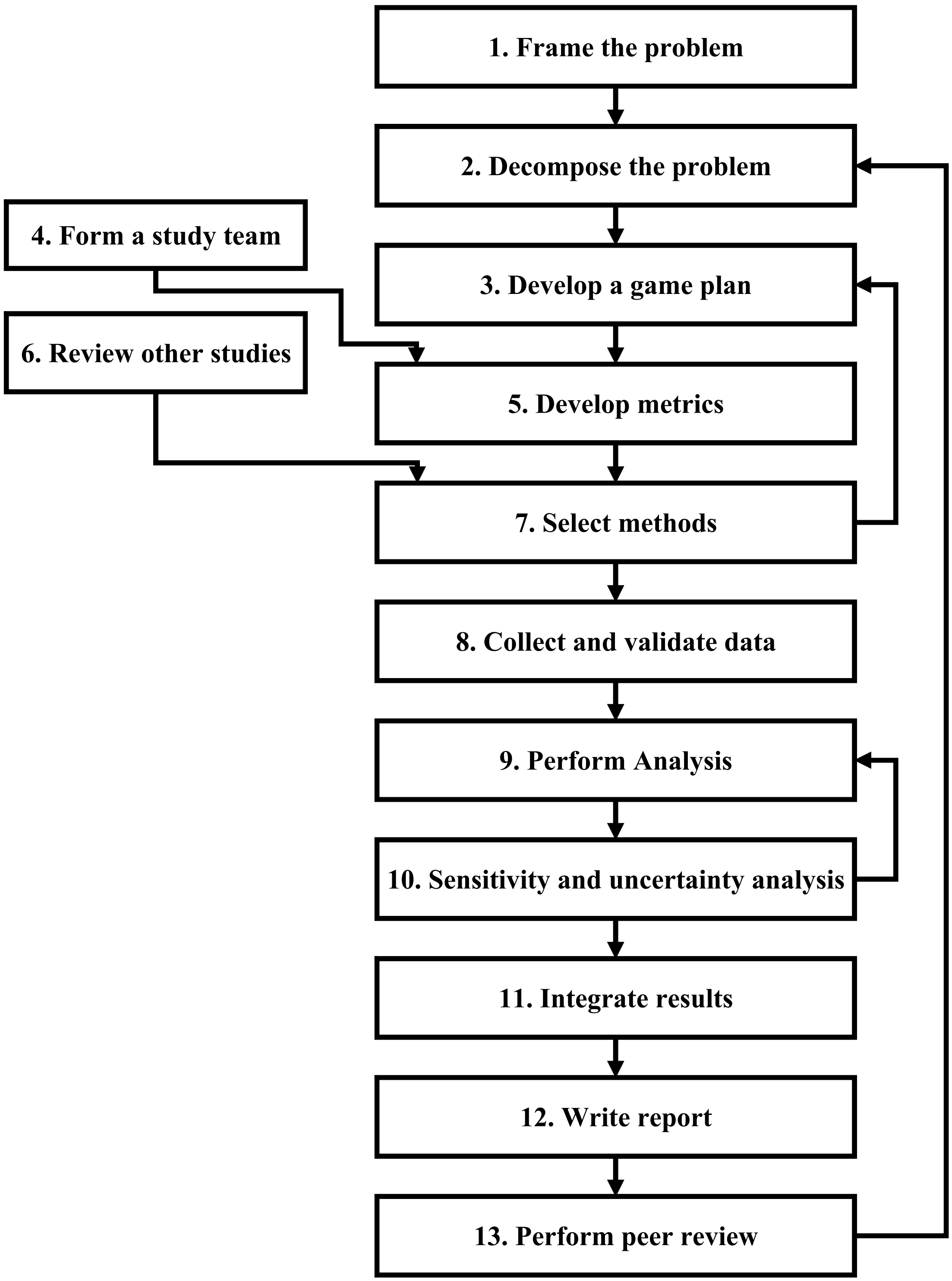

Figure ES-1. Elements of an Assessment Project

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Guidelines for the Performance of Nonproliferation Assessments

1.0 Introduction

The National Nuclear Security Administration (NNSA) Office of Nonproliferation and International Security is responsible for the performance of nonproliferation policy assessments. These assessments arise from time to time in response to export licensing questions or to address a particular policy question. In the past, the quality and rigor of these assessments have varied, and they have been primarily qualitative. For these reasons, NNSA has initiated a program (Ref. 1) that will develop a hierarchy of methodologies to address a wide spectrum of issues, such as the proliferation resistance of specific nuclear reactor and fuel cycle concepts, the proliferation risks associated with identified inventories of weapon useable materials, or similar questions that may arise. The program will also develop a baseline of information that will establish the historical perspective to both validate the methodology and populate the databases that the methodology will employ.

In order to provide technical guidance for the development of NPAM, the NNSA has established a Nonproliferation Assessment Methodology (NPAM) Working Group (see Appendix A) of senior personnel from Department of Energy laboratories and academia. The initial charge from NNSA to the Working Group was to prepare guidelines for the performance of nonproliferation assessments. This report is that guidelines document.

The bases for this report were developed in five Working Group meetings in which the group discussed the types of methods that had been previously used or could potentially be used to perform nonproliferation studies. The Working Group also explored a variety of related topics including definitions of proliferation terms, proliferation metrics, expert elicitation, threat definition, historical proliferation scenarios, and the establishment of benchmark problems.

Within the NPAM program, other activities have been initiated related to methodology assessment, development of historical proliferation benchmarks, threat definitions, and the characterization of material attractiveness. To the extent that the results of those studies are relevant, they have been included within this document.

1.1 Purpose of Guidelines

These guidelines serve more than one programmatic objective. First, for someone with a defined proliferation issue to study, the guidelines provide a state-of-the-art assessment of tools that are available for that specific problem. The guidelines discuss advantages and disadvantages of methods within the scope of the analyst's problem. They describe how to undertake a study, potential pitfalls, how to present results, and provide reference to similar studies.

The NPAM program is being undertaken because of recognized deficiencies in previous studies. One of the objectives of the guidelines is to direct development work on the use of methods, particularly to the extent they can be made more rigorous. The Working Group has recommended that NNSA undertake a series of application studies in which methods will be further developed. It is quite possible that following this development work, this guidelines document will be updated.

1.2 Scope of Report

One of the first issues addressed by the Working Group was the definition of terms. Within the NPAM program activities, a common set of definitions will be used. A glossary of terms is provided as Appendix B to this report.

The following definition of proliferation[1] was adopted by the Working Group: "Proliferation is the acquisition of one or more nuclear weapons by a nation or sub-national group that currently does not have nuclear weapons." Although there is currently a great deal of concern about sabotage of nuclear facilities resulting in the release of radioactive material and about radioactivity dispersal devices, the scope of NPAM is limited to assessing the potential for production of nuclear weapons. The NPAM scope also excludes the assessment of theft of nuclear weapons from existing stockpiles.

This report provides guidelines for the performance of nonproliferation assessments. It addresses the selection of methods, choice of metrics, evaluation of threats, treatment of uncertainty, and documentation of results. It provides a catalog of methods rather than a detailed exposition on the application of these methods.

References

1. NNSA, Program Plan for the Development of a Nonproliferation Assessment Methodology, Draft, November 2001.

2.0 Background

In January of 2001 a task force of DOE's Nuclear Energy Research Advisory Committee issued a report titled "Technological Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems (TOPS)" (Ref. 1). The first recommendation of that study is "Development of improved methodologies, for assessing the proliferation resistance of different systems, including those that further the understanding of tradeoffs between intrinsic features and extrinsic measures." The need is further described in the report to develop "improved and standardized methodologies including quantitative ones, for performing comparative assessments of the proliferation attributes and merits of different reactor and fuel cycle systems."

In order to address the needs identified in the TOPS report, NNSA has undertaken a program for the development of nonproliferation assessment methods. The plan for this effort is described in

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[1] A variety of definitions are commonly used for the term 'proliferation.' The International Atomic Energy Agency (IAEA) adopts a narrow definition that only includes state diversion or undeclared production of nuclear materials from facilities operated within a state. At the national level, a broader definition is commonly applied, that also includes the theft of nuclear materials by subnational groups or by other states. This report adopts the broader definition.

the document "Program Plan for the Development of Non-Proliferation Assessment Methodology (Ref. 2)." The goals described in this program plan are:

- Develop a standardized hierarchy of methodologies for assessing the proliferation resistance and risks of various nuclear reactor designs, fuel cycle concepts and processes, and threat scenarios
  - The methodology must be capable of assessing tradeoffs among concepts and systems.
  - The methodology must include the capability to produce quantitative assessments to support technical rigor.
- Successfully demonstrate the methodology.

The NPAM program has four work breakdown structure major elements:

WBS 1.0 Develop Functional Requirements
WBS 2.0 Develop Methodology Structure
WBS 3.0 Program Definitional and Supporting Studies
WBS 4.0 Application Studies

At the time that the NPAM Working Group was developing this guidelines document, WBS 1.0 activities had been completed and a number of other program activities were in progress. The functional requirements are discussed below. The WBS 2.0 sub-elements develop the structure of the NPAM development effort. A number of these sub-elements are being performed by the NPAM Working Group and are documented in this report. Assessment of the applicability of available techniques is WBS 2.2, development of a methodology structure is WBS 2.3, and documentation of the guidelines is WBS 2.5. The program definitional and supporting studies, WBS 3.0, are activities that provide direct input to nonproliferation methodologies, such as the characterization of threats, the compilation of data from historical proliferation scenarios, and the characterization of material attractiveness. Studies have been initiated by NNSA in each of these areas. The development of a glossary of terms (Appendix B) has been undertaken within this program element. Finally, WBS 4.0 addresses application studies. Recommendations by the NPAM Working Group for application studies are provided in this document.

NNSA established a Peer Review Group to review the approach and recommendations of the NPAM Working Group. The document was subsequently modified. The peer review information is provided in Appendix E.

The first activity that was initiated in the program was the development of functional requirements for the NPAM. The FRD (Ref. 3) states that the NPAM project objective is to assure that solid, consistent, technically-grounded analysis underpins nonproliferation policy decisions and policy makers are fully informed of the comparative proliferation risks associated with various policies and programmatic decisions. The primary goal is to consistently apply a logical assessment methodology to help minimize the risk that U.S. Government policy decisions would either result in, or encourage, the proliferation of nuclear weapons through the theft or diversion of nuclear materials for weapons production, or through the transfer of related nuclear technologies. Consistent with this goal, NPAM should describe procedures for conducting objective analysis of the impacts of technical, regulatory, existing foreign and domestic policy, and regional security issues to inform current decision-making.

The FRD provides the following guidance for the team charged with developing the NPAM.

> *"The methodologies should be described in a guidelines or best practices document that describes a process for addressing nonproliferation questions in a consistent and rigorous manner. The best practices document should include a catalogue of existing analytic methods and, where necessary, newly developed tools. It should also specify which of these methods are best suited for the generic areas of questions and issues that fall within NA-24's nuclear nonproliferation portfolio. This matching of methods with issues and questions should include consideration of levels of detail required and the time available to perform an assessment. In addition, it should provide a framework for a presentation of study results to NNSA management and other USG agencies."*

The following capabilities are established as functional requirements of NPAM:

- Provide a uniform and consistent way to express proliferation resistance.
- Allow comparisons of diverse options, decisions, etc., in terms of proliferation resistance.
- Allow for use of a combination of qualitative and quantitative approaches, as needed in specific assessments.
- Allow for use of different methods, each more amenable to specific portions of the assessment.
- Provide for an integrated policy overlay (policy levers)
- Produce useful results commensurate with the constraints of budget, schedule, and data availability through use of a range and hierarchy of analysis methods (a "tool box")
- Provide results that are understandable and useful to the expected audiences
- Treat uncertainty in the input
- Treat uncertainty in the process
- Present uncertainty in the results clearly
- Facilitate sensitivity analyses
- Facilitate the use of expert information/opinion
- Incorporate weighting techniques to vary priorities and levels of importance of objectives, goals, and criteria
- Employ transparent processes to facilitate the interpretation of results and facilitate external reviews
- Incorporate information from existing databases
- Employ consistent use of terminology based on an included glossary

<u>References</u>

1. NERAC, "Technological Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems (TOPS)," January 2001.

2. NNSA, Program Plan for the Development of a Nonproliferation Assessment Methodology, Draft, November 2001.

3. NNSA, Functional Requirements Document, January 2002.

3.0 Nature of Problems to be Assessed

3.1 Types of Nonproliferation Studies

During the Carter administration, concern about domestic plans for the recycle of plutonium in commercial nuclear power plants led to the undertaking of a national assessment (NA) of the proliferation implications of different fuels cycles, NASAP (Ref. 1), and an international fuel cycle examination, INFCE (Ref. 2). These landmark studies resulted in major changes in U.S. domestic plans for the disposal of radioactive waste and the recycling of plutonium. NA-24 potentially addresses a variety of similar issues for which analysis methods are required. The FRD (Ref. 3) identifies the following specific types of study that would be undertaken using the nonproliferation methods discussed in this document:

- Nuclear Fuel Cycle (NFC) Assessments:
  - Detailed design level support: NPAM will be used to answer technical questions about the proliferation significance of specific design concepts.
  - Future nuclear systems proliferation risks: NA-24 conducts comparative analyses of proposed nuclear fuel cycle technologies.
  - Existing domestic nuclear fuel cycles: NA-24 evaluates the nonproliferation aspects of options for a wide range of fuel cycle proposals, initiatives, and programs that involve nuclear material production, use, and disposition.
  - International assessments: NA-24 evaluates the nonproliferation implications of a broad spectrum of foreign nuclear fuel cycle initiatives and ongoing activities.

- Support to bilateral/multilateral negotiations and technical assistance: NA-24 provides technical policy support to USG negotiations with associated nuclear nonproliferation issues.

- Evaluation of risks of weapon useable material inventories: NA-24 assesses the proliferation risks of weapons useable material inventories held outside of nuclear weapon states and develops strategies for their secure disposition.

- Support to domestic policy reviews: NA-24 provides technical policy support to U.S. Government policy makers regarding proliferation issues associated with the development of domestic energy policy and the management of the nuclear weapons production infrastructure.

- Regional Security: NA-24 supports geo-political studies of nonproliferation and regional security issues, to further the strategic view that reduction in regional tension reduces the demand for proliferation.

- Export control: NA-24 is responsible for assessing the proliferation issues associated with export licensing.

- International Safeguards: NA-24 is responsible to support the International Atomic Energy Agency (IAEA) in the assessment, development, and application of safeguards measures to civil nuclear fuel cycles worldwide.

- Nuclear fuel cycle assessments
  - Detailed design level support:
    - What is the relative proliferation risk of a large number of distributed plutonium recycle plants or a smaller number of centralized plants?
    - What is the nonproliferation impact of fuel additives?
    - How is proliferation resistance affected by specific engineering processes or designs?
  - Future nuclear systems proliferation risks:
    - What are the implications of commercial actinide incineration and plutonium recycle?
    - Should the U.S. support development and export of small modular reactors, e.g., fast spectrum reactors, Pebble Bed Modular Reactor?
  - Existing domestic nuclear fuel cycles
    - What is the impact of utilization of additional excess nuclear weapons materials in the domestic nuclear fuel cycle?
    - How should the United States dispose of legacy material?
    - Should the U.S. revitalize the Integrated Fast Reactor program or implement accelerator transmutation of waste?
  - International assessments
    - What is the proliferation impact of a country exporting nuclear technology to a third country?
    - Should the U.S. support a Taiwan initiative to send spent fuel to Russia for storage and/or reprocessing?

- Support to bilateral/multilateral negotiations:
  - What are the relative merits of various inspection regimes?
  - What is our position, in specific situations, on countries exporting U.S. obligated nuclear material to Russia?
  - What are the proliferation impacts of a given negotiation position?

- Evaluation of risks of fissile material inventories:
  - What are the proliferation risks of transportation of nuclear material?
  - What is the proliferation risk associated with fissile material inventories (quantity, form, and location) in a particular country?

- Support to domestic policy reviews:
  - Should the U.S. support a renewed domestic uranium enrichment R&D program?
  - Should the U.S. provide advanced technologies for safeguards to the IAEA?

- Regional Security Studies:
  - Should the U.S. engage in cooperative R&D with India/Pakistan/China, etc?
  - What is the proliferation impact with respect to Russia/China of U.S. ballistic missile defense?
  - What are the proliferation implications of changes in foreign governments?

- Export Control:
  - What are the proliferation impacts associated with particular cases of export of nuclear fuel cycle technologies, materials, and information?

- International Safeguards:
  - What is the nonproliferation implication of widespread implementation of [integrated or strengthened] safeguards?

3.2 Scope of Nonproliferation Assessment Methodology

The types of assessment described in the preceding section support the development of policies that would decrease proliferation potential. NPAM can also be used as design upgrade tools to improve proliferation resistance of an existing fuel cycle design. Another possible use of nonproliferation analytical tools would be to assist in the identification of proliferating organizations by examining signs of proliferation. The NPAM development effort does not address this latter type of application.

NPAM specifically addresses nuclear proliferation, i.e. the acquisition of nuclear weapons by a nation or sub-national group that currently does not have nuclear weapons. Radiation dispersal devices are addressed by organizations other than NA-24. Although NPAM may be helpful in assessing issues related to radiation dispersal devices or other issues, the development effort was limited to assessments of the acquisition of nuclear weapons capability.

References

1. USDOE, NASAP, Nonproliferation Alternative System Assessment Program, U.S. Department of Energy, Report No. USDOE/NE-001, 1980.

2. IAEA, International Nuclear Fuel Cycle Evaluation, International Atomic Energy Agency, Working Group Reports, 1980.

3. NNSA, Functional Requirements Document, January 2002.

4.0 Guidelines for Performance and Documentation of Nonproliferation Assessment Studies

The following general guidelines are provided to the analyst for the performance of nonproliferation studies. Figure 1-1 illustrates the sequence of steps that are followed in the setup, performance, and documentation of a nonproliferation study. The steps are not necessarily sequential. Some activities can be undertaken in parallel and some iteration is required between steps. In the following description of the steps, reference is made to other sections of the guidelines document to provide background and more detailed guidance. As a greater experience base is developed in the performance of these studies, the guidelines can be made more specific.

Step 1. Frame the problem clearly and concisely.

a) Define the objectives of the study.
b) Identify policy, legal, and treaty constraints that could impact the alternatives under consideration.
c) Identify the user of the results
d) Define the critical audience
e) Determine the amount of time available
f) Determine the financial and technical resources available
g) Identify specific products of the analysis.
h) Establish the level of quality assurance required.
i) Determine how sensitive or classified information will be handled
j) Determine the frequency of project reviews.

Once the approach has been fully defined and the cost and resource requirements have been estimated in later steps, it may be necessary to revise the approach to stay within resource limits or to renegotiate the available resources.

Step 2. Decompose the problem into manageable elements. Section 5 provides a discussion of the ways in which a nonproliferation assessment problem is typically decomposed, including: the uses of barriers to proliferation, sets of discrete threat categories, and system segmentation. Section 7 provides a detailed discussion of the definition of threat characteristics. Section 6 discusses alternative overall analysis approaches as well as specific assessment considerations, such as the use of multiple attributes versus proliferation-specific studies, the perspective of the analyst, treatment of time-dependence, and region-specific versus generic analyses. The development of a master logic diagram (see Section 9.8) can help to visualize the proliferation process that will be assessed.

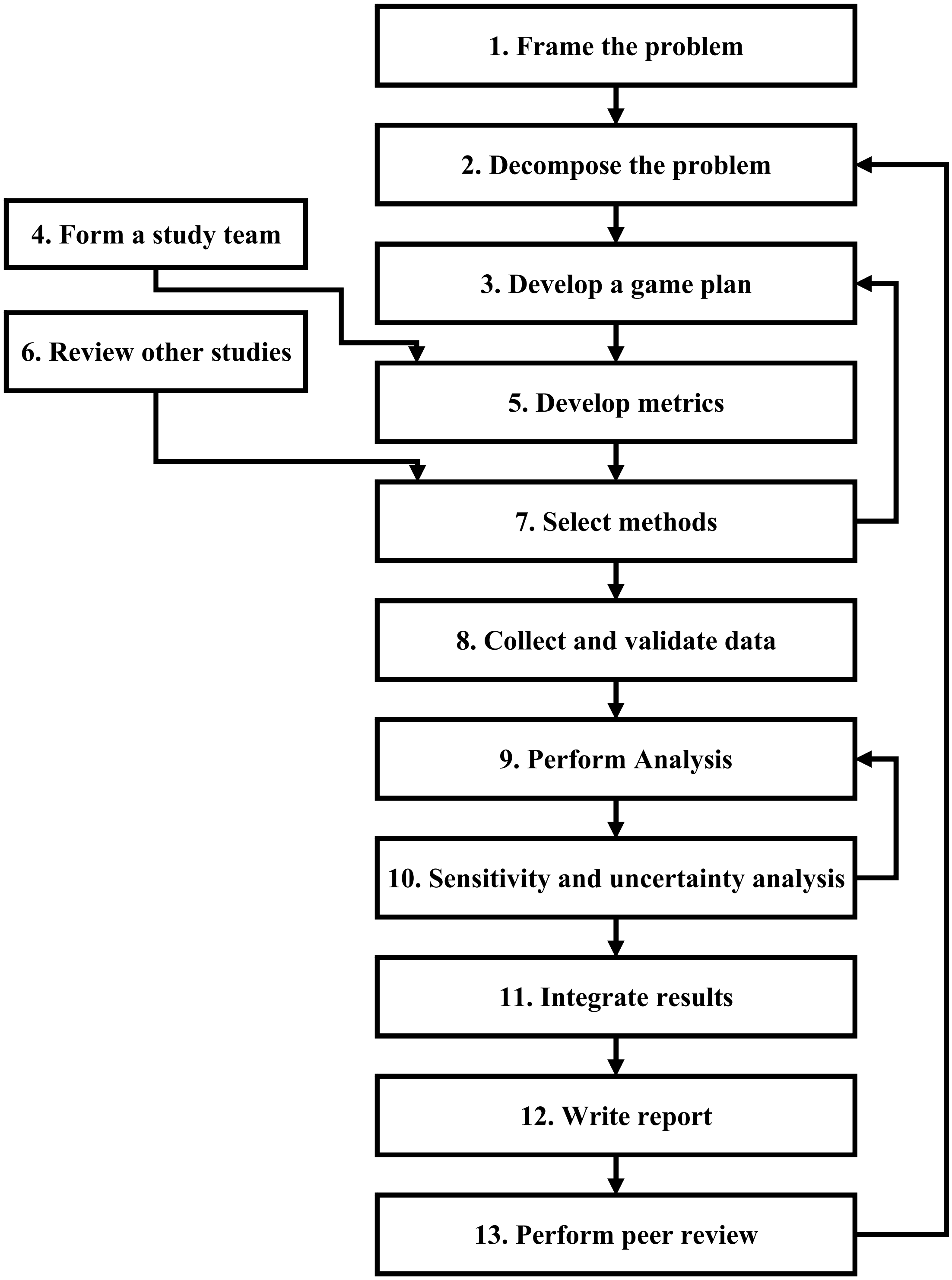

Figure 1-1. Elements of an Assessment Project

Nonproliferation assessment involves substantial uncertainties. It is important to be realistic in recognizing the limits of the methods. An approach should not be taken that requires a level of system detail that is unavailable or is unwarranted within the bounds of associated uncertainties. A benefit of developing systematic and reproducible methods for assessing proliferation resistance is the ability to draw upon and add detail to analysis performed in previous studies. This requires the methodology produces results that can be systematically and logically archived for use in subsequent analyses.

Step 3. Develop a game plan describing the approach and desired results. Before undertaking a major effort, the study plan should be documented. This includes manpower loading, costs, durations, and a clear description the result documentation. Study milestones should be developed particularly for regular reporting to study sponsors. It is important to be certain the end user or sponsor has bought into the approach.

Step 4. Form a study team that provides required expertise. The team should include experts in all required technical areas, including those areas from which expert judgment will be elicited. At least one team member should be a nonproliferation specialist and one team member should be a specialist in the analysis methods. One of these two should probably be assigned as the team leader. The team may also include stakeholders to provide value judgments for the development of utilities and weights. The team should participate in the development of the detailed program approach.

Step 5. Develop metrics. Section 8 describes the types of metrics that are typically used in nonproliferation studies and some of the pitfalls to avoid in the metric selection (such as attribute dependencies). In addition to being capable of satisfying the defined program objectives, top-level measures must be understandable to the user of the study and adequate to provide a means to discriminate between alternatives.

Step 6. Review the results of existing related studies and papers. Reference 1 identifies a number of previous nonproliferation studies. These studies should be reviewed to determine how effectively they have met their objectives and identify lessons that can be of value. The results of earlier analyses can also be helpful in calibrating experts in the process of eliciting expert judgment.

Step 7. Select methodologies. The analyst must select a general approach to the problem. Section 6 describes two general categories of integrated analysis: attribute analysis and scenario analysis. The analyst must decide which general approach is most appropriate to the problem based on the analysis objectives, the availability of system description detail, and financial and time constraints. Section 10 discusses integrated methodologies. Appendices C and D describe two integrated methodologies that are currently under development. Section 9 and Reference 1 describe a toolbox of tools and methods that can be used for the overall assessment approach or can play a supporting role. A study will typically employ a number of these available methods, as appropriate.

Step 8. Collect and validate input data. The quantities and sources of input data depend on the analytical approach. Sources of data and tools for data analysis are discussed in Section 6. Scenario simulation analyses and region-specific analyses require the collection of data characterizing the fuel cycle systems, country capabilities, and pathways to proliferation in an effort to make objective estimates of the probabilities of scenario branches. The data required for attribute analysis methods tend to be more subjective, requiring the elicitation of expert judgment (Section 9.7). Validation of input data implies either the independent review of the data sources or examination of the consistency and bases for expert elicitation. To the extent that information and input data used in the analysis come from classified or sensitive sources, the analyst must assure this information is protected appropriately, including the possibility of classification of the study results.

Step 9. Perform analysis. The analysis is typically performed for an alternative under review and a baseline case (e.g., the currently existing fuel cycle). The details of two analysis approaches are provided in Appendices C and D. The general flow of analysis is described in Section 5.0 and illustrated in Figure 5-5.

Step 10. Perform sensitivity and uncertainty analyses. A study must provide a means for the user to judge the significance of results. Approaches to the performance of sensitivity and uncertainty analyses are described in Section 9.9.

Step 11. Integrate results. In Step 2, the problem is decomposed for analysis. At the completion of the analysis, the results must be integrated. Section 11 discusses the integration and presentation of results. In a fully-mature, integrated methodology, the analysis algorithm may perform the aggregation of results and prepare the output in a form for presentation to the study user. As integrated methodologies are under development, the aggregation of results must be done carefully. Section 8 discusses the metrics used in a nonproliferation assessment and their rollup to high level measures for presentation. Section 11 identifies some of the pitfalls encountered in the aggregation of results.

Step 12. Write the report. Presentation is very important. The authors must provide the results in a form that can be understood by the user and enables the user to draw appropriate conclusions. If the report contains classified or sensitive information, it may be necessary to abstract an unclassified summary of the report. The general contents of a study report are as follows:

- Policy Transmittal Letter (one or two pages)
- Executive Summary (brief but with sufficient information to convey the key messages of the study to someone that only reads the summary)
- Unclassified summary, if needed
- Introduction (fully define the issue and context of the assessment)
- Policy Context (Tell the reader how things evolved leading to the study and describe the policy context)
- Approach (Flow chart of steps; description of methodologies used, including any notable strengths and weaknesses, with details in an Appendix.)
- Analysis of results (Present data in a clear and transparent form; address sensitivities to key variables and uncertainties.)

- Conclusions (results relative to the issue at hand)
- Recommendations (As requested by the study sponsor)
- Appendices, e.g.
  - Study charter
  - Details of methodologies
  - Technical specifications
  - Detailed results
  - Glossary

Step 13. Conduct peer reviews. Peer review is a well-established approach to improving the quality of scientific studies. This approach has been used effectively in the review of probabilistic risk assessments performed to evaluate the safety of nuclear power plants. For any nonproliferation study that will receive wide exposure, a peer review should be performed to assure the quality of the product.

References

1. Jones, E.D. "Review of Methodologies for Assessing Nuclear Proliferation Resistance," Draft, November 2002.

5.0 Problem Decomposition

The steps that should be taken by an analyst in formulating an approach to a nonproliferation problem are outlined in Section 4 of these guidelines. The first step is to clearly define the objectives of the analysis. Existing policy, legal, and treaty constraints should be identified. The analyst must then develop an approach to attack the problem. From experience, nonproliferation analysts have developed some preferred approaches to decomposing nonproliferation problems.

In most policy studies, the purpose of the analysis is to select from alternative options. For example, as illustrated in Figure 5-1, the purpose of the analysis may be to compare the proliferation resistance of Fuel Cycle Option A with Fuel Cycle Option B. The comparison could be between a proposed alternative and an existing system, with a reference case, or with a standard of acceptability. Thus, in order to satisfy the objectives of the analysis, the analyst needs measures of proliferation resistance to indicate whether A is better or worse than B. The analyst also needs to know the uncertainty in the measures to be able to determine whether the indicated difference between A and B is significant. Thus, as indicated in Figure 5-2, the comparison between Fuel Cycle Option A and Fuel Cycle Option B may have to be interpreted within the context of the uncertainty. Whereas the policy maker may conclude from examining Figure 5-1 that Fuel Cycle A is more proliferation resistant than Fuel Cycle B, the more appropriate conclusion may be the one drawn from Figure 5-2. Because the bands of uncertainty overlap, the policy maker can only draw the weaker conclusion that Fuel Cycle A is probably more proliferation resistant than Fuel Cycle B. The selection of analysis metrics is discussed in Section 8 of these guidelines. The specific metrics selected depend not only on the character of the nonproliferation issue being addressed but also on the analysis approach that is being taken.

5.1 Barriers to Proliferation

Defense-in-depth is a design strategy used to prevent theft or diversion of nuclear material by the use of multiple barriers to proliferation. Typically, a nonproliferation assessment identifies the barriers to proliferation and evaluates their effectiveness. The physical protection system of a nuclear facility is designed to withstand design basis threats through physical barriers, detection, response and interdiction. The challenge to the proliferant organization is to defeat the physical protection system. A nonproliferation assessment evaluates the likelihood the proliferant organization would be successful or the extent to which the system is resistant to the proliferant actions. The attribute analysis approach described in Appendix C is referred to as MAU Barrier Analysis. However, the barrier concept is used in almost all nonproliferation analyses, including the scenario analysis approach described in Appendix D. The manner in which scenario analysis and attribute analysis approaches assess the barrier effectiveness differs.

Barriers are typically characterized as either intrinsic, with features inherent to a particular fuel cycle system, or extrinsic, involving administratively-added measures such as physical protection and international safeguards. There is a dynamic interplay between extrinsic and intrinsic barriers. To satisfy international standards for adequacy of protection against the diversion of nuclear material, external barriers can be added to compensate for weaknesses in intrinsic barriers. A possible metric of a system is the cost (either monetary or in person-days) of the compensatory extrinsic measures needed to meet a nonproliferation objective, such as the IAEA's timely detection standard.

The nature of the proliferation threat can impact the relative effectiveness of intrinsic and extrinsic barriers. If a nation state decides to remove its facilities from IAEA safeguards and use its commercial nuclear facilities to produce weapons material, some extrinsic barriers could become completely ineffective in deterring the production of weapons material but intrinsic barriers would still be in place.

5.2 Threat Description

Another standard strategy for the decomposition of nonproliferation problems is to define a set of threats and to evaluate the proliferation resistance of the option under consideration for each threat separately. Consider, for example, a fuel cycle facility that is under IAEA safeguards. One threat could be a country with a high level of technical competence that decides to divert material covertly. Another threat is a small subnational group that attacks the facility and attempts to escape with weapons material. The relative resistance to these different proliferation threats varies depending on the alternative fuel cycle system under consideration. Typically, the analyst will compare the proliferation resistance of Fuel Cycle A for Threat 1 with the proliferation resistance of Fuel Cycle B for Threat 1 and similarly the resistance of the Fuel Cycle A for Threat 2 with the resistance of Fuel Cycle B for Threat 2, as illustrated in Figure 5-3. The selection of threat characteristics is discussed in Section 7.

5.3 System Segmentation

A nonproliferation issue relates to some type of system composed of materials, facilities, processes and controls. Frequently, the system involves an element (e.g., an enrichment facility) or multiple elements of a fuel cycle system. It is general practice to subdivide the system into discrete segments. The subdivision often occurs at the facility level, as illustrated in Figure 5-4. However, depending on the detail of the analysis approach, it may be necessary to further subdivide these facilities to the level of a distinct process line. In the example in Figure 5-4, the accessibility and characteristics of fuel are different in the fresh fuel storage area, reactor core, and spent fuel storage pool. Thus, the nuclear power plant is subdivided into three elements. Similarly, at the final repository, accessibility of material is different in surface facilities than in subsurface facilities. This facility, therefore, would be subdivided into two subunits for analysis. Figure 5-4 is only intended as an example of the level at which system segmentation may occur. The analyst must develop a specific level of segmentation for the type of fuel cycle (or nuclear system) being analyzed.

Transportation between facilities can also be a point of diversion. Important transportation links can be identified as segments of the fuel cycle system in the same manner as facilities.

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As indicated in Figure 5-3, the analyst examines the proliferation resistance of each segment of the fuel cycle separately for each threat.

Figure 5-5 illustrates how the analysis is typically performed from the decomposed elements. The down and up arrows indicate an iteration over each of the elements in the top box. Thus, the complete analysis is performed for the first alternative and then for the second alternative. Within the analysis for each alternative, an assessment is made for each threat. Within each alternative and threat, an assessment is made for each segment of the fuel cycle (facility). The dashed box indicates the proliferation measurement algorithm, either a scenario analysis or extrinsic, administratively-added measures. For each alternative/threat/facility, the assessment measures the applicable barriers to proliferation. The weighting of metrics may occur within the measurement algorithm, or it may occur, as indicated in the figure, as a weighting of high-level metrics before the comparison of alternatives.

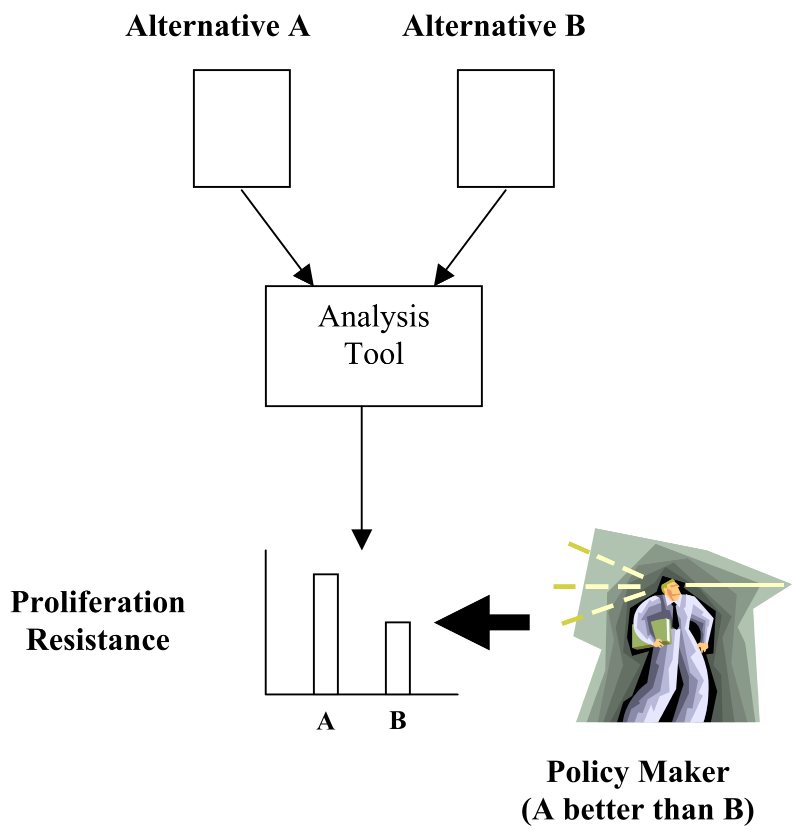

Figure 5.1 Concept of a Nonproliferation Assessment Study

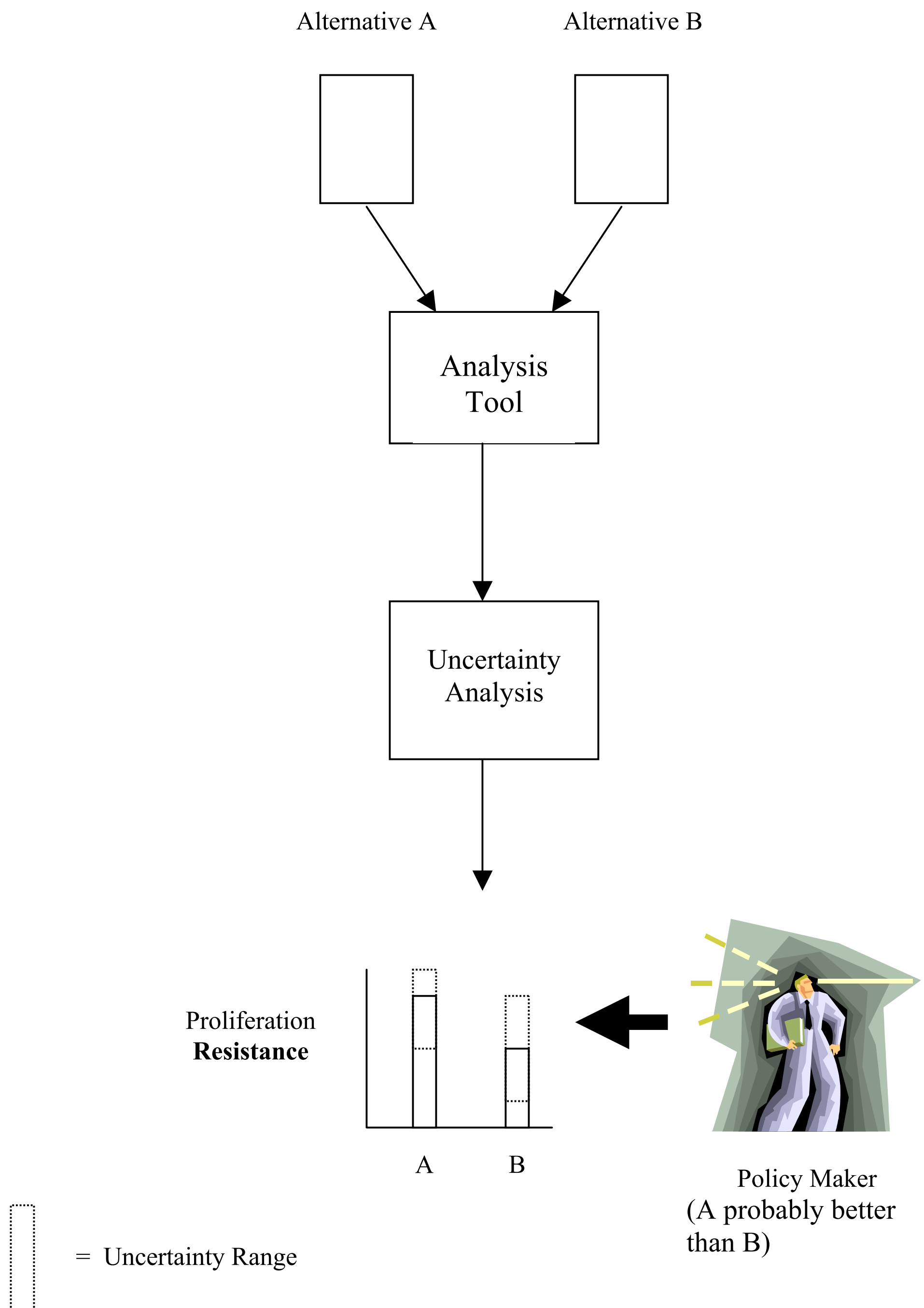

Figure 5-2. Results with Uncertainties

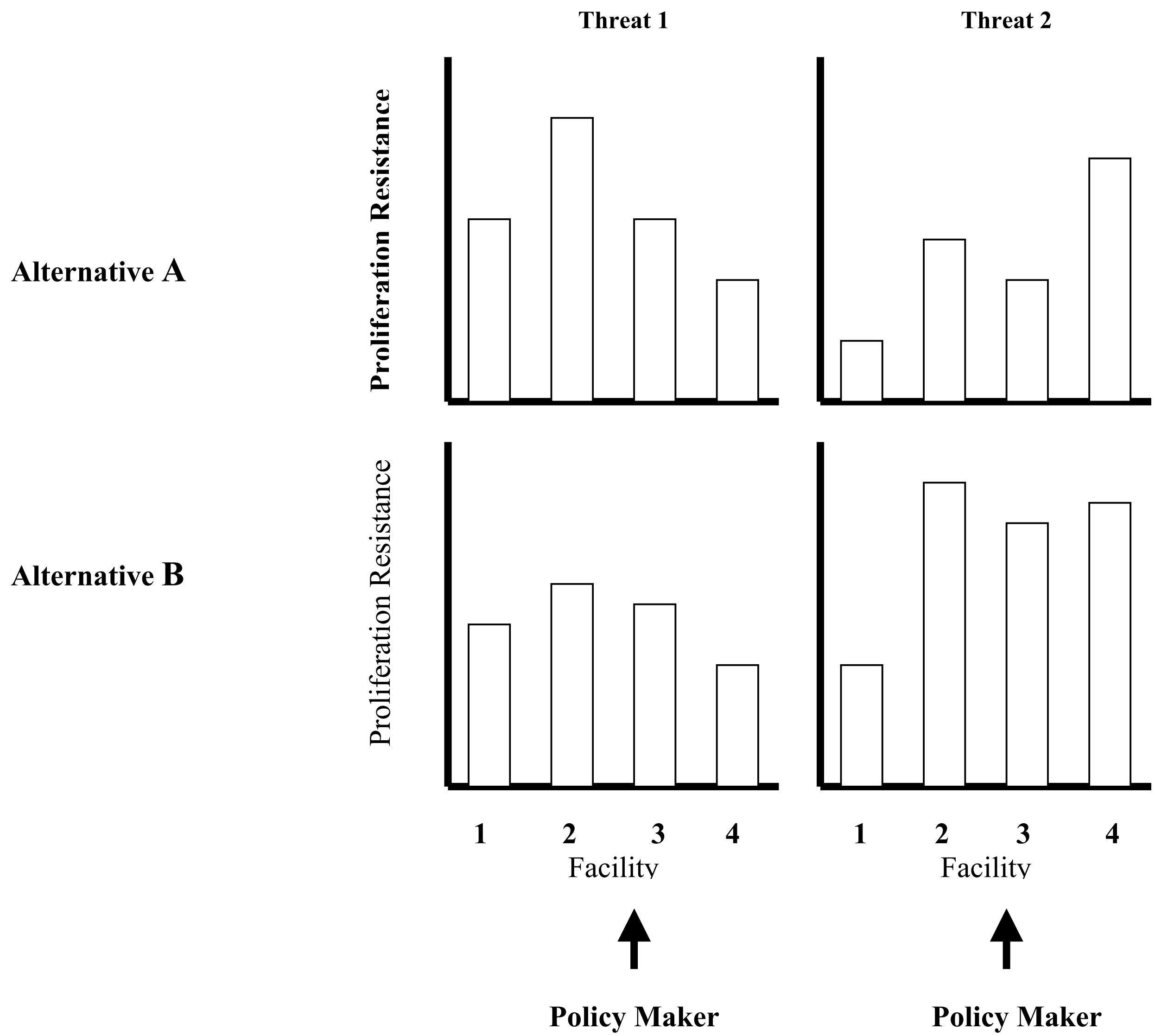

Figure 5-3. Comparison of Alternatives

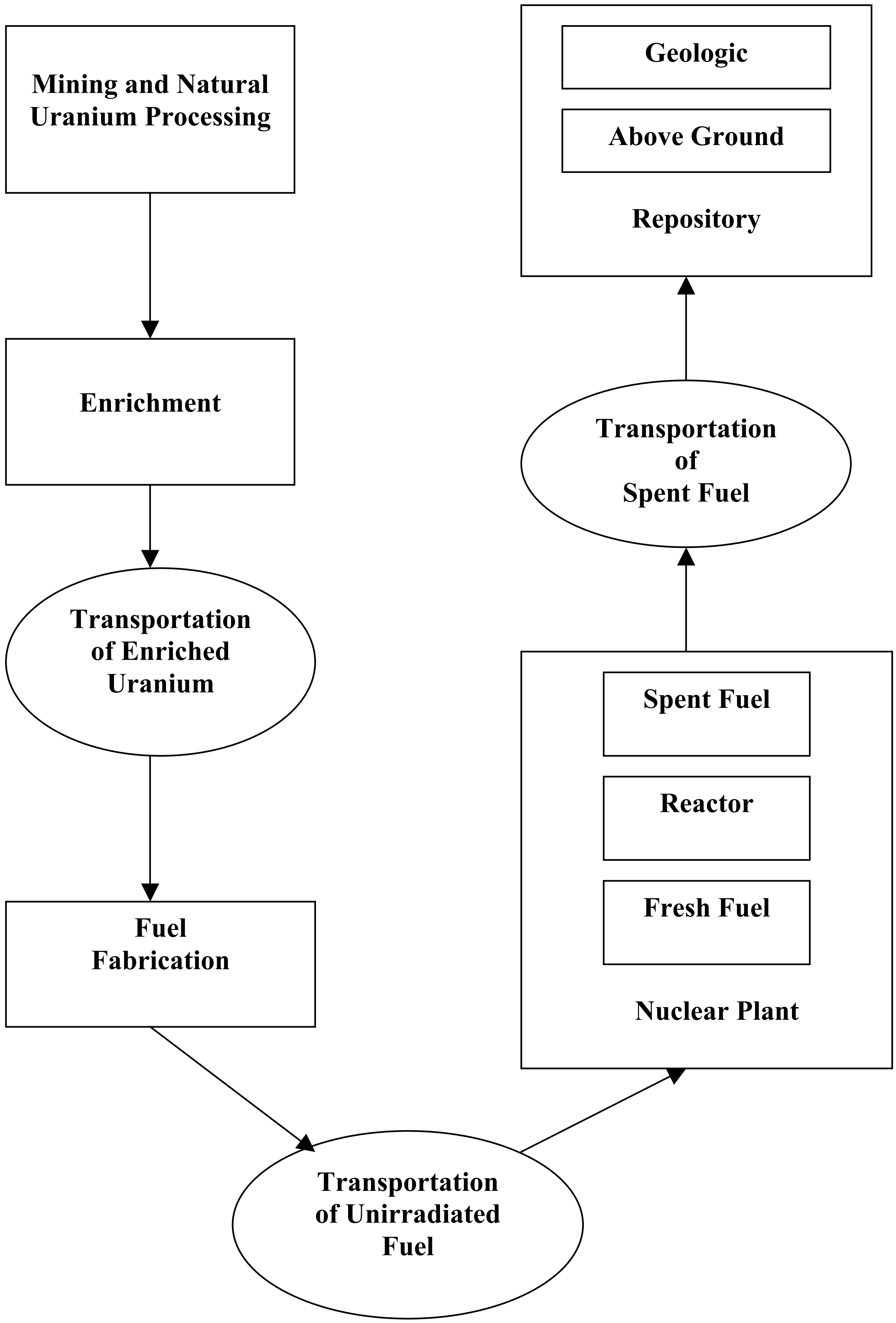

Figure 5-4. Segmentation of Fuel Cycle

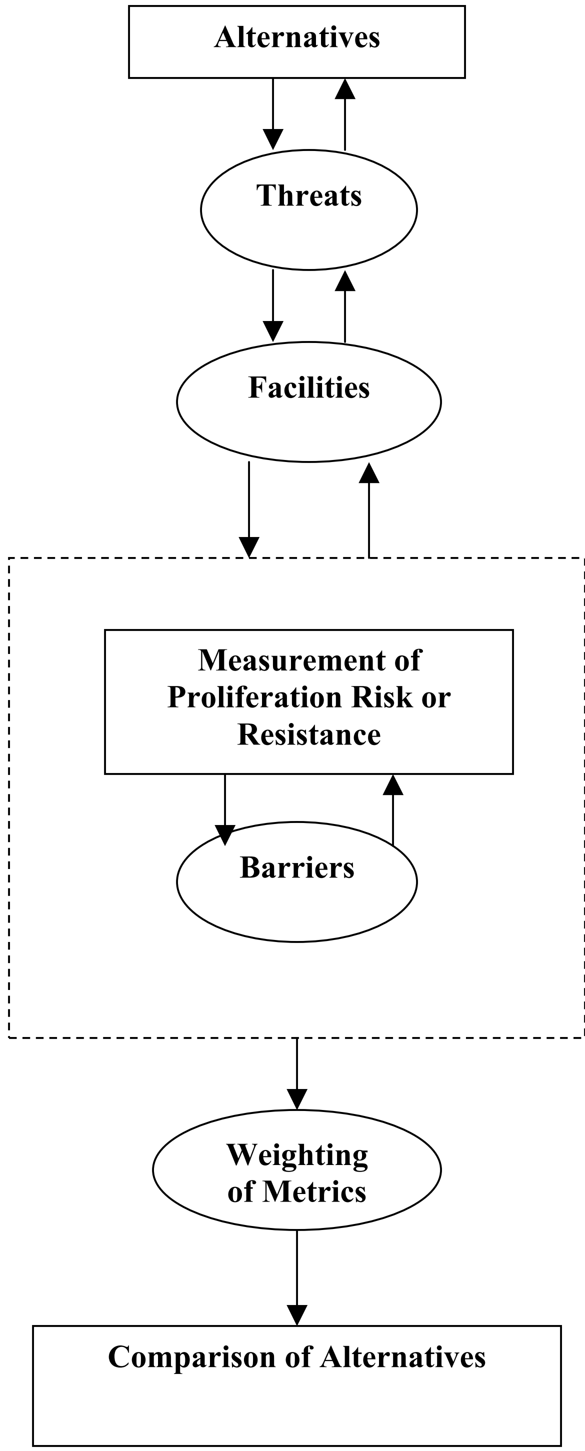

Figure 5-5. Typical Problem Decomposition and Analysis Flow

6.0 Assessment Approach

6.1 Analysis Approaches

Section 9 describes the tools and methods that are available to the analyst. It is difficult to establish a taxonomy of tools and methods that fits them into clearly distinct categories. Methods have overlapping characteristics. A nonproliferation assessment can also use different techniques effectively to treat different aspects of the problem. There is no clearly defined difference between a tool and a method. In this document, tool is used to refer to a technique with broad applicability that could be used in a supportive role in a wide variety of studies. The term method is used for techniques that are used as the framework for the analysis.

In examining the overall methodologies that historically have been used for nonproliferation assessments, two general categories were identified: attribute analysis and scenario analysis. Although the distinction between "scenario analysis" and "attribute analysis" is not always clear, there is value in discussing the philosophical differences in approach between the two categories of methods. However, it is not intended to imply that a study must adopt one or the other approach. The two categories of methods are often used in combination. A third category of analysis methods with significant potential to support nonproliferation policy development is two-sided methods, in which the interplay between opponents is assessed. Of the two-sided methods, wargaming appears to have the most potential to provide policy insights that are not effectively addressed by other methods.

Attribute analysis. In this approach, attributes of the systems being evaluated (often fuel cycle systems) are identified that affect their proliferation potential. For a particular system under consideration, the attributes are weighted subjectively. Typically, these studies are more qualitative than the scenario analysis studies. There is an extensive history of the use of formal methods of decision theory (such as MAU theory) to assist in decision making using this type of approach.

Scenario analysis. In these studies, hypothesized scenarios of pathways to proliferation are examined. The analyst models the process undertaken by the proliferant to overcome barriers to proliferation and estimates the likelihood of success in achieving a proliferation objective. Typically, these studies use logic modeling techniques (often probabilistic techniques). The results are quantitative but rely in some respects on subjective judgments of experts.

Wargames. A wargame is a role-playing exercise where human participants make sequential decisions to allow a scenario to unfold. Wargames are characterized by the active and central involvement of human beings, often with opposing goals, and making sequential decisions.

Attribute analysis, scenario analysis, and two-sided methods have complementary roles in the performance of nonproliferation assessments. Section 10 discusses integrated methodologies that can be used to assess measures of the proliferation potential of alternative nuclear systems.

Either attribute analysis or scenario analysis methods could provide the basis for this type of assessment. Each type of method has strengths and weaknesses that determine the type of study for which each is preferred. For some applications, it is quite possible that a combination of attribute analysis and scenario analysis could be the most effective approach.

Wargames are not competitive with attribute analysis or scenario analysis for the performance of these types of integrated assessments. The results of a wargame represent a possible outcome but not necessarily the most likely outcome of an interaction. They can, however, provide valuable insights into the thought processes of adversaries as input to an integrated assessment.

One of the purposes of the guidelines identified in the FRD is to "specify which methods are best suited for the areas of questions and issues that fall within NA-24's nuclear nonproliferation portfolio. This matching of methods with issues and questions should include consideration of levels of detail required and the time available to perform an assessment." As discussed in Section 5, the typical nonproliferation assessment involves a comparison of alternatives with regards to their proliferation resistance or proliferation risk as a basis for the development of policy. The NNSA issue areas listed in Section 3.1 can be addressed by the following combinations of nonproliferation assessment characteristics:

- System – materials, facilities, processes, safeguards
  - Commercial fuel cycle
  - Nuclear weapons infrastructure
- Design level
  - Detailed
  - Conceptual
- Location
  - Domestic
  - International – generic
  - International – regional specific

In addition, geopolitical analyses may be required to support "regional security" related policies.

In evaluating the strengths and weaknesses of the different analysis approaches in addressing the NNSA policy issues, the Working Group concluded that the principal discriminating features of the assessment are the detail of design information and the amount of time (and associated effort) available to perform the study. Table 6.1 summarizes the Working Group's evaluation of strengths and weaknesses of the analysis approaches for these different analysis constraints.

In Table 6.1, High (H), Medium (M) and Low (L) represent the strength of the analysis approach for the indicated level of design detail and project duration. The dividing point between a short duration and a long duration project is assumed to be one month. Sometimes requests for policy input can be as short as one day. Unless there is substantial information already available on the topic, it is difficult to use any of these methods in a period of less than one week. An in-depth, integrated assessment is expected to require approximately six months.

Table 6.1. Strengths and Weaknesses of Approach as a Function of Analysis Constraints

System	Location	Design Detail Duration	Approach Attribute Analysis	Scenario Analysis	War-gaming*
Nuclear Fuel Cycle or Nuclear Weapons Infrastructure	Domestic, Foreign-Generic, or Region Specific	Detailed Short	M	M	L
		Detailed Long	H	H	M
		Conceptual Short	H	L	M
		Conceptual Long	H	H	H
Geopolitical	Global or Regional	Short	M	L	H
		Long	M	L	H

*Wargaming typically is only one element of a nonproliferation assessment.

Attribute analysis methods do not require the level of detailed design information as scenario analysis methods. They can, however, require substantial effort. The Analytic Hierarchy Process, an attribute method, can be used for quick response projects. However, the reliability of the result is highly dependent on the expertise of those providing input to the process.

Scenario analysis methods can be applied at a conceptual level but their strength is in studies in which detailed design information is available to support the analysis. This type of assessment requires substantial time and effort.

Some time and effort is required to set up a wargaming exercise. However, the actual execution of the exercise is short. Thus, it is quite practical to obtain meaningful results in less than one month. Wargames provide insights that are of value in developing a better understanding of the conflict between the proliferant and actions to prevent proliferation. They are usually an element of a larger nonproliferation assessment.

6.2 Multiple-Attribute vs. Proliferation-Specific Studies

Proliferation resistance is typically not the only attribute on which decisions are based. Section 9 discusses the application of MAU theory to decisions in which the different attributes all relate to different aspects of proliferation potential. Real decisions are seldom made on bases that are this narrow. The cost of an alternative frequently has an impact on the decision process. Other attributes may either be important considerations or might dominate the decision relative to proliferation considerations. Krakowski (Ref. 1) recommends greater consideration be given to the balancing of all factors in a decision rather than limiting the analysis to proliferation considerations.

The purpose of this document is to provide guidance on performing the nonproliferation portion of the analysis. The analyst should recognize that proliferation resistance is not the only factor likely to be considered by the policy maker and should try to provide perspective on the significance of the proliferation resistance analysis. For a particular issue, it is possible proliferation resistance is not a good discriminator between alternatives. The analyst must provide not only a nonproliferation ranking of alternatives but also guidance on whether the nonproliferation differences among alternatives are significant.

6.3 Perspective of the Analyst

Typically, the analysis can be framed from either the viewpoint of the proliferant or the viewpoint of the organization trying to prevent proliferation. For example, in terms of a fault tree, the top event could be failure of the barriers to proliferation, measured as the probability of proliferation. From the viewpoint of the defender against proliferation, the various barriers are identified and the logic developed to determine failure combinations leading to proliferation. Conversely, the proliferant looks at the system as a success tree in which he assesses the combinations of events that can lead to success in achieving the proliferation objective.

There are advantages to analyzing the process from both viewpoints. The client (policy maker) for the analysis has the perspective of the anti-proliferant. The client is trying to develop alternatives that will prevent proliferation. The probability that a proliferant will take a certain pathway toward proliferation must be assessed from the proliferant's viewpoint, however. The proliferant can be expected to make an assessment of practical options involving times and quantities required to achieve its weapon objective and likelihood of success. Time, cost, non-detection probability, and ultimate success probability could be factors in the proliferant's selection of a pathway or pathways to proliferation.

Saaty (Ref. 2) discusses forward planning and backward planning. Backward planning involves deductive reasoning analogous to the development of a fault tree. Forward planning involves inductive reasoning analogous to the development of an event tree. In a combined iterative process of backward planning and forward planning, backward planning could be used to develop a protective system to meet nonproliferation criteria and forward planning could be used to evaluate the likelihood of satisfying those criteria.

6.4 Regional-Specific vs. Generic Characteristics of Proliferant

Often, the decision-maker has a specific group of potential proliferants in mind when developing nonproliferation policy alternatives. The analyst must decide whether to formulate the analysis within the context of specific countries or regions or represent potential proliferants by generic categories. Collection of data for individual countries can require significant effort. The fidelity of a country-specific analysis may also decrease as conditions change with time. Nevertheless, some policy decisions must be framed within the context of a specific perceived threat.

6.5 Time-Dependent vs. Static Analysis

Clearly, proliferation potential for a country or organization changes with time. Typically, less-developed countries obtain technical capabilities over time that might make proliferation easier. Geopolitical models are used to predict the evolution over time of economic environments and capabilities using dynamic modeling techniques. A time-dependent nonproliferation assessment, which accounts for projected changes in capability, would probably only be performed for a regional study that addresses specific potential proliferants (e.g., Iraq). In a study that treats potential proliferants within the context of generalized threat categories, the capability of the proliferant is determined by the characteristics of each threat category. Typically, these are assumed to be static during the time frame of the nonproliferation assessment.

6.6 Data Analysis and Sources

The types of data that are required to support nonproliferation assessment depend on the nature of the assessment. Typically, the analyst must characterize both the proliferant and the system under evaluation. For studies using generic threats, the characteristics of the proliferant are defined by the analyst in establishing the set of threats to be used. The data needs are greater for a country or region-specific analysis in which it may be necessary to collect extensive data to characterize the proliferant. Financial and technical resources and acquisition time would normally be used to characterize a specific country or subnational group. These data could include publicly available information, such as gross domestic product of a country. They could also include technical information, such as the availability of specific facilities or process technology within the country, either as the result of nuclear activities or from allied industries. Some of these data could be obtained from classified sources.

The IAEA prepares State Evaluation Reports (SERs) that assess the current nuclear capabilities of each State. The SERs, made and updated annually by the IAEA, are based on declarations by the States and on independent verification. The analysis includes regional security, political and economic stability, and military capability. Design information verification activities by the IAEA begin early during the construction of a new facility and continue through commissioning, routine operations, maintenance and upgrades, shut-down, and decommissioning.

In addition to characterizing the proliferant, the analyst must characterize the system under evaluation. The types of resources that should be obtained are: system design descriptions, including surveillance and protective systems; process descriptions; process flow diagrams indicating material quantities and characteristics; and line drawings, including physical barriers. Physical walkdowns of existing systems could be taken to assure that drawings and descriptions represent the actual system. The extent to which these design and process details will be available will be problem specific.

Depending on the nature of the analysis, it may be necessary to assess the likelihood that a proliferant will select a specific pathway or the probability that a barrier will be successful in preventing proliferation. The available data to support these assessments are sparse. Some data can be obtained by examining the history of proliferation activities. One of the activities in progress in the NPAM program is developing a database of this type from historical evidence. (Ref. 3) The analyst must consider the quality of data based on the directness, reliability, and objectivity of the source. Newspaper articles are a notoriously error-prone source of data. In the absence of objective data, it is necessary to rely on expert judgment. Methods of expert elicitation are described in Section 9.7. Bayes' theorem can be used to augment sparse system specific data with generic data. This approach to data treatment is described in Section 9.2.2.

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7.0 Characterization of Threat Space

The largest historical proliferation threat has been the nation/state. There have been at least nine successful attempts at nuclear proliferation in the past 60 years, with several other programs abandoned due to changes in the geopolitical climate. During recent years the subnational threat has grown, which further complicates nonproliferation considerations. In designing and evaluating fuel cycles, it will be critical to balance nonproliferation measures so that each class of credible threat is addressed appropriately.

Understanding the spectrum of proliferation threats is a critical step that will contribute to the overall assessment of nonproliferation. The enumeration of threats is necessary because different classes of threats are constrained by different resource considerations, strategic goals, and technical capabilities.

Because of this spectrum of capabilities, a proliferation-resistant measure that strongly deters one threat may not be at all effective against another. Worse, some proliferation-resistant measures designed to deter one class of threat may be useful to another class of threat in masking proliferation activities. In looking at the threat spectrum, we will briefly summarize historical proliferation examples, and attempt to project these to the larger problem of future nonproliferation.

7.1 History

7.1.1 Nonproliferation Treaty Nuclear-Weapons States

The US, USSR (and later Russia), Great Britain, France and China are the five states recognized by the Nonproliferation Treaty (NPT) as nuclear-weapons states. Although there are a few instances of dual-purpose (civilian and weapons-related) facilities in several of these countries, weapons material was generally acquired through enrichment or reprocessing facilities that were dedicated to nuclear weapons production. Each of these countries has capabilities in both highly enriched uranium and plutonium production.

7.1.2 Declared and De Facto nuclear weapons states external to the NPT

India and Pakistan are de facto nuclear weapons states external to the NPT. Prior to becoming a non-nuclear weapons state NPT signatory in 1991, South Africa had nuclear weapons capability that has subsequently and verifiably been dismantled. Although Israel has a publicly ambiguous position, many believe that Israel is a *de facto* nuclear weapons state, also external to the NPT.

If open source information is correct, pathways toward proliferation among these four states are thought to be split, as two focused their early programs on uranium enrichment and two focused on plutonium generation and reprocessing. Of these, all programs were in facilities that were not subject to international safeguards. Thus, at the nation-state level, there have been at least two routes to proliferation: enrichment or generation and reprocessing. Design issues (plutonium versus highly enriched uranium weapons), alone, do not seem to be strong drivers; and infrastructure issues (i.e., harder to develop enrichment or reprocessing capability for special nuclear material production) are also not strong drivers. The *system* of capability within a state (natural resources, intellectual resources, cooperation from other states, infrastructure and national goals) appears to be the strongest driver that determines the proliferation route of choice

7.1.3 Proliferation roll-back

There are four known cases where countries, based on their own national interest, decided to roll back from the proliferation of nuclear weapons. During the 1970s and 1980s, South Africa developed an indigenous nuclear weapons capability. However, under F.W. de Klerk, the weapons program was halted and dismantled, with the country placed under full-scope IAEA inventory and safeguards between 1990 and 1994 (Spector, et al 1995). Kazakhstan, Ukraine and Belarus temporarily became *de facto* nuclear weapons states when the Soviet Union quickly dissolved in December of 1991. However, through a series of agreements, these states agreed to relinquish control of Soviet nuclear weapons, return them to Russia and join the nonproliferation regime as non-nuclear weapons states: December 21, 1991 Declaration on Nuclear Arms between Russia, Kazakhstan, Belarus and Ukraine; the December 30, 1991 Minsk accord; the May 23, 1992 Lisbon Protocol; and accession to the NPT as non-nuclear weapons states.

7.1.4 States of proliferation concern.

Iraq, Iran and North Korea have been noted as states that have ambitions to acquire nuclear weapons, contrary to their commitments as signatories to the NPT. As noted above for other cases, there does not appear to be a common “optimum” proliferation pathway that potential proliferant states have selected to pursue. Most recently, North Korea admitted openly to enriching uranium for weapons purposes. (Ref. 1)

7.1.5 Industrialized nuclear countries.

Most industrialized countries with civilian nuclear programs have the technical *potential* to become nuclear weapons proliferants. However, the nonproliferation regime, including the NPT, IAEA safeguards commitments, bilateral and multilateral agreements, contributes to the assessments by non-nuclear weapons states that it is in their continued national interest to remain non-nuclear weapons states. (Ref. 2)

Several other states had nascent nuclear weapons programs that were terminated before they achieved nuclear testing. These countries include Argentina, Brazil, and Sweden. In each of these cases and for a variety of reasons, it was determined that continued pursuit of nuclear weapons was not in the state’s national interest. Their acceptance into the community of nations, prospects for international commerce and overall national security were judged to be better assured without nuclear weapons than with them (Ref. 3, 4).

7.1.6 Subnational threat.

A growing concern, particularly after the 9/11/2001 terrorist attack, is the potential for subnational organizations to acquire nuclear weapons. Some terrorist organizations have a clear interest in acquiring nuclear materials, as indicated by attempts to smuggle such materials across international borders. It is less clear, however, as to whether and which subnational organizations have the desire and ability to engage in nuclear weapons development (as opposed to using them in radiological dispersal devices). Nevertheless, the potential for subnational threats to use special nuclear material in a nuclear explosive must be considered in development and analysis of nonproliferation. A State with nuclear weapons capability could sponsor terrorism or be incapable of controlling activities within its borders. On the subnational level, the most likely means of obtaining weapon material is through theft or purchase.

7.2 <u>Guidance for the Characterization of Threats</u>

The spectrum of potential threats of nuclear proliferation is complex and ranges from small terrorist cells to industrialized countries with advanced nuclear fuel cycles. Adding to this complexity, the potential objectives of these threats are highly multidimensional. Detailed objectives of particular proliferants are difficult to ascertain with any degree of certainty and even more difficult to predict. As a result, evaluating the overall global proliferation resistance of possible fuel cycles on a country-by-country basis is probably impractical (although estimating specific proliferation risk for a particular country may be more tractable).

A partial list of objectives that may be important to potential proliferants is identified below, followed by approximate possible ranges within each objective.

- Numbers of nuclear weapons
  - 0-1000s
- Production rate
  - 0-100s/year
- Yield
  - 0-MegaTons
- Reliability
  - 0, ~50-100%
- Details of targets
- Limitations of collateral damage
  - Minimal collateral damage to no restrictions
- Delivery mechanism
  - Truck, plane, missile, boat
- Precision of yield
- Options for stockpiling
  - 0-1000s
- Intended lifecycle of weapons
  - <1 year to 10s of years
- Concern about detection
  - Minimal to substantial

The next section of this report identifies potential metrics that might be used in evaluating nonproliferation. In general, nonproliferation measures contribute to the difficulty that a given proliferant must overcome to meet its objectives.

Although there is a continuum of threats across many dimensions, analysis can be simplified by classifying threats in groups and identifying key salient objectives for these groups. Understanding the relationship that nonproliferation measures have in addressing proliferant objectives is important in developing meaningful groupings of threats.

One example grouping of proliferant threats is given in Table 7.1. This grouping was developed principally considering features of nuclear material attractiveness in evaluating nonproliferation. Note that the aspirations of the different types of proliferant organizations vary widely. The terrorist organization does not need a highly reliable or high yield weapon to achieve its objectives. The developed state considering the use of nuclear weapons in a potential battle with another developed state has quite different needs. The probability of success of a proliferant organization depends on its motivation, capabilities and ultimate objectives.

There are a number of ways to group proliferation threats, by adjusting the coarseness of the resolution and the number of potential objectives considered. This represents only one possible grouping. In practice, it is likely that threat groupings, nonproliferation metrics and evaluation methodologies will need to be developed iteratively, for they may be highly dependent on each other.

7.3 Observations

The entire spectrum of threats is of concern and should be addressed. Arguably, however, historical trends suggest, both qualitatively and quantitatively, the national threat requires the most focus from a fuel cycle proliferation resistance perspective. Open literature documents several hundred cases of nuclear smuggling, but these have generally involved very small quantities of nuclear material and/or involve radiological, but not fissionable material. Similarly, several sub-national groups may have an interest in nuclear capability, but support appears to have been met with very limited success.

Looking at historical proliferation activities, it seems clear national security is the biggest driver as to whether or not a government decides to proliferate. Two significant factors in this area of national interest are regional stability/security and totalitarianism. Regional stability/security was a stated reason for South Africa, India and Pakistan's decisions to proliferate and is undoubtedly a factor in Israel's position. North Korea appears to have been motivated in its weapons development program as a means to blackmail the international community into political acceptance and economic support. In addition, totalitarian regimes were also factors that enabled North Korea, Iraq and Iran to pursue nuclear programs. It is, however, also important to point out that in many cases regional stability and political regimes can change dramatically on the timescales of nuclear fuel cycles. Thus, what may appear to be a proliferation resistant fuel cycle under a given set of assumptions appropriate for one era may be much less resistant during a different geopolitical era. Policy decisions regarding whether to proliferate and technical capabilities of a proliferant organization can reinforce one another. Capabilities can stimulate policy decisions and policy decisions can stimulate growth of capability. The environment influencing an organization's decision to proliferate is continually changing.

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Table 7.1 Nominal Weapons Aspirations of Various Types of Proliferation Threats.

		Nominal Weapon Aspirations				
Threat Categories		number	yield	reliability	delivery	to be stockpiled
1	sub national	1 or 2	any	any	truck/boat	no
2		5 to 10	any	any	truck/boat	no
3	non-industrialized State	1 or 2	any to 20kt	50-95	plane	maybe
4		5 to 10	any to 20kt	50-95	plane	maybe
5		10 to 50	any to 20kt	50-95	plane	maybe
6	developed State	1 or 2	any to 20kt	50-95	plane	no
7		5 to 10	any to 20kt	95	plane	yes
8		10 to 50	20-200kt	95	missile	yes

8.0 Nonproliferation Metrics

The results of nonproliferation assessments must be expressed in terms that inform the user of the assessment. Measures of the proliferation potential (or proliferation resistance) must be clearly defined. The measures must be quantifiable in some respect; that is, they should relate to a readily quantifiable physical characteristic or be amenable to be expressed in terms of a figure of merit based on a utility or value function.

The measures to be used in proliferation potential or proliferation resistance assessments are usually referred to as either measures or metrics. In the present document, measures refer to the high-level comprehensive variables for expressing proliferation risk or resistance, and metrics refer to the lower level, more concrete nonproliferation-related characteristics of materials, facilities, processes, or actions.

Nonproliferation assessments generally attempt to measure the proliferation resistance of a particular alternative or the proliferation risk of a certain action or proposition. It is important to distinguish between the two types of assessment because they rely on different measures. Consistent with the glossary developed for this project, the following definitions apply:

> *Proliferation* – Acquisition of one or more nuclear weapons by a nation or subnational group that currently does not have them. a readily quantifiable physical characteristic or be amenable to be expressed in terms of a figure of merit based on a utility or value function.

The measures to be used in proliferation potential or proliferation resistance assessments are usually referred to as either measures or metrics. In the present document, measures refer to the high-level comprehensive variables for expressing proliferation risk or resistance, and metrics refer to the lower level, more concrete nonproliferation-related characteristics of materials, facilities, processes, or actions.

Nonproliferation assessments generally attempt to measure the proliferation resistance of a particular alternative or the proliferation risk of a certain action or proposition. It is important to distinguish between the two types of assessment because they rely on different measures. Consistent with the glossary developed for this project, the following definitions apply:

> *Proliferation* – Acquisition of one or more nuclear weapons by a nation or subnational group that currently does not have them.

> *Proliferation Resistance* – Degree of difficulty that a nuclear material, facility, process, or activity poses to the acquisition of one or more nuclear weapons.

> *Proliferation Risk* - The likelihood of a nation or subnational group acquiring one or more nuclear weapons within a given time period.

Proliferation resistance can apply to an entire nuclear complex as well as to particular elements of a nuclear complex (a commercial fuel cycle, a facility, transportation of nuclear material, etc.) Proliferation risk, on the other hand, can apply to actions or activities not necessarily part of a physical nuclear complex. Acquisition of specific technologies or skills, industrial capabilities, etc., can bear on the risk of proliferation.

The measures for proliferation resistance must focus on expressing the difficulty in obtaining the nuclear weapons. This can, in general, be expressed as a measure of the barriers to the acquisition of the material and a measure of the barriers to successfully using the acquired material in nuclear weapons in a given time. These barriers relate to the availability of the desired materials, the practical difficulties in removing that material from its intended use, and the detectability of diversion by national technical means, by export control bodies, or by IAEA inspectors.

In addition to proliferation resistance, measures of proliferation risk are also needed to assess the likelihood of a given action involving a nuclear facility, process, or activity, to contribute to proliferation. Measures of proliferation risk will assess, in addition to proliferation potential (the inverse of proliferation resistance) of the material, facility or process, the likelihood of a nation or subnational group successfully pursuing the development of nuclear weapons in a given time. The likelihood of successfully developing nuclear weapons will include elements related to political issues (motivation of the nation or subnational group) as well as to the economic and technical capabilities of the proliferant.

In general, estimating overall measures of proliferation resistance and proliferation risk involve a complex set of elements. The challenge is to select a set of a few top-level measures that can comprehensively represent the assessment. The need for the development of a hierarchy of metrics and measures depends on the type of assessment. In the scenario analysis approach, the output of the analysis yields high-level metrics directly. The analyst may decide to present the results for some metrics at an intermediate level to assist the policy maker in understanding the reasons for the top-level results. For example, if the top-level result is probability of successful diversion of material and production of a weapon, the policy-maker may want to understand the time required to achieve the production of weapons or the total cost. In an attribute analysis, the hierarchical relationship is a critical aspect of the analysis. Typically, the analyst's judgment enters into the assessment of the contribution of the lower level attributes to the higher level measures.

These top-level measures in turn depend upon intermediate and lower level metrics. The low level metrics can represent a variety of elements, ranging from intangible properties to specific characteristics of the process, facility or material that can be described in terms of physical parameters. The appropriate degree of decomposition of the top-level measures into intermediate and basic metrics will depend on the type of assessment being performed. In-depth assessments of facilities or processes defined in great detail will tend to use several layers of metrics and base the assessment on metrics associated with the physical characteristics of the materials and the protection systems in the facility. On the other hand, more generic assessment types needing to be performed in a short time may use only a layer of intermediate metrics without dividing the measures into a more basic metric level.

Desirably, the same top-level proliferation resistance measures should apply to the different types of assessment, differing only on the approach and level of detail in estimating the top level measures. Top level measures, or their relative importance, may also depend on the threat being evaluated. Some measures appropriate for a subnational group threat, for example, may not be too relevant for a nation-state threat or vice versa.

8.1 Nonproliferation Measures in Previous Studies

Different studies, using different approaches to proliferation assessments, have employed a variety of metrics. Krakowski (Ref. 1), in his review of methodologies applied to proliferation assessments, provides an overview of the proliferation measures that have been used.

Typical top-level measures used in proliferation risk studies are:
- Development time
- Warning period
- Inherent technical difficulty associated with materials processing
- Inherent technical difficulty associated with NW fabrication

The following nonproliferation measures have been used by Heising (Ref. 2):
- Development time
- Warning period
- Material quality
- Cost
- Material processing difficulties
  - State of information
  - Radiation level
  - Criticality problems

Ahmed and Husseiny, as reported in (Ref. 3), have defined measures in terms of weapons acquisition factors:
- Resources required
  - Technical sophistication
  - Facilities required
  - Instrumentation capabilities
  - Personnel requirements
- Difficulty
  - Information available
  - Accessibility to weapons-usable material
- Cost and schedule
  - Cost
  - Time
- Risks
  - Risks to personnel
  - Risks of project detection
- Weapons capability
  - Rate of production of weapons-usable material
  - Reliability of nuclear weapons product

More recently, the TOPS report proposed a barrier approach to proliferation resistance assessment. Table 8.1 lists a comprehensive set of barriers and their attributes, discussed further in the appendix to the report (Ref. 4).

The list of barriers and their attributes, as suggested by TOPS, offer an extensive list of the basic metrics (closely related to the physical characteristics of the facility, material, and administrative measures) that can be considered in proliferation assessments. The top-level measures, however, which would result as a combination of the intermediate and lower level metrics, need to be developed. On the other hand, top-level measures used in other studies, as reported by Krakowski, need to be related to specific physical parameters in the performance of a thorough assessment. For example, *inherent technical difficulty associated with materials processing* cannot be directly quantified, as it involves many different aspects. Moreover, measures used in previous studies, such as those suggested by Ahmed and Husseiny, tend to express proliferation assessments as a set of measures affecting an overall weapons development program, rather than focusing on the evaluation of the resistance to proliferation of nuclear installations or processes.

The IAEA has developed standards and metrics for the purposes of monitoring, detecting and preventing the diversion of nuclear material. Although the objective differs slightly from assessing proliferation resistance or proliferation risk, many of the metrics used are common (Ref. 5). Nuclear material categories, significant quantities, timely warning, and inspector man-days needed to meet safeguards objectives are metrics that could be used in nonproliferation assessment studies. There is value in the use of metrics that have received international acceptance.

Additional difficulties with the top-level measures originate with the need to facilitate the understanding and use of the results of an assessment. For this purpose, measures that can be associated with physical or measurement units (monetary units, time, dose, concentration, mass, probability of a specific event (e.g. detection)) convey information more easily than measures that need the use of artificially defined and dimensionless value or utility functions.

A lack of independence of the measures or metrics adds another complexity. For example, cost and development time may be two attributes of proliferation resistance that are not independent. If cost includes manpower costs, which are closely related to development time, the effect would be to double count. It might be possible to remove the dependency by limiting cost to capital cost of equipment, which is unrelated (or less related) to development time. Although there are formal ways to treat dependency between parameters, as a practical consideration, most methods are designed to work under the assumption of independence. If the hierarchy cannot be developed in a manner that provides independence, the results must be interpreted and used with the knowledge of the elements of dependence among the top measures.

8.2 Guidelines for Nonproliferation Measures and Metrics

This section focuses on the measures or metrics for assessing nonproliferation. Measures of proliferation resistance can be related to proliferation risk by the addition of further metrics relating to the motivation and capabilities of the potential proliferant. Figure 8-1 illustrates this relationship between proliferation resistance and risk from the point of view of measures and metrics.

Table 8.1 Proliferation Barriers and Example Attributes Listed in the TOPS Appendix[a].

Barrier type	Barrier	Attributes
Material barriers	Isotopic	Critical mass Degree of isotopic enrichment Spontaneous neutron generation Heat generation rate Difficulty presented by radiation to weapons design
	Chemical	Degree of difficulty in refining weapons material
	Radiological (dose to humans)	Degree of remote handling normally required
	Mass and bulk	Concentration of material, ease of concealment
	Detectability	Degree of passive detection capability Active detection capability Hardness of radiation signature Uniqueness of material's signatures Uncertainties in detection equipment
Technical barriers	Facility unattractiveness (degree of difficulty of production of weapons material inherent in a facility)	Complexity of required modifications Cost of modifications Safety implications of modifications Time required to modify Facility throughput Effectiveness of observable environmental signatures
	Facility accessibility	Difficulty and time to perform operations Need for specialized equipment Manual versus automatic, remote operation Frequency of operational opportunity to divert
	Available mass	Amount of potentially weapons-useable material at a given point in a fuel cycle
	Diversion detectability	Type of material and processes with respect to accountability Uncertainties in detection equipment Form of material as amenable to counting
	Skills, expertise and knowledge	Dual-use skills and knowledge Applicability of dual-use skills Availability of dual-use information
	Time	Time materials in a facility or process are available to proliferant access
Extrinsic (Institutional) barriers	Safeguards	Availability and access to information Minimum detectability limits for material Ability to detect illicit activities Response time of detectors and monitors Precision and frequency of monitoring Degree of incorporation into process design and operation
	Access control and security	Administrative steps for access Physical protection and security arrangements Existence of effective back-up support Effectiveness of access control and security
	Location	Remoteness and/or co-location of facilities

[a] TOPS did not develop attributes for all barriers at the same level of detail. Depending on the application, the analyst may want to develop some of these attributes to a greater level of detail

Proliferation resistance is strictly related to the nuclear element under study (material, facility, process or operation). The measures and metrics for proliferation resistance will therefore relate to the characteristics of the facility or process and the nuclear material it involves.

The characteristics include material characteristics that may hinder its use in weapons, engineering features and characteristics that affect the access to nuclear material, and institutional controls such as safeguards, security and monitoring. This division coincides with the TOPS classification of barriers: material, technical, and institutional. The material and technical barriers are often referred to as *intrinsic*, while the institutional features or barriers are referred to as *extrinsic.* This distinction may be important to make in some nonproliferation assessments in order to evaluate the separate element contributions that depend on the specific nuclear system design verses elements that are driven by policy and regulations.

Expanding on the definition provided above, proliferation resistance can be summarized as the combination of two elements, (1) the difficulty in stealing or diverting material from the nuclear facility or process, and (2) the difficulty in converting and in using the material in nuclear weapons production. Both measures provide adequate protection for the two general threats being contemplated: (1) diversion of material by a Nation-State, and (2) theft of material by a subnational group.

- <u>Material acquisition</u> – the measure for expressing the robustness of the facility or process in preventing material diversion or theft without detection can be represented in terms of a probability (P_1):

  P_1 = 1 - Probability of undetected acquisition of sufficient material, in a given amount of time.

  Although the general structure of the hierarchy matrix is the same for diversion and theft, they are distinctly different processes. In the case of diversion, the physical protection forces at the facility assist in the removal of the material. For theft, physical protection forces respond to bar access to the material, to contain the materials from being removed, and to pursue the thieves, if removal is successful. Thus, the factors assessed to obtain the probability P1 differ. All elements of technical and institutional barriers play a role in estimating this measure. The measures to express the likelihood of material diversion or theft are understood to be conditional to an attempt at diversion or theft being made.

- <u>Conversion and use of material in nuclear weapons</u> – the measure for expressing the difficulty in converting the material to a successful weapon can be characterized by the overall *attractiveness* of the material. Material attractiveness will be estimated on the basis of all the material barriers and attributes and how they hinder or facilitate use in building a successful nuclear weapon. High material barriers will lead to low attractiveness of the material. The material attributes represent different physical characteristics (radiation levels, mass, heat generation rate, chemical form, etc.). It is convenient to express all these characteristics in a single metric. This can be accomplished by (1) developing a pre-defined utility scale for attractiveness, or (2) developing distributions expressing the probability of obtaining a successful weapon as a function of each material characteristic and combining the separate distributions into a single distribution for unattractiveness.

Figure 8-1a shows the top-level measures for proliferation resistance, and the Figure 8-1b shows the intermediate and basic level metrics into which the top measure can be broken down. As illustrated, the material acquisition measure is to be estimated as a combination of the following intermediate metrics:

- Probability of failure of the facility and process barriers (item B in Figures 8-1a&b),
- Probability of detection (item C in Figures 8-1a&b), and possibly
- Time, which may be included explicitly to account for the material acquisition rate from the facility or process, or implicitly in the probability of detection (in a given time) and/or
- Cost, which a variety of methods use as a top level measure, but can have different meanings.

Time and cost are shown in Figure 8-1a without specific hierarchical relationships to the rest of the metrics and measures. This indicates the special nature of these parameters, signifying the possibility of including time implicitly in the other intermediate metrics, and the lack of independence of cost metrics.

Depending on the method and the depth of the assessment, the probability of failure of the facility and process barriers may actually represent a full vector of pathways, each with two measures representing the material extracted and its associated probability. The failure of the systems must account for the characteristics of the process and the facility, that is, all the technical barriers.

The probability of detection must account for the IAEA safeguards, domestic materials control and accounting, and domestic physical protection systems in place for the facility or process. Time constraints, to ensure timely detection, must also be included, although they may be determined by the specific study.

A top-level measure or intermediate metric that is used in numerous previous studies is the cost. Depending on the study, this may be interpreted as the cost of acquiring the material, the cost of protecting the material, or the cost of developing a successful nuclear explosive. There are advantages and disadvantages to using cost as a top-level measure. First of all, it is a parameter that can be expressed in monetary units, easily understood, and easily used in comparisons. On the other hand, monetary cost can be considered a variable that is fully dependent on the physical characteristics and parameters discussed so far. For example, an improved probability of detection will impact the cost that a proliferant must incur to obtain the material in an undetected manner. Similarly, unfavorable material characteristics such as high radiation doses will increase the cost of manufacturing the weapon. Reducing different proliferation metrics to a measure of cost may not be advisable as useful information about the major elements contributing to the resistance of the process or facility would be lost. Therefore, if cost is desired as a top-level measure, it should be provided along with the other measures, noting that it is a dependent quantity.

An additional problem in interpreting the contribution of the costs to the proliferation resistance of a nuclear facility or process is that the relative impact of the cost on the resistance cannot be fully asserted unless the characteristics (motivation, capabilities, willingness to accept risks) of the proliferant are considered. This is a factor that affects proliferation risk more than the resistance, with those terms defined as above.

In summary, a hierarchy of measures and metrics for use in proliferation studies has been suggested. It is believed that the set of proposed measures are appropriate to different types of anticipated proliferation resistance assessments and are also adequate for assessments involving different levels of detail. The level of detail, however, could affect the ability to quantify specific metrics. Figure 8-2 provides a summary of the suggested metrics, while Figures 8-1a&b provide a more complete listing and shows the relationship among the various levels of metrics.

While the hierarchy of top-level measures and metrics summarized in this section is applicable to the basic threat types being considered (Section 7), the relative importance of the different metrics may be dependent upon the threat. This hierarchy was developed with consideration of the covert diversion of nuclear material by a state under international safeguards. It may be possible, by tailoring the definitions of the lower level metrics, to apply the hierarchy more broadly to include other proliferation scenarios including theft or breakout from international safeguard controls. However, each proliferation scenario must be closely examined to determine the most meaningful hierarchy. Therefore, this hierarchy of measures and metrics must be used in conjunction with the method to combine the individual metrics into intermediate metrics and top-level measures.

An illustrative example of the potential relative importance of the metrics to each threat is shown in Table 8.2.

References

1. Krakowski, R.A., "Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle," Los Alamos National Laboratory Report, LA-UR-01-169, January 2001.

2. Heising, C.D. et al., "A Comparative Assessment of the Economics and Proliferation Resistance of Advanced Nuclear Fuel Cycles," Energy, 5, 1131 (1980).

3. Ahmed, S. and S. S. Husseiny, "Risk Assessment of Alternative Proliferation Routes," Nuclear Technology, 56, 507 (1982).

4. NERAC, "Technological Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems (TOPS)," January 2001.

5. IAEA, The Physical Protection of Nuclear Material and Nuclear Facilities, INFCIRC/225/Rev.4, March 2002.

Table 8.2. Potential Relative Importance of Intermediate Metrics to Threat Types[a].

Metrics		**Threat**			
		National International or regional power	National small scale threats	Sub-national, State supported	Sub-national
Material Attractiveness		Low	Medium	High	High
Facility and process barriers		Low	Medium	Medium	High
Detection		High	Medium	Medium	High
Time	Warning time	High	High	Medium	Medium
	Production time	High	High	High	High
Cost		Low	Medium	Medium	High
Technical sophistication		Low	Medium	High	High
Facilities required		Low	Medium	High	High
Institutional barriers		High	High	Medium	Low
Motivation		Dependent on the specific potential proliferant rather than the threat type			

[a]Note: The relative importance entries in the table are for illustrative purposes, and they are likely to be evaluated in individual nonproliferation assessments, particularly time, cost and the metrics related to the characteristics of the proliferant

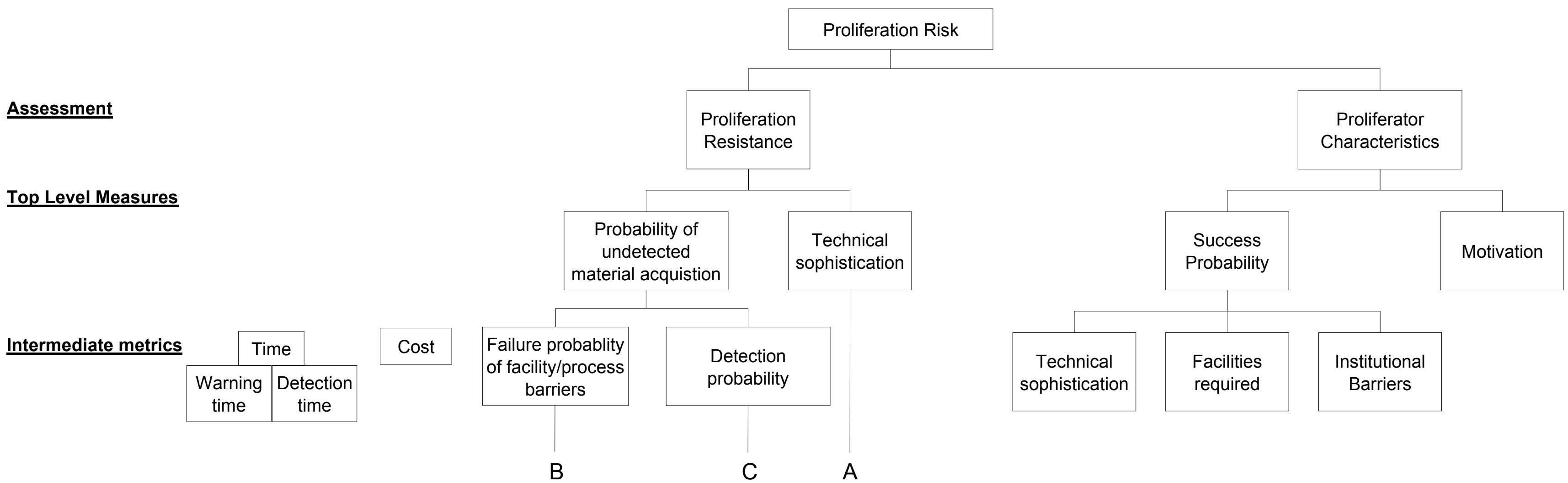

Figure 8-1a. Hierarchy of Nonproliferation Measures and Metrics

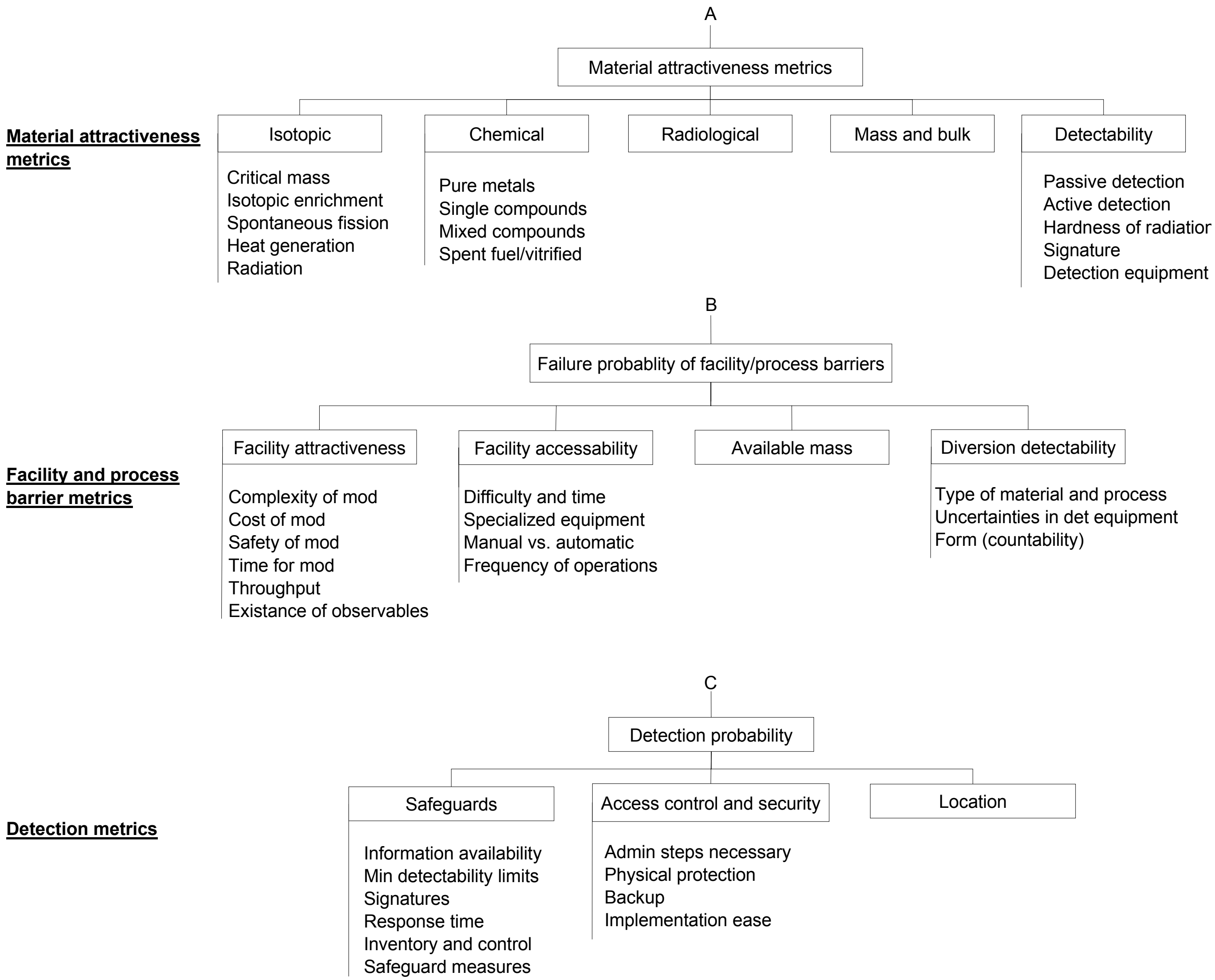

Figure 8-1b. Hierarchy of Nonproliferation Measures and Metrics

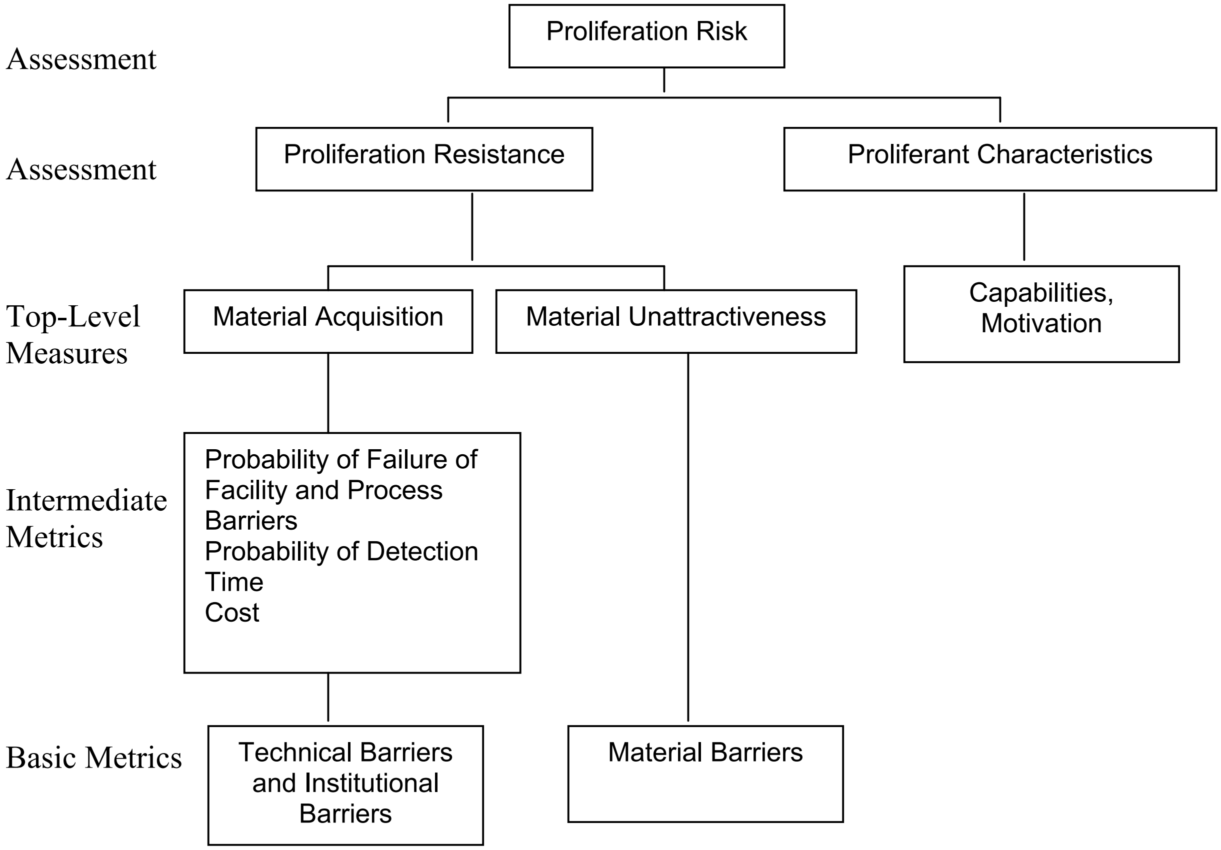

Figure 8-2. Proposed Hierarchy Of Metrics For Proliferation Resistance Assessments

9.0 Assessment Methods and Tools

One of the objectives of this document is to provide a toolbox of methods and tools[2] to support the performance of nonproliferation assessments. Some of the methods can be used as the overall approach to a nonproliferation assessment, such as the attribute analysis and scenario analysis categories of methods discussed in Section 6. Other methods are tools that can be used in a supportive role in any type of nonproliferation assessment. References 1 and 2 provide reviews of the application of different methods to nonproliferation assessments.

References

1. Jones, E.D. "Review of Methodologies for Assessing Nuclear Proliferation Resistance," Draft, November 2002.

2. Krakowski, R.A., "Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle," Los Alamos National Laboratory Report, LA-UR-01-169, January 12, 2001.

9.1 Multi-attribute Utility Theory

This section provides a brief summary of the elements of multi-attribute decision analysis and utility theory. Decision problems that involve simultaneous and conflicting objectives can be addressed by multi-attribute utility decision (MAUD) analysis. This theory informs a decision maker on a choice among a set of pre-specified alternatives, where the consequences of choosing a given alternative can be expressed in terms of the levels that a number of "values" or "attributes" attain. Decision problems can be divided into two categories: those that involve decisions under certainty and those that involve decisions under uncertainty. In the former, the consequences of each alternative are well defined; that is, the outcome of a particular course of action can be predetermined. For the latter the consequences of some alternatives are uncertain (i.e., the outcome of a given course of action cannot be predetermined). However, the probability with which each possible outcome will occur is known. The early applications of MAUD analysis to the nonproliferation problem were performed in the context of the NASAP (Ref. 1) and the INFCE (Ref. 2). Representative studies during this period are reported in References 3-6. Potential applications of attribute analysis to the problem of proliferation resistance analysis have been suggested by Hassberger (Ref. 7) and Krakowski (Ref. 8).

The theory of MAU decision analysis was developed by R.L. Keeney and H. Raiffa (Ref. 9) and is summarized in Appendix A of the report by Papazoglou et al (Ref. 5). The certainty category, described first, is followed by a brief discussion of decision making under uncertainty.

9.1.1 Multi-attribute Preferences under Certainty: Value Function

Decision analysis under certainty pertains to the problem of establishing the preferences of the decision maker for each outcome. Each alternative course of action is uniquely related to an

[2] In this document, the term tools is used to describe methods that have very general applicability in the support of a nonproliferation assessment, as opposed to the types of methods that form the central approach to an assessment.

outcome and thus a preference structure over the outcomes implies a preference structure over the alternatives.

We denote an alternative by **a** and the set of all possible alternatives by A. For each **a** we associate the n indices of value or attributes X1(**a**), X2(**a**), . . ., Xn(**a**). Each attribute Xi refers to a general property of **a** (e.g., cost, development time, radiation level) and is associated with a metric (or evaluator) x_i that measures this attribute (e.g., dollars, years, rads). These n attributes constitute a mapping of A into an n-dimensional space which we call evaluation space. It is noteworthy that given a point $(x_l, \ldots, x_n)$ in the evaluation space, the magnitudes of x_i and x_j for i not equal to j cannot be compared since they are usually expressed in different units, (e.g., dollars, years, rads). One solution to this problem is to postulate an index that combines X1(**a**),...,Xn(**a**) into a scalar index (i.e., a number) which denotes preferability or value. Hence, we specify a scalar-valued function v, called the value function defined on the evaluation space with the property that $v(x_1, \ldots, x_n) \geq v(x'_1, \ldots x'_n)$ if and only if $(x_l,\ldots,x_n) \geq (x'_l,\ldots,x'_n)$ where the symbol $\geq$ reads "preferred or indifferent to". Other names for the value function are: preference function, worth function, or ordinal utility function. Given the value function v, the problem reduces to one of ordering the set **a** in A, in a descending order of values v.

Alternatively, if the number of attributes is not too large, then they may be presented to the decision maker directly for selection. For example, if there were just two attributes-- a proliferation-resistant system X and its associated cost C – and there were two alternative designs of X, the decision maker could arguably be faced with the decision of one design at a particular cost and a better design at a higher cost. A hypothetical example is provided here.

9.1.2 Hypothetical Example: Two Alternatives and Two Attributes

Consider two choices of reactor fuel cycles, called L and P, and two attributes of proliferation resistance: radiological barrier (D) and the cost (C) of its implementation. The decision maker would like to choose the fuel cycle with the highest radiological barrier at the least cost. D is expressed in kilorads and C is expressed in mega-dollars. From engineering analysis of both fuel cycles, the following is known.

	Fuel Cycle L	Fuel Cycle P
D = Radiological Barrier	5	20
C = Cost	10	30

The decision maker must trade off a lower radiological barrier at lower cost against a higher (more desirable) barrier, but at higher (less desirable) cost. Which one does the decision maker choose? The decision maker's value function is constructed as

$$V = D - wC.$$

This expression combines the two attributes into one parameter, V, and introduces the parameter w, which has the units of kilorads/mega dollars. V can be thought of as the "effective barrier" because it accounts for the actual radiological barrier and the cost-equivalent of the barrier. Thus for specified values of w, V can be computed for each fuel cycle. It is easily seen that for w > 0.75, fuel cycle L always preferred, as the effective barrier is higher. The converse is true for w <

0.75.

9.1.3 The Utility Function

The decision maker could have valued the radiological barrier differently. For example, if it was more important to the decision maker, then a quadratic dependence on the barrier could have been chosen as

$$V_1 = D^2 - gC.$$

Here the new weight, g, is expressed in $(\text{kilorads})^2$/megadollars. Again it is readily seen that for g > 18.75, fuel cycle L always preferred. The functions V and V_1 can be thought of as "utility" functions for this system of two attributes, with D and C representing the individual utilities of the two attributes. For the first value function, the radiological barrier is linear in rads and in the second it is, according to the preferences of the decision maker, quadratic.

More formally, or at a higher level of abstraction, the value functions or ordinal utility functions illustrated above can be transformed into a dimensionless measure of the value. In this transformation process, the physical measure (D in the example) is replaced by (or transformed into) a unitless measure that is denoted u(D). The function u is defined in the range $0 \leq u(D) \leq 1$ and is more ubiquitously referred to as the utility function. Each attribute now has a utility function ascribed to it that is scored in the range zero to one rather than physically measured. The properties of u are defined such that the notion of preference contained in the original physical problem are preserved, allowing rigorous mathematical manipulations to be performed within the more abstract formulation (Ref. 9). Some of the challenges for the engineer and the decision maker are to transform the original problem in physical space to the decision-theoretic space and then to use the results of the theory to make practical decisions.

9.1.4 The Efficient Frontier

More generally, we introduce the concepts of the efficient frontier by assuming, for convenience, that preferences increase with each x_i. It is denoted that x' dominates x'' whenever $x'_i \geq x''_i$ for all i and $x'_i > x''_i$ for some i. If x' dominates x'', then obviously **a**' is preferred to **a**'', since **a**' is at least as good as **a**'' for every evaluator and strictly better for at least one.

The concept of the efficient frontier is essential to decision analysis. Ideally, the technical analyst would develop the alternatives that form the efficient frontier and the decision maker would choose preferences (based on policy constraints, biases, etc) among the set of alternatives defined by the efficient frontier. The selection of the alternatives could be ranked using the value function.

9.1.5 Multi-attribute Preferences under Uncertainty

Decision analysis under uncertainty addresses the problem of establishing the preferences of a decision maker under uncertainty. Each alternative is not associated with a unique outcome, but with a probability distribution over the outcomes. Thus the decision analysis under uncertainty consists in establishing the preferences of the decision maker over probability distributions.

With the notation of the previous section where x_i designates a specific label of Xi, the problem is to assess a (system) utility function $u(x) = u(x_l,...,x_n)$ over the n attributes. The utility function u has the property that, given two probability distributions A and B over the multi-attribute consequences x, probability distribution A is at least as desirable as B if and only if the expected value of u over A is greater than or equal to the expectation value of u over the distribution B. This establishes the expected utility as the appropriate criterion to use in choosing among alternatives.

9.1.6 Hypothetical Example: Uncertain Performance of Radiological Barriers

In this hypothetical case, the engineers cannot specify a precise value for the radiological barrier for each fuel cycle. They are only able to provide probability distributions for the radiological barriers of each fuel cycle. The cost of each alternative is known precisely, however. The function V (or V_1) can now take on a range of values for each fuel cycle. How is the preference made? The expected value of V can be computed, by the engineers, over the given probability distributions. Hypothetically, this could yield the following results.

	Fuel Cycle L	Fuel Cycle P
<D> = Radiological Barrier	3	15
C = Cost	10	30

Here <D> is the expected or average value of D over the appropriate probability distributions. The problem now is identical to the decision under certainty except that the certain parameter D is replace by its average value <D>. One now compares the values of <V> and it is readily seen that for w > 0.6, fuel cycle L is always preferred.

9.1.7 Utility Independence

The fundamental concept of MAU theory upon which various utility representations are based is that of utility independence. Utility theory is simplified when the multi-attribute (system) utility function is an additive or multiplicative function of the individual attributes (Ref. 9). Thus u(x) can be expressed as a linear sum of individual $u_i(x_i)$ with weights (w_i), associated with each $u_i(x_i)$. The weights are determined subjectively, perhaps by an expert elicitation process as discussed in Section 9.4 or 9.7.

9.1.8 Potential Applications to Nonproliferation Assessment

As indicated above and in Appendix D, there are several examples of applications of the notions of MAUD to the problem of determining proliferation resistance. The enumeration of barriers to proliferation, as presented in the TOPS report, and the identification of these barriers as attributes to be characterized by utility theory methods provides the foundations of a structure in which to frame the proliferation problem. The degree of subjectivity in formulating the utility functions for the individual attributes, the construction of the overall system utility function in term of a linear sum of individual utility functions, and the degree of subjectivity in assigning weights have all been recognized (Refs: 3 & 5) from the earliest applications of this approach.

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9.2 Probabilistic Methods

Methods of analysis that predict the future evolution of a system can be classified as either deterministic or probabilistic. For deterministic processes, if the models that describe the behavior of the system are known and the initial conditions and boundary conditions can be prescribed, the future evolution of the system can be uniquely determined. Deterministic analyses are sufficient for many problems. Frequently, uncertainties in models, initial conditions, and boundary conditions are accommodated by conservatisms in the analysis. In the design of nuclear power plant safety systems, deterministic analyses are performed in which a margin of safety is incorporated into the design by the use of conservative assumptions. This is the typical approach taken by engineers in the design of many systems. For the analysis of proliferation, the uncertainties are so great and such an important aspect of the problem, that probabilistic methods are of much greater applicability than deterministic methods.

Probabilistic methods are used to characterize problems in which there is uncertainty. The sources of uncertainty are typically divided into two types: stochastic uncertainties that reflect inherent variability in processes, and state of knowledge uncertainties associated with parameter, model, and completeness uncertainties (See Section 9.9.3). The measure that is typically used to characterize the outcome of probabilistic studies is risk.

Risk is commonly defined in a non-technical sense as danger, hazard, peril--exposure to death, injury, loss, or some other negative consequence. Thus, risk implies an unrealized potential for harm.

To quantify a risk, the likelihood of actually experiencing a given set of consequences must be estimated. While many definitions of risk have been proposed, the following definition is consistent with such estimates: Risk is the frequency with which a given set of consequences would be expected to occur.

It is sometimes desirable to combine the risks associated with high, moderate, and low consequence accidents into an overall risk measure. For this purpose, the concept of actuarial or consequence-weighted risk is used. The consequence-weighted risk associated with an accident is the product of the accident's frequency and its consequence. The total consequence-weighted risk is the sum of the consequence-weighted risks of the individual accidents.

A more general approach to characterizing risk is to treat it as a set of triplets $\{s_i, l_i, x_i\}$ where:

s_i = a scenario "i"
l_i = the likelihood of the scenario
x_i = the consequences of the scenario

The triplet represents the risk of the specific scenario s_i. The set of all scenarios $<\{s_i, l_i, x_i\}>$ represents the total risk. One approach to characterizing this risk is to order the scenarios according to the magnitude of the consequence x and to sum the likelihoods of the scenarios with $x<x^*$ to obtain the cumulative distribution function CDF($x<x^*$) or the complementary cumulative distribution function CCDF($x>x^*$). The CDF or CCDF contains more information than the actuarial or consequence-weighted risk in that it presents the likelihood of events as a function of their consequences.

In the nuclear field, Probabilistic Risk Analysis (PRA) has become a key element of the regulatory process. The methods of PRA have become formalized over the past twenty-five years as applied to assessing the safety of nuclear power plants. The combination of event trees and fault trees, as used in PRA, is a particularly effective approach to treating the safety of nuclear power plants probabilistically because of the manner in which standby safety systems are analyzed. Other approaches to probabilistic assessment, such as the RIPA approach discussed in Section 9, may be found to be more appropriate for performing nonproliferation studies.

A major difficulty encountered in applying probabilistic methods to nonproliferation analysis is determining the frequency of initiating events. In safety-related risk studies, historical data on accident-initiating events are used to determine the initiating event frequency. Although the database of significant accidents in nuclear power plants is very limited, the minor events that can lead to significant accidents when compounded by the failure of safety systems happen with sufficient frequency to form a basis for analysis. In proliferation events, the initiating frequencies depend on the motivation and opportunity of humans. In this case, there is very little historical data and predicting the motivations of humans is a difficult art. For this reason, probabilistic studies of proliferation may remove the initiating frequency from the analysis by making the analysis conditional on the proliferant undertaking a pathway to proliferation. Under this assumption, the results of the risk analysis would be expressed as a probability rather than a frequency.

9.2.1 Probabilistic Risk Assessment

The following discussion on PRA tools is largely taken from Reference 1. Reference 2 provides a complete description of the application to Reactor Safety Analysis.

PRA is the systematic, quantifiable process of

1. Identifying accidents that could endanger the public health and safety,
2. Estimating the frequencies of such accidents, and
3. Estimating the consequences of such accidents.
4. Integrating items 2 and 3 into an overall assessment of risk.

Of benefit to nonproliferation assessment, PRA addresses three basic questions:

1. What is possible?
2. How likely is it?
3. What are the consequences?

PRA methods are extremely powerful as they provide a systematic process for identifying vulnerabilities. Traditionally, nuclear power plant PRAs have been conducted at one of three levels. The Level 1 PRA identifies potential accident initiators and models possible sequences of events that could occur as the plant responds to these initiators. To identify the potential accidents and quantify their frequency of occurrence, event trees and fault trees (See Sections 9.8.1 and 9.8.2) are developed and quantified using historical data on initiating event frequencies, component and system failures, and human errors. The Level 2 PRA analyzes the thermal-hydraulic progression of the accident in the reactor coolant system, interfacing systems, the containment, and, where relevant, surrounding buildings. These analyses yield estimates of the frequencies and magnitudes of potential radiological source terms. The Level 3 PRA estimates the potential health and economic consequences associated with the source terms from the Level 2 PRA. An example of an integrated reactor safety analysis approach is outlined in Figure 9-1.

The first step in performing a PRA is to identify possible initiating events and determine their frequencies. Risk assessment methodologies have strengths and limitations that depend on the type of initiator considered. These strengths and limitations should be understood if PRA results are to be properly interpreted and employed in making regulatory or non-regulatory decisions.

The identification of accidents leading to core damage is undertaken by the use of *event trees*. An event tree is developed for each initiating event or group of similar initiating events. The questions asked at the top of an event tree usually concern the success or failure of front line systems used to prevent core damage.

The frequency associated with any particular outcome of the event tree is the product of the initiating event frequency and the successive, often dependent success or failure probabilities at each branch. For nuclear power plants, system failure probabilities are generally small, much smaller than unity; hence, success probabilities like ($1-P_{fail}$) are essentially equal to one.

The fact that system failure probabilities are small is, of course, desirable; however, it also means that the failure probabilities of such systems cannot be directly quantified based on failure data. Instead, a logical model for each system must be developed to express the system's failure probability as a function of the failure probabilities of its components and supporting systems. Such logical models are developed through the use of *fault trees*.

For a particular event called the top event (usually a failure of a system to perform some intended function), a fault tree is used to identify the combinations of base events (usually component failures or operator errors) that could lead to the top event. Fault trees for actual nuclear power plant systems commonly involve hundreds of logic gates and hundreds of base events. The first step is to find the minimal combinations of events that lead to system failure. These are called minimal cut sets for the system. Computer codes are used to perform such logical substitutions. Repeated events and duplicate cut sets are subsumed in this process, and low probability cut sets may be deleted. The results of the solution process are the minimal cut sets associated with each path leading to core damage.

Proper use of PRA results requires an understanding of the limitations and uncertainties associated with the results. The limitations and uncertainties vary for different types of events and failures. Consequently, the methodology and databases for treating such accidents are better developed than for initiators requiring hazard analyses. There is substantial agreement within the risk assessment community that PRAs can determine the most likely sequences of equipment failures and operator omission errors (failures to follow procedures in response to equipment failures) that could lead to core damage.

There is less agreement, however, on the interpretation of the absolute magnitude of the calculated core damage frequencies and other risks obtained from such PRAs. This is due to the fact that, along with statistical uncertainties associated with data collection and analysis, there are scope and methodology limitations inherent in the current state of the art of PRAs. For example, PRA methods have difficulty in addressing human errors of commission, design and construction errors, or the influence of plant management on estimated risk. Consequently, PRAs do not (and do not claim to) represent the total public risk from the analyzed plants.

To characterize uncertainty, analysts use a distribution of possible values and discuss each risk measure in terms of the mean, median, and various percentiles of its distribution. Comparing a risk estimated for one plant to that estimated for another plant or to some absolute limit or goal is not simply a matter of comparing two numbers. It is more appropriate to observe how much of the uncertainty distribution lies below a given value, which translates into a measure of the certainty that the core damage frequency is less than the given value.

Application of PRA to Sabotage

One issue that PRA has not been able to effectively address is sabotage. This particular issue is important to the application of PRA to nonproliferation analysis, as sabotage and proliferation have similar characteristics.

Sabotage can involve a wide variety of different types of initiating events, depending upon the particular scenarios followed by the saboteurs. All of these threats, especially insider threats, are well known to security analysts. However, because acts of sabotage are related to the human will to cause damage, they are difficult to quantify in probabilistic terms. In the application of PRA to the safety of nuclear power plants, the frequencies of the initiating events are quantified based on the history of accident precursor events. A similar database of sabotage initiating events does not exist. The likelihood of accident initiators can be expected to vary widely depending on geopolitical issues and unrest. Therefore, in probabilistic studies, acts of sabotage are treated on a conditional basis, that is "If (condition), then (risk)". PRA results obtained from accident analysis are used to identify critical safety components that must be protected from saboteurs. PRA is not used to estimate the frequency of core damage events from sabotage in the same manner that it is used to estimate the frequency of core damage from accident events. Rather, the probability of successful sabotage is determined conditional on the occurrence of a sabotage attempt. In this manner, PRA can be used to test the effectiveness of the physical protection system given a challenge to the system.

Potential Application to Nonproliferation Assessment

The foregoing discussion on PRA tools for reactor safety analysis has several important features that can assist in the analysis of proliferation issues.

In the case of proliferation analysis, risk implies an unrealized potential for the diversion of nuclear material and/or technology for the purposes of obtaining a nuclear weapon or weapons. A measure of proliferation risk is the probability of the proliferant organization achieving its proliferation goals, conditional on an attempt by the organization to proliferate. As indicated in Table 7.1, different organizations have different proliferation goals

Event and fault trees can be very useful to layout and visualize the logical and physical relationship of threats to facilities and processes and identify barriers to proliferation. They also provide a means for quantification of the complex events they model by providing a framework for problem decomposition. Tools for Level 1 PRA analyses may be particularly useful and provide insight on how barriers combine to minimize proliferation. Rather than identifying plant damage states, Level 1 PRA tools may identify proliferation targets.

The use of Level 2 and Level 3 PRA techniques is less obvious.

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9.2.2 Bayesian Methods

Bayes' Theorem (Refs 1 & 2) provides a method for updating the probabilistic state of knowledge by recognizing a logical association among the joint probability of events.

The theorem consists of the observation that one can express the probability of the intersection of two events, A and B, in two mathematically equivalent ways.

$$P\,(AB) = P\,(B|A)\;P\,(A)$$

and

$$P\,(AB) = P\,(A|B)\;P\,(B)$$

Here P (B/A) denotes the conditional probability of B given A. These two expressions can be formally equated to yield

$$P\,(B|A) = \frac{P\,(A|B)\;P\,(B)}{P\,(A)}$$

This equation can be generalized to the case of N mutually exclusive events B_i

$$P\,(B_i|A) = \frac{P\,(A|B_i)\;P\,(B_i)}{P\,(A)}$$

Now P (A) can be written as $\sum_{j=1}^{N} P(A|B_j)\,P(B_j)$,

where N runs over the complete set of mutually exclusive events B_j.
The practical use of this expression derives from the observation that the probability of any B_i given event A can be obtained from the inverse question. The set of probabilities $\{P(B_i)\}$ is regarded as "prior" information (before knowledge of the information imparted by event A). The set $\{P(A|B_j)\}$ is the inverse information: the probability of event A given the set $\{B_j\}$.

Let us illustrate this for a simplified proliferation problem.

Suppose that we would like to know the probability that a 10 kt weapon will be produced (event B_1), given that 20 kg of Pu239 has been obtained by a potential proliferant (event A). Thus we seek P (B_1|A). Note that $B_2 = \overline{B_1}$ = event that a 10 kt weapon has not been obtained. Prior to our knowledge that the material has been obtained, we say that B_1 and B_2 are equally likely, $P(B_1) = P(B_2) = \frac{1}{2}$. Based on our knowledge of weapons production we assess, using hypothetical numbers for illustration,

P (A|B_1) = P (20 kg obtained/20 kt weapon) = 0.6

P (A|B_2) = P (20 kg obtained/no 20 kt weapon) = 0.1

Thus Bayes' Theorem yields

$$P(B_1|A) = \frac{(0.6)\frac{1}{2}}{(0.6)\frac{1}{2} + (0.1)\frac{1}{2}} = \frac{0.6}{0.7} = 0.86$$

and

P (B_2|A) = 0.14

(Note that P (B1|A) + P (B_2|A) = 1, as it should)

The important point is prior to our knowledge that material was obtained, the likelihood of the weapon was "fifty-fifty". Knowledge of the material being obtained increased the probability to 86 percent.

This method can be extended to more germane and specific questions. Note the inference, P (B_1|A), is derived based on our knowledge of the inverse (or reverse engineering) questions, P (A|B_1) and P (A|B_2). The analyst should, in general, be able to answer such retrospective questions more readily than addressing the inferential questions directly.

Typically, in a probabilistic study the term "probability" is used in a very subjective manner to represent the state of knowledge or belief of the analyst, rather than as an inherent property of a system. Analysts' that take this approach to probability treatment are termed Bayesians, in contrast to classical statisticians who measure probabilities by performing replicated tests. Applying the Bayesian approach to probabilistic analysis is appropriate to nonproliferation assessment, which relies on integration and presentation of belief states concerning the proliferation resistance of a system within a specific context. Such beliefs, formulated on available evidence, provide the basis for nonproliferation decisions.

Potential Applications to Nonproliferation Assessment

Bayes' Theorem can be used as a stand-alone tool or as part of a more integrated assessment that needs data to arrive at a final result. One of the primary applications of Bayes' Theorem is in the strengthening of sparse databases by combining specific data with generic databases.

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9.2.3 Dynamic Probabilistic Methods

One of the limitations of the fault tree/event tree approach used in PRA is that the analysis is static. Prior to performing the analysis, the analyst establishes the sequence of major events within the event tree. If the results of analysis indicate that this sequence of events is not correct under some circumstances, the analyst can develop a new event tree to address those specific conditions. However, the methods are not sufficiently flexible to allow for the scenario analysis to determine the sequence of events as a function of the manner in which the conditions evolve in the scenario. Reference 1 provides an example of the inability of static methods to accurately predict the effect of human intervention on the reliability of critical safety functions. Furthermore, in systems with multiple top events, the complex interactions between system components and process variables can influence competition between top events. The occurrence of top events can be affected by the order of failure of components and by the timing of their failures. Furthermore, static methods cannot handle uncertainties well. Within the uncertainty band, the order of component failures can easily change. The dynamic event tree, a modification to the static event tree used in PRA, enables branching to be initiated as a result of conditions calculated in the scenario analysis as a function of time (Ref. 2).

A Markov chain is a state transition diagram that visually represents a system moving from one state to another state. A Markov process is one in which the transition from state j to state i depends only on states i and j. Figure 9-2 illustrates a Markov system in which there are five possible states for a redundant physical protection monitoring system. There is a failure rate (λ) that results in an operable unit becoming inoperable and a repair rate (μ) that can return a unit to operability. The system is unprotected in either State 3 or State 4. The equations for this system can be used to determine the fraction of the time that the system is unprotected.

State	Description
0	Unit 1 in operation; Unit 2 in standby
1	Unit 1 under repair; Unit 2 in operation
2	Unit 2 under repair; Unit 1 in operation
3	Both units inoperable; Unit 1 under repair
4	Both units inoperable; Unit 2 under repair

Aldemir (Ref. 3 and 4) has developed a cell-to-cell mapping approach based on a Markov chain model (Ref. 4). The cells represent possible states of the system. If there were no uncertainty, at a point in time the system would be in a unique state (cell). If there is uncertainty, there are a number of possible states (cells) each with a probability. The method predicts the probabilities that in the next time step the system will move from a set of current states to a set of future states. The model automatically accounts for modeling and monitored data uncertainties, as well as small stochastic variations.

Potential Applications to Nonproliferation Assessment

Dynamic methods may be required for nonproliferation assessment because of the large number of uncertainties, the unpredictability of human performance, and the effect of changing conditions with time. Section 9.5 discusses dynamic modeling and simulation methods. Dynamic probabilistic modeling methods can be considered a subset of the general category of dynamic modeling methods.

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9.3 Two-Sided Approaches

The two-sided modeling approaches discussed here can potentially provide useful insights when proliferation analyses must consider cooperative or disruptive effects of interacting human actors. When a fundamental modeling uncertainty is the actions human beings might take, and when these actions are critical to the outcome of the scenario under investigation, then two-sided approaches (or more generally, n-sided approaches) help explore the space of possible outcomes.

9.3.1 Wargaming

A wargame (Ref. 1) is a role-playing exercise where human participants make sequential decisions that determine the unfolding of a scenario. Models, simulations, lookup tables or human umpires can be used to determine the consequences of the decisions and to advance game time.

Wargames are characterized by the active and central involvement of human beings, generally with opposing goals, making sequential decisions over time.

Despite the name, the activity being gamed need not be a "war", but can be almost any activity with opposed human players. For example, the political-military game was popularized in the U.S. by the Rand Corporation and Massachusetts Institute of Technology in the late 1950s (Ref. 1). Political-military games have been used to examine complex political scenarios involving multiple states. An early example retaining relevance today investigated a scenario resulting from a coup in Poland and involved Soviet, Eastern European and American teams (Ref. 2).

Strengths

- Wargames can explore the complicated and sometimes unexpected consequences when intelligent, opposed humans make sequential decisions.
- Wargames are useful as an exploratory tool, especially when the underlying dynamics and motivations of the players are not well understood.
- Wargames can reveal previously unconsidered opponent strategies, which can then be tested with other tools.
- Wargames can provide insight into the dynamics of processes that are dominated by the actions of competing human actors.
- Wargames capture the "intent" and "motivation" of the participants.
- Wargames offer the opportunity to involve non-engineers (e.g., political scientists or terrorism experts) in the analytical process.

Peter Perla (Ref. 1) says that: "By explicitly allowing human decisions that are made under the press of time and on the basis of imperfect or incomplete information, and by incorporating the capricious effect of randomness and 'luck', wargaming comes closer than any other form of intellectual exercise to illuminate the possible dynamics of warfare."

Weaknesses

- Wargames explore what can happen, but not what will happen or even what is likely to happen.
- Wargames are of little use in providing rigorous, quantitative measures to "objectively" prove or disprove technical or tactical theories. They identify one possible sequence of events.
- The observed outcome of a wargame may be very unlikely and not reproducible.
- Wargames can create a misleading illusion of reality; as the wargame may not capture all important aspects of a complicated issue, and the missing aspects may not be obvious.

Potential Applications to Nonproliferation Assessment

As a prelude to a more detailed, technical or quantitative analysis, a wargame could help identify potential proliferators motivations and previously unconsidered proliferation vulnerabilities.

For example, when the actions of a potential proliferating state or group do not appear logical or consistent, a wargame using subject matter experts could provide insight into possible motivations and intent. A possible scenario would be to consider a nominal East Asian country with a history of hostile relations with its neighbors. At one time this country had pursued a weapons-grade plutonium production program, but had agreed to suspend its plutonium production -- in return for Western assistance in energy production. Recently, this country is suspected of having begun a uranium enrichment program. A wargame could be designed to explore possible alternative negotiating strategies for dealing with this situation. Or, a different wargame could be designed to explore the alternative acquisition strategies of the adversary and corresponding strategies for identifying and blocking these efforts.

Another candidate scenario, the exploration of an interim spent fuel program in Russia, would involve designing a wargame that examines potential proliferation issues with such a program. Players could represent Russia, some neighboring countries, donor nations, the U.S., and possible sub-national terrorist threats. Various insider and outsider scenarios could be postulated that highlight issues associated with various program aspects, including transportation, storage, and related processing.

Additional scenarios might deal with research reactors, in the U.S. or other countries, nuclear smuggling, or border security at any number of locations in the world.

Another example would be the use of “black-hat” teams to hunt for vulnerabilities in the physical and procedural security systems protecting nuclear facilities. This form of wargaming can examine proliferations threats posed by an “insider.”

9.3.2 Game Theory

Game Theory was essentially invented by John von Neumann in the 1920s and popularized in 1944 by the publication of *Theory of Games and Economic Behavior* by von Neumann and Morgenstern (Ref. 3). This book was very well received by the scientific and popular press. Considerable development in Game Theory occurred in the 1950s, especially at Princeton and RAND. Initially, it was hoped that Game Theory would provide a template for examining all types of conflict situations, but that proved too grand an expectation. For games with more than two actors, there has not developed a generally accepted notion of a game solution. Also, Game Theory has been criticized as only being able to analyze simple games, which may not adequately capture all the important features of realistic competition. Nonetheless, casting a complex problem as a simple, competitive game sometimes reveals insights not otherwise obvious.

The Two-Person Zero-Sum Game (Ref. 4 and 5)

For games where two players (called here I and II) have diametrically opposed objectives, Game Theory can sometimes provide recommended strategies for both players and a "value" of the game. "Diametrically opposed" means that whenever I wins, II is assumed to lose. For each play of the game, the sum of the payoffs to I and II is zero.

Examples of such Two-Person Zero-Sum (TPZS) games include all competitive games and sports with exactly two players or teams. Since some of these sports were developed to mimic warfare, it is not surprising that many military problems can also be expressed as TPZS games. In theory, board games such as checkers and chess and card games such as bridge can be "solved", but in practice these TPZS games are too large for practical solutions, as there are too many possible moves to consider. Non-TPZS games include competitive situations with more than two sides; e.g., poker and economic games involving coalitions and markets. These games, while of continuing interest in the Game Theory literature, have resisted solution to the degree attained for TPZS games.

Example: An Inspection Game

Consider the problem faced by an inspector (Player I) with limited assets trying to determine a location (or path or process) to inspect to detect proliferation activity. And, a diametrically opposed proliferant (Player II) is attempting to choose a proliferation location (or path or process) so as to avoid detection.

Player I is the "maximizer", as he attempts to maximize probability of proliferation detection (P). Player II is the "minimizer", attempting to minimize P.

If Player I selects inspection location i, and Player II selects proliferation location j, the $P(i,j)$ is the resulting probability of proliferation detection.

If Player I can select only one location to inspect, how should that location be determined? If Player I knew with certainty that Player II would select proliferation location $\hat{j}$, then Player I would select that location i which maximizes $P(i,\hat{j})$.

But how would Player I make a decision if the player is unwilling to specify a $\hat{j}$? This is where Game Theory can help. The game-theoretic approach for Player I is to select a location i which looks over all of Player II's options and maximizes the smallest possible probability of detection. That is, Player I selects i to maximize the quantity $\min_j P(i,j)$. Then Player I is guaranteed of a probability of detection of at least $v_I = \max_i \min_j P(i,j)$.

In symmetric fashion, if the proliferant, Player II, selects location j so as to minimize $\max_i P(i,j)$, then Player II is guaranteed that the probability of detection will not exceed $v_{II} = \min_j \max_i P(i,j)$.

It is not difficult to show $v_I \le v_{II}$. One of the early results of Game Theory was if the set of options is generalized to allow *mixed strategies* that are probability distributions over single strategies, then $v_I = v = v_{II}$, where v is the *value of the game.* In this case, there is an optimal mixed strategy for each player as well as a unique value of the game.

One of Game Theory's lessons is when dealing with an intelligent opponent, it is sometimes advantageous to randomize one's strategy. When being predictable can be exploited, the best strategy sometimes includes a random component. For the inspection problem discussed here, allowing Player I's inspection location to be selected from a probability distribution can increase the minimum possible probability of detection above that obtainable when mixed strategies are not allowed.

Potential Applications to Nonproliferation Assessment

The Inspection Game example illustrates how Game Theory might be applied to reducing the likelihood of proliferation.

9.3.3 Agent-based Simulation

According to Sanchez and Lucas (Ref. 6), an agent-based simulation (ABS) is
"… a simulation made up of agents, objects or entities that behave autonomously. These agents are aware of (and interact with) their local environment through simple internal rules for decision-making, movement, and action. ABS has been proposed for many situations involving a large number of heterogeneous individuals, such as vehicles and pedestrians in traffic, people in crowds, artificial characters in computer games, agents in financial markets, and humans and machines on battlefields. The aggregate behavior of the simulated system is the result of the dense interaction of the relatively simple behaviors of the individual simulated agents."

A major emphasis of ABS application and research has been on agents with relatively simple behavior rules, such as flocks of flying birds or people leaving a stadium after a sports event. It has been found that even simple rules between individual agents can lead to complex and chaotic aggregate behavior.

Potential Applications to Nonproliferation Assessment

Similar to the SimCity game genre, where a goal is to combine computer agents of different types (e.g., cyber engineers, teachers, politicians, firemen, etc.) to create a city, country, or an entire world, one can imagine a "SimNuclearTerrorist" game where the object is to put together a team of simulated terrorists to build or steal a working nuclear weapon. The agents could evolve and get smarter, like players in a wargame. The term "coevolution" is used when the agents and the environment change during the simulation (Ref. 7). Vince Roske (Deputy Director, J8, Wargaming, Simulation and Analysis, The Joint Staff) says of evolving agents (Ref. 8):
"One technique that seems to demonstrate emergent behavior and adaptation involves embedding genetic algorithms to breed increasingly effective changes in the physical characteristics and decision rules of the Red and Blue agents."

When coevolution is allowed, ABS has the potential of automating and making reproducible n-sided wargames. Humans are replaced by autonomous, interacting and evolving, rule-based cyberagents. By using the computer to speed up scenario time, sufficient replications could potentially be run to establish statistical significance in the results.

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9.4 Analytic Hierarchy Process

The Analytical Hierarchy Process (AHP) was developed in the 1970s in response to the need to understand complex systems and to develop informed judgment about controlling or predicting an outcome (Ref. 1). AHP is a methodology for modeling and assessing otherwise unstructured problems where absolute measurement is not possible, as in the social and behavioral sciences. It is designed to assist decision making typically consisting of planning, generating alternatives, setting priorities, choosing the best policy, allocating resources, determining requirements, predicting outcomes, designing systems, measuring performance, and optimizing and resolving conflict.

AHP utilizes a "systems approach" to problems. A system is an abstract model for a real-life structure. AHP evaluates the impacts of various components of a system on the entire system and finds their priorities. A system can be defined in terms of its structure, its functions, and its objectives based on the perspective of a particular individual or group. A *hierarchy* is an abstraction of the system structure to study the functional interactions of its components and their impacts on the entire system. This abstraction can take several related forms. AHP address the question of how to structure the functions of a system hierarchically, as well as how to measure the impacts of any element in the hierarchy.

A hierarchy is a particular type of system based on the assumption that identified system entities can be grouped into disjoint sets, with the entities of one group influencing the entities of only one other group. The elements in each group, or level, of the hierarchy are assumed to be independent. The purpose of a hierarchy is to seek understanding at the highest levels from the interactions of the various levels of the hierarchy, rather than from the level elements directly. The advantage of hierarchies is that they give details of information on the structure and function of a system in the lower levels and provide an overview of the actors and their purposes in the upper levels.

AHP uses a process of measurement through pair-wise comparison to achieve consistent synthesis of diverse views on complex hierarchies. For problems where there is no scale to validate the result, the pair-wise comparison process can prove to be an asset, such as in the social and behavioral sciences. Properties that change in time and space, and in conjunction with other properties and contexts, may have their meaning and significance change. Universal scales for social events cannot be improvised. Therefore, judgments must be sufficiently flexible to take into consideration the contextual setting of the property being measured. In this sense, properties are relative and the unit of measurement may have to be adjusted to compare one setting with another. AHP shows it is possible to do this using the pair-wise comparison technique.

The method allows the prioritization of decision options given the relative value the decision maker(s) assigns to attributes or factors that impact the attractiveness of each option. The method assumes that an informed and interested group is considering several activities. The goal is to derive, from the group's unified judgments (i.e., from the relative values associated with pairs of activities), a set of weights to be associated with individual activities. Given the elements of a hierarchy level, the method is to construct the matrix of pair-wise comparisons among those elements in relation to each element of the next higher level, which serves as a criterion or property with respect to which the lower level is compared. If the next higher level of the hierarchy is the apex, then such evaluations of the next-level elements determines the preferred course of action to achieve the goal of the apex. The individuals who give the judgments are asked the following type of question: Given a pair of elements in the matrix, which one do you believe is more dominant in possessing or contributing to the property or objective in question?; and how relatively strong is this dominance? Having recorded such quantified judgments on all possible pairings in the matrix, the problem now is to assign to the elements or activities a set of numerical weights that would reflect the just-recorded judgments.

These weights are determined through the solution of the pair-wise matrix, relying on a mathematical matrix manipulation. Consider the elements of a specific level in a hierarchy. The objective is to obtain the weights of influence, $w_{1, \ldots,} w_{n,}$ of each of the elements at this level on some element in the next level. The basic tool is a matrix $A = (a_{ij})$ of numbers representing the judgments of pair-wise comparisons, indicating the strength of element i when compared with element j. In AHP, the eigenvector of the matrix A with the largest eigenvalue is chosen to furnish the priorities[3]. In other words, if A is the matrix of pair-wise comparison values, in order to find the priority vector, or the preferred weights of influence w_i, it suffices to find the vector w that satisfies

$$Aw = \lambda_{max} w$$

where λ_{max} is the largest eigenvalue. w is properly normalized to ensure that this linear matrix eigenvalue equation has a unique solution.

The quality of the output may be evaluated by the logical satisfaction of the answers. They must, in some sense, conform to the original input. For example, a member of a level that is favored over the other members through the original pair-wise judgments should come out with the highest ranking and so on down the line. Of course, it is the very purpose of the model to develop a consistent order. Note that the total ordering is not known at the beginning, but only pair-wise comparisons, which may in fact be inconsistent. The results must conform with reasonable outcome expectations; otherwise, there would be discrepancy between the operation of the theory and the judgments provided.

Integrating diverse stakeholder views can be difficult, particularly for complex problems. The result may be skewed (i.e., not represent the true intent of the group) if issues are not ranked carefully and/or issue convergence is not achieved. Group dynamics effectively constrain the size of a panel. If the number of stakeholders is large, the number of panels must increase whose integration can become cumbersome. In addition, the stakeholders must be selected carefully. With all of these factors considered, AHP requires strong leadership, straightforward ownership and effective management of the process.

Potential Applications to Nonproliferation Assessment

Over the years, there have been many derivatives of AHP (Ref. 2) and it has been applied to an increasing number of systems where clarification and consensus building are crucial (e.g., National Security, Economic Competitiveness, Environmental Quality, Energy Security, Government RD&D Portfolios, Disposition of Nuclear Material in the Former Soviet Union, and Health Care). It helps decision makers and their constituencies in organizing the complexity of problems faced and in deriving priorities that reflect participants' values, beliefs, and attitudes. In working toward an assessment(s) of the non-proliferation qualities of a nuclear system, AHP could be useful (1) by itself to determine stakeholder views, to inform other stakeholders (e.g., decision makers) of expert opinions in a broad context, and to enhance dialogue; and (2) as a way to present the results of other methodologies and integrate their results in a manner that is meaningful to decision makers. Specific proposals for the use of AHP in non-proliferation assessment methods include the determination of weightings for the relative importance of barriers to proliferation in an extension of the TOPS methodology and/or in general MAU barrier

[3] An operator "operates" upon a function and produces another function. For every operator, there is a collection of functions which, when operated on by the operator, produces the same function, modified only by a constant factor. Such a function is called an **eigenfunction** of that operator and the multiplicative constant factor is called the **eigenvalue** of that eigenfunction. In equation form, this looks like $\hat{A}f(x) = af(x)$
This is an eigenvalue equation where $f(x)$ is an eigenfunction of $\hat{A}$ and a is the eigenvalue of $f(x)$.

analysis; and a systematic method of determining the relative weight of each barrier during each stage of the fuel cycle, in an overall decision theory analysis approach (Ref. 3). This latter will be important in both MAU analyses and the early stages of scenario methods.

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9.5 Dynamic Modeling and Simulation

Dynamic Modeling describes a large class of computer simulations where the operation of a complex system over time is simulated. Model output is often graphically presented to allow easily communicable results. Also, critical system parameters are typically adjustable to allow the analyst to investigate the effects of parameter changes on system performance. Examples of successful applications include models of electrical power plants, signal processing systems, entire national economies and aircraft in flight. There are several available computer packages for the construction of these models including MATLAB Simulink and iThink. In some cases, modeling characteristics of nuclear fuel cycle components can provide insights for evaluating proliferation resistance of that component.

Dynamic models calculate and display material flows and stocks as perturbations are introduced in the system. The calculations rely on models associated with each node, which determine the relationship between inputs and outputs as a function of the process that takes place at the node. These relationships are often the result of underlying physical processes that need to be analyzed with external tools. For example, a node that represents a nuclear reactor must rely on neutron physics and burn-up analyses to establish relationships between actinides loaded to and discharged from the reactor. The level of detail of these underlying physical analyses is very important to the fidelity of the dynamic models. Often it is not feasible to use underlying physical analyses in real time in the dynamic models.

For the purposes of modeling and simulation, most nuclear facilities can be characterized as a series of processes that consume resources from preceding processes and create new resources to be used by successor processes. For example, in a mixed oxide (MOX, plutonium and uranium oxide) fuel fabrication facility, one of the processes is a Primary Blender that consumes the contents of a container holding MOX fuel and a container holding clean scrap plus uranium oxide (UO2). It produces a single container holding the blended result of the two input containers. Each one of these nodes refers to a single processing unit in a facility for which we want to know certain types of information:

- What receipts have come into this node?
- What shipments have gone out?

- What is the current inventory including clean scrap, dirty scrap, holdup, waste, and material being processed?

Individual nodes can be agglomerated to provide information on a larger portion of a facility. In addition to modeling the real material flow in a facility, statistical models of the measurement error are used to determine the standard deviation of the inventory difference.

The types of information in a model and the level of detail to which a model specifies processes are determined by the types of questions that a model/simulation needs to answer. It is best if only minimal necessary information is contained in the model to keep the model as simple as possible and the simulation free from unnecessary calculations. The most important aspect of developing a simulation is coming up with an accurate representation of facility nodes; simulation frameworks are available for controlling the simulation mechanics, such as queuing processes waiting for resources and tracking simulation time.

Potential Applications to Nonproliferation Assessment

Modeling and simulation of facility operations can provide important input to metrics for nonproliferation assessments of nuclear fuel cycle facilities. A particular example is simulating material accountancy, including variance propagation, for planned facilities. This requires detailed information regarding planned operations, characteristics of materials to be measured, safeguards measurements, and materials throughput throughout the facility operation.

Such simulations can identify locations or operations that may dominate the limit of error on materials unaccounted for (LEMUF) long before planned facilities are built. This information can provide quantitative comparison facility options and allow for mitigation of identified limitations, optimizing safeguards and contributing to overall nonproliferation performance.

Dynamic simulations of facility operations can also provide information on accumulations of nuclear materials under both normal and non-standard operations of nuclear fuel cycle facilities. Modeling materials quantities provides value to nonproliferation assessments, particularly in cases where more than a single significant quantity of material accumulates in a given location.

9.6 Fuzzy Sets and Possibility Theory

A number of approaches can be used in addressing the problems of imprecision and uncertainty in dealing with complex systems. A very common approach to represent imprecise and uncertain information is probability theory. Another possible approach is the theory of fuzzy sets and possibility theory based on fuzzy sets theory (Refs. 1-3).

Possibility theory has been proposed as an approach for information analysis, when the emphasis is in the meaning rather than the measure of the information. Formally, the possibility theory development has been based on the theory of fuzzy sets. Possibility theory, as a branch of fuzzy sets theory, assesses the possible, rather than probable, values that a variable can take.

The theory of fuzzy sets, and by extension possibility theory, is believed to be of particular applicability to represent information that is vague or fuzzy by nature. In very complex systems, the system state may be described in terms of a linguistic, rather than numerical, characterization; that is, the values of variables may be expressed in words or sentences rather than in numbers. These can be referred to as linguistic variables. Applications based on fuzzy sets are particularly well suited for operating with linguistic variables.

The theory of fuzzy sets is a theory of classes in which an element can assume a degree of membership in the set that is between full membership and non-membership. A fuzzy set has a continuum of degrees of membership. The set is characterized by a membership function that assigns the degree of membership to each member. Operations with fuzzy sets have been defined, including containment, union, intersection, etc.

As a simple example, a fuzzy set "high enrichment" for a variable fissile concentration in percentage can be characterized by the membership function:

{ (1, 0), (5, 0), (10, 0.2), (20, 0.5), (30, 0.8), (40, 1), (50, 1) }

The degree of membership of 30% enrichment in the set "high enrichment" is 0.8.

An application of fuzzy sets theory is Possibility Theory, which can be used in characterizing imprecision inherent in linguistic variables. The possibility distribution function for a variable is equated with the degree of membership of that variable in a fuzzy set. For example, given a proposition such as "Material X is highly enriched," the possibility that the material enrichment is 30% would be 0.8.

The definition of possibility distributions on the basis of fuzzy sets implies that the mathematical manipulation of fuzzy sets is applicable to the manipulation of possibility distributions.

The concepts of possibility and probability are different. A simple illustration of the differences between possibility and probability is provided by Zadeh (Ref. 1).

Proposition: "John ate X eggs for breakfast" X = { 1, 2, 3, 4,…}

Π_X, a possibility distribution, represents the ease with which John can eat a specific number of eggs. An associated probability distribution P_X would denote the probability that John ate a specific number of eggs.

A plausible shape for the distributions, for illustration purposes, is:

u	1	2	3	4	5	6	7	8
Π_X (u)	1	1	1	1	0.8	0.6	0.4	0.2
P_X (u)	0.1	0.8	0.1	ε[4]	ε	ε	ε	ε

Another application of fuzzy sets is fuzzy logic and approximate reasoning. In this case, the reasoning rules and statements in traditional logic are characterized with fuzzy sets. Perhaps the

[4] Where "ε" represents a negligibly small probability

most extensive application of fuzzy sets has been to expert systems used in decision-making and fuzzy logic control. An expert system compiles and processes information provided by a group of experts, often in terms of linguistic variables. The information that the expert system will manipulate will therefore be linguistic and imprecise and the use of fuzzy set theory is a natural choice. By extension, fuzzy logic controllers are based on control strategies provided by experts in an imprecise (fuzzy), linguistic manner.

Potential Applications to Nonproliferation Assessment

In nonproliferation assessments, metrics will often need to be estimated on a qualitative basis, based on expert opinion. Furthermore, it is likely that some of the statements that the experts will use in their judgment will be fuzzy, that is, they will represent vague, imprecise and uncertain information. Fuzzy sets and possibility theory appear to be particularly well suited for representing statements with natural language, such as those that may be frequently made in assessment of proliferation resistance ("the isotopic barrier for material A is *very high,* while for material B is only *moderately high.*")

The estimation of metrics in proliferation resistance assessments may be an area of applicability for the theory of fuzzy sets or the theory of possibility. Assessment of barriers, for instance, could be performed on the basis of using fuzzy sets to replace the utility function definitions. Combination of the fuzzy sets/possibility estimates for multiple attributes could be performed following the arithmetic for fuzzy sets.

An approach using fuzzy sets could be established at a high degree of detail (at the level of the attributes of the individual proliferation barriers), or it could also be applied to less detailed assessments where only a reduced number of metrics is used.

A possible advantage of the fuzzy set/possibility theory approach is the ability to provide a structured, reproducible approach, regardless of the level of study detail. Fuzzy sets may implicitly provide the method of combining the expert opinions for multiple metrics into a reduced set of top-level metrics. Other methods may have to rely on (also subjective) weighting factors.

It could be difficult to establish the fuzzy sets and membership functions to be used in the assessment, as these activities are subjective and require participating expert agreement. This is, however, also true of other methods that require establishing value or utility functions. For the fuzzy sets approach, it might become more acceptable to repeatedly use an initial definition of sets and memberships functions.

The nature of the nonproliferation assessments, with numerous metrics and complex relationships, heavy reliance on expert opinion, and the use of imprecise terminology or scales for measuring specific attributes, points towards the possibility of applying a fuzzy set theory approach. No specific attempts at using this approach in proliferation studies has come to our attention and no conclusion can be stated about the successful application of this method. Exploring its applicability and comparing its results and application difficulties with other, more established methodologies may be valuable.

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9.7 Expert Elicitation

The risk analysis of uncertain events, such as those related to assessment of proliferation, inherently involves the consideration of parameters for which little or no experiential data exist. Expert judgment is needed to supplement and interpret available information. The MAU theory approach (Section 9.1) and the probabilistic methods approach (Section 9.2) need to use judgment in parts of their analysis. The Analytical Hierarchy Approach described in Section 9.4 is also an approach to codifying expert judgment. An expert group Delphi method was applied to the proliferation problem several years ago (Ref. 1). In this method, the preferences of experts (e.g., plant designers, nuclear engineers) are sought by providing key information on a facility or process and structuring the issues and factors (facility attributes). Average and composite rankings of attributes by the group are developed with this method.

In order to obtain unskewed and informed expert knowledge, a structured and detailed process is needed. Formal elicitation of experts on key issues can be performed using a set of procedures as outlined in Reference 2. The principal steps of this process are shown in Figure 9-7. Briefly, these steps are:

- Selection of Issues. The total number of uncertain parameters that should be included in an uncertainty analyses is somewhat limited. The parameters considered should be restricted to those with the largest uncertainties, expected to be the most important to risk, and for which widely accepted data are not available. In addition, the number of parameters that will be determined by expert panels should be further restricted by time and resource limitations.

- Selection of Experts. Panels of experts should be assembled to consider the principal issues in the sub-areas of the overall analysis. The experts are selected on the basis of their recognized expertise in issue areas. Representatives from the nuclear industry, the DOE and its national laboratories, the Department of State, non-governmental organizations, and academia are assigned to panels to ensure a balance of "perspectives." Diversity of perspectives can be viewed as allowing the problem to be considered from more viewpoints and thus leading to better quality answers.

- Training in Elicitation Methods. Both the experts and analysis team members would receive training from specialists in decision analysis. Team members would be trained in elicitation methods to become proficient and consistent in their elicitations. The experts' training includes an introduction to the elicitation and analysis methods, to the psychological aspects of probability estimation (e.g., the tendency to be overly confident in the estimation of probabilities), and to probability estimation. The purpose of this training is to enable the experts to transform their knowledge and judgments into the probability distribution format and to avoid particular psychological biases such as overconfidence. Additionally, the experts are given practice in assigning probabilities to sample questions with known answers (almanac questions).

- Presentation and Review of Issues. Presentations should be made to each panel on the set of issues to be considered, their definition and relevant issue data. Other parameters considered by the analysis staff to be of somewhat lesser importance should also be described. The purposes of these presentations are to permit the panel to add or drop issues depending on judgments as to importance; to provide a specific definition of each issue chosen and sets of associated boundary conditions imposed by other issue definitions; and to obtain information from additional data sources known to the experts.

  In addition, written descriptions of the issues are provided to the experts by the analysis staff. The descriptions provide the same information as provided in the presentations, in addition to reference lists of relevant technical material, relevant plant data, detailed descriptions of the types of scenarios of most importance, and the context of the issue within the total analysis. The written descriptions also include suggestions of how the issues could be decomposed into their parts using logic trees. The issues should be decomposed if it eases the cognitive burden of considering complex problems and improves the accuracy of judgments.

  In an initial meeting, DOE, researchers, facility representatives, and other interested parties are invited to present their perspectives on the issues to the experts, which may take several days.

- Preparation of Expert Analyses. After the initial meeting, the experts are given time to prepare their analyses of the issues. The experts are encouraged to use this time to investigate alternative methods for decomposing the issues, to search for additional sources of information on the issues, and to conduct calculations. During this period, several panels may meet to exchange information and ideas concerning the issues. At these meetings, expert panels may be briefed by the project staff on the results from other expert panels to provide the most current data.

- Expert Review and Discussion. After the expert panels prepare their analyses, a final meeting is held where each expert discusses the methods he/she used to analyze the issue. These discussions may lead to modifications of the preliminary judgments of individual experts. However, experts' actual judgments are not discussed in the meeting as group dynamics can cause people to unconsciously alter their judgments in the desire to conform.

- Elicitation of Experts. Following panel discussions, each expert's judgments are privately elicited, via a team typically consisting of an individual expert, an analysis staff member trained in elicitation techniques, and an analysis staff member familiar with the technical subject. With few exceptions, the elicitations are done with one expert at a time so they can be performed in depth and that an expert's judgments would not be adversely influenced by other experts. Initial documentation of the expert's judgments and supporting reasoning are obtained in these sessions.

- Composition and Aggregation of Judgments. Following the elicitation, the analysis staff composes probability distributions for each expert's judgments. The individual judgments are then aggregated to provide a single composite judgment for each issue. Each expert is weighted equally in the aggregation because this simple method has been found in many studies to be most effective.

- Review by Experts. Each expert's probability distribution and associated documentation developed by the analysis staff is reviewed by that expert. This ensures potential misunderstandings are identified and corrected and the issued documentation properly reflects the experts' judgments. It is also advisable to have the experts review how the results of their elicitations are used in the study. An expert that disagrees with the use of his or her elicitation can easily discredit the entire process.

  Recent work in expert elicitation has moved away from seeking the experts' judgment and moved towards using the experts to bring a wide variety of evidence to the table (Ref. 3 & 4). These approaches argue that it is important to get to the bases of opinion and have the group try to present a consensus distribution that has a good chance of representing diverse views in the technical community.

Potential Applications to Nonproliferation Assessment

There is much subjectivity in the assessment of proliferation problems. Some data exists on the physical characteristics of some attributes (e.g., value of isotopic composition of material), but in areas of untested systems and human behavior there is much uncertainty. Thus expert opinion becomes important to the analyst. A structured and unskewed approach to obtaining such information is highly desirable.

A recent application to the problem of detecting undeclared activities in connection with IAEA safeguards can be found in Reference 5.

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9.8 Logic Diagrams

The development of pathway scenarios is greatly facilitated by the use of logic diagrams to describe the flow of events and their interdependencies. Various tools are currently available and have been in use for many years in safety analysis (Ref. 1), particularly by the nuclear industry. Four tools that have some relevance are: fault trees, event trees, influence diagrams, and master logic diagrams. Variations of these approaches and tools have already been suggested by some analysts (Refs. 2-4) for the proliferation resistance problem. Here we present a brief description of these approaches.

Regardless of which method is chosen for a scenario analysis, the next step after identification of initiating events is to construct potential scenarios. A scenario is defined as a specific unplanned sequence of events that could result in an undesirable consequence. Therefore, an important product of the pathway analysis consists of a description of all sequences identified and recorded during the analysis process. To identify potential sequences, either inductive or deductive approaches can be applied, each having its own advantages.

The inductive (bottom-up) approach attempts to identify possible sequences by examining deviations from normal operating conditions (event trees and influence diagrams). The deductive approach identifies a top event (usually a severe consequence), and attempts to explain the various ways that the top event can occur (fault trees and master logic diagrams). Generally, the inductive approaches are useful in identifying a broad range of potential scenarios, while the deductive approaches provide a deeper understanding of the mechanism by which a particular undesired event might occur.

Like event trees, influence diagrams display interdependencies but do so in a more transparent and intuitive manner. Master logic diagrams, similar to a fault tree in structure, have been found useful in assuring completeness in the identification of initiating events.

The logic model identifies those events that are undesirable in the proliferation risk arena. Event trees and fault trees have their foundation in Boolean algebra. In the event tree approach (Ref. 5), succeeding branches of the event tree are generated in an inductive manner to produce a general representation of all possible states of a system from specific events. Although event trees do not imply a time relationship between events, they are often generated beginning with an initiating event and proceeding forward in time. Event trees typically involve events with binary branches (yes/no; fail/success) but have been used effectively with multiple branches. The fault-tree approach starts with a top undesired event (e.g., diversion of material) and moves downward through the tree to identify the events that are the potential proximate causes for each higher level event. Like event trees, fault trees do not have an implicit time relationship between events other than through causality. Thus, because causes of events typically precede the events, the generation of the fault tree tends to move backward in time as the analyst moves from higher level events to lower level events.

9.8.1 Event Trees

Figure 9-3 provides a simplified example of an event tree. The event tree begins with an initiating event (IE) with two separate systems designed to respond or react to the initiating event. The initiating event can be regarded as a proliferation threat. Given that the IE occurs, we ask whether System A and B was found in a success state or failure state, and probabilities are assigned to these branches. A and B can be conceptualized as two barriers to proliferation: A = Materials Barrier and B = Technical Barrier. In actual situations, this model would be much larger and more involved. If there were N systems, there would be 2^N possible states at the end. When only System A or B is sufficient to perform the overall safety function for the IE, then an event where A is successful, but B fails, will be a safe event. Similarly, the complementary situation (A fails and B is successful) will not be hazardous. As shown in the figure, three events present no hazard, but the failure of both systems will lead to the hypothetical environmental release (or other undesirable outcome).

The development of potential scenarios requires a clear understanding of the systems and operating procedures required for the functioning of the subject facility or process, and also as a prerequisite, requires a team of qualified analysts with training for performing risk analyses.

The development of an event tree is sometimes facilitated by constructing an event sequence diagram (Ref. 5) that represents the possible combination of system function and operator responses following the occurrence of each of the initiator groups. An event sequence diagram, therefore, describes the sequence of events that, following an initiating event, lead either to a successful state or to a failed state of systems and operator actions intended for mitigating the consequences of initiating events.

Event trees are not well-suited for all problems. The events must be distinct and independent or the effects of dependence added into the analysis. Typically events are ordered in time, since prior events may preclude the occurrence or alter the probabilities of subsequent events. Event trees do not address a continuous spectrum of possible outcomes of an event. However, event trees are not necessarily restricted to the consideration of bi-modal events.

<u>Potential Application to Nonproliferation Assessment</u>

The event tree approach clearly has broad application to non-proliferation analysis. It can be very helpful in defining scenarios that may evolve and in understanding the proliferation resistance of a system.

9.8.2 Fault Trees

The fault tree models, as shown in Figure 9-4, are used when we desire to examine a system that is comprised of sub-systems. Here, one goes backwards in time through the fault tree using the “and” and “or” gates in the basic logic models. The example chosen is based on a tree given in Reference 4 except that it is expressed here as a fault tree.

System failures are logical combinations of simpler events (e.g. component failures). It may be convenient to represent the system response as multiple discrete states, rather than simply binary (success or failure).

In a completely equivalent logical way, success trees can be used instead of fault trees. The top event then becomes the event that the system works instead of fails. The logic is then developed in terms of the combinations of subsystems that produced the desired top event. The choice of approach will depend on the tastes of the analyst and the nature of the problem. For the proliferation problem, we note that failure for the proliferant is success for the non-proliferant and vice versa.

The fault tree linking technique uses AND gates to model the top events of the event tree, and systems and components and their interdependencies for ensuring success or failure of each top event are logically modeled in the fault tree. The resultant linked fault trees could be large and complex. In these situations, computer codes may be used (Ref. 5).

If fault trees are used in conjunction with event trees, system dependencies can be explicitly modeled in the event tree. Each system in an event tree is quantified for every set of boundary conditions that have a unique effect on the system failure probability. The set of boundary conditions consists of a set of components and systems, including dependencies that affect the failure state of the system being quantified. Because the conditional probabilities are calculated for each top event to explicitly account for the dependency effects, the resultant fault trees for the event-tree top events are thus simpler and independent. In some cases, analyses can be performed by hand without resorting to computer assisted fault-tree reductions.

Potential Application to Nonproliferation Assessment

The fault tree approach clearly has broad application to non-proliferation analysis. It can be very helpful in determining the contributing events to a scenario and in understanding the proliferation resistance of a system.

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9.8.3 Influence Diagrams

Influence diagrams are graphical representations of decisions where specified variables, decisions, and consequences are represented by nodes and their relationships are indicated by arcs. Influence diagrams are an easily understood representation of a decision problem that can be mathematically solved. For a given decision problem there may be a number of influence diagrams that correspond to a particular decision. Thus, there is not a unique influence diagram for any given decision. An application to fire analysis is given in Reference 1 and its use in proliferation analysis is illustrated in Reference 2. More general discussions can be found in the literature (Refs. 3 & 4).

Influence diagrams are similar to event trees because they also use an inductive logic to move forward in time from an initial condition to a result or consequence. They do not, however, rely on the binary logic (yes/no) of the event tree approach and their topological expression allows for a more direct and intuitive display of the interactions among the subevent variables.

Further, influence diagrams:

- Represent probabilistic and informational dependencies among problem variables,
- Provide an intuitive and rational line of reasoning, and
- Facilitate the identification of the portions of existing knowledge that need improvement for the greatest improvement in the decision of interest.

The main components of influence diagrams are nodes and arcs. The nodes represent:

1. Decision variables, which are quantities over which the decision maker exercises direct control;
2. Value variables, which represent aspects of the preferences of the decision maker; and
3. Chance variables, which are uncertain quantities that represent properties of the states of the world.

The two types of arcs are informational and conditional. Informational arcs point to a decision variable. All other arcs are conditional arcs. The analyst could also develop submodel nodes, which is just a logical collection of the above nodes.

In Figure 9-5a, a minimal influence diagram is shown. The rectangular node labeled Proliferation Barrier is a decision variable. It could correspond to the decision of whether or not to build a materials barrier or an engineered barrier. The hexagonal node represents a value variable. The arc connecting these two nodes is a conditional arc (i.e., result depends upon the decision). If two nodes are independent there is no arc connecting them. Thus a non-conditional arc is the arc not drawn. Figure 9-5b shows the first figure expanded by two chance nodes, materials and costs. Here all the arcs are conditional arcs.

An influence diagram can be viewed at three levels: relationship, functional, and numerical. Figure 9-5b shows the relationships between four variables. At a deeper level, the functional relationship of, say, the materials node can be given and included in its description. At a still deeper level, numerical values can be assigned where appropriate and computed elsewhere.

The model of the decision process described by Figure 9-5 is very simple. However, in general, decisions are much more complex. For example, the cost node, rather than being a chance node, could be a submodel. This submodel would include all the variables relevant to determining the cost variable. Therefore, influence diagrams can consist of many submodels. This allows the construction of a model that at the highest level can be understood by the decision maker without the confusion of all the details. It also allows specialists to determine submodels associated with their specialty without being distracted by other specialized areas or the total picture. This is an example of the decomposition technique of solving complex problems.

Potential Application to Nonproliferation Assessment

The Risk Informed Proliferation Analysis method, which relies on influence diagrams, is described in Appendix D.

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9.8.4 Master Logic Diagrams

Master logic diagrams (Ref. 1) are tools used to facilitate the identification of initiating event categories. The analyst starts by following a deductive line of thought (like a fault tree) that leads to the identification of possible categories of initiating events. An initiating event is any event that upsets the normal operation of the facility that, together with other failures, results in a sequence of events that may lead to undesirable consequences. A Master Logic Diagram (MLD) is a high-level logic diagram. Development of a MLD starts with the definition of the ultimate, undesired outcome. It then seeks to logically and progressively identify the causes for the occurrence of the higher-level consequences. Deductive logic is used to successively enumerate all possible ways each level of outcome may occur.

An example of one possible master logic diagram is shown in Figure 9-6. It is a based on a diagram developed in Reference 2.

The event "Weapons Material Obtained" is the top event. The events in the MLD are identified by the level they appear in the tree. The use of levels is an ordering technique to assist in locating events by approach to materials obtained. In principle, the strategy is to achieve completeness of event by level.

As can be seen from Figure 9-6, the MLD is essentially a fault tree used to more formally organize the search for initiating events. When the diagram has reached its lowest level of resolution, basic failures or misoperations that could lead to the undesired top event are identified. A comprehensive listing of such events should provide for a complete definition of all-important initiating events.

The initiating events defined by the master logic diagram are already grouped by the barriers (in the proliferation problem) they most threaten. However, "barrier most threatened" is usually not sufficiently descriptive to serve as the sole means of grouping initiators. A further breakdown according to more specific barrier system requirements may be necessary.

Potential Application to Nonproliferation Assessment

If scenario analysis is the methodology of choice in analyzing a proliferation problem, then a set of initiators, as complete as possible, should be determined. Application of the MLD tool, by itself, can be useful, as it helps the analyst in systematic problem reduction to the constituent parts on a conceptual basis. It can also be a helpful visual and communication aid decision makers can use in gaining an understanding of the key subelements of a problem.

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9.9 Sensitivity Studies, Importance Measures, and Uncertainty Analyses

The reason for using the attribute approach or the scenario approach and not just deterministic means for characterizing or quantifying a process or a phenomenon is the probabilistic nature of the problem and the associated uncertainties due to natural phenomena and limited human knowledge base. Sensitivity analysis, importance analysis, and uncertainty analysis are essential aspects of either an attribute analysis or a scenario analysis approach to nonproliferation assessment. This section discusses these three important analyses and provides some guidance on how these analyses may be performed.

9.9.1 Sensitivity Analysis

The purpose of sensitivity analysis is threefold: (1) to determine sensitivity of the calculated nonproliferation measures specified to the analyst; (2) to address modeling assumptions suspected of having potentially significant impact on the results, and (3) to provide a basis for uncertainty characterization in success criteria and other assessment elements. These assumptions are generally in areas that lack information and rely heavily on analyst judgments. Sensitivity analysis can then be accomplished by substituting alternative assumptions for conservatisms and evaluating their individual impacts on the results. If significant sensitivities are exhibited to certain dependency failures, the analysis should describe the conditions, precautions, and actions in place to ensure against them; if the results are data sensitive, then the data should be closely scrutinized to ensure accuracy and adequacy in underlying representations.

Sensitivity analyses should be performed on: potential subsystem failure dependencies, potential human performance dependencies and major assumptions or data employed. For component failure dependencies, sensitivity analysis is carried out by searching for sensitivity to dependence (hardware coupling) on a system-by-system basis, so that each system can be examined in more depth than would be the case if entire sequence/scenario cutsets were searched. When the effect of a given dependence failure is substantial, the corresponding impact on the risk results should be assessed, including a discussion of measures to be taken to reduce the potential dependence failure or its contribution to the calculated risk.

Human error dependence sensitivity analysis should be performed similarly to the subsystem dependence sensitivity analysis. The suspected dependence cutsets (see Reference 6 in Section 9.8.2) are identified as containing multiple human errors of any type. These suspected dependence cutsets should be analyzed, not requantified. Management controls or conditions should be implemented, if possible, to eliminate the human error dependencies in the suspected cutsets.

The sensitivity analysis of assumptions or data employed in the attribute or scenario analysis can be performed by first searching for suspected conservative assumptions or data having an important impact on final analysis results. Then, employ alternative assumptions or different data sets and assess their impact on the results.

Potential Applications to Nonproliferation Assessment

There is much literature (Ref. 1) on PRA that documents the applications of sensitivity analysis of complex systems. This technique can be used in the proliferation area by highlighting and focusing on the significant intrinsic and extrinsic components of proliferation resistance.

Sensitivity analysis of the utility function was suggested in Reference 2 and is also applicable to the weights. Sensitivity studies serve as an attribute screening tool and suggest how to perform a more formal uncertainty analysis.

9.9.2 Importance Analysis

The purpose of the importance analysis is to identify the important initiating events or causes, scenarios, system and subsystem failures, and human errors that are the primary contributors to the final (and intermediate) results. The importance measures are usually calculated in a hierarchical fashion to allow tracing from the important sequence/scenario to system failures to important subsystem failures or human errors contributing to system failure. For a process involving active and passive systems, importance measures may require considerations of subsystems that may function either in a binary state or in a continuous fashion, as discussed below.

There are a number of importance measures (Refs. 3-5) that have been frequently applied to reactor PRAs, such as Fussell-Vesely and Birnbaum. Related measures are the Risk Reduction Worth and the Risk Achievement Worth. These importance measures calculate either the fractional contribution of the sequence containing the primary event of interest to the final result (Fussell-Vesely) or the rate of change (Birnbaum) of the risk due to the change in the probability of an individual event. The Risk Reduction Worth measures the change in risk when a basic (failure) event is set equal to zero (i.e., a perfect component). Risk Achievement Worth is just the opposite. It measures the change in risk when a basic event is set to unity. The four measures are mathematically related and all probe aspects of the results of a PRA with regard to contributing event importance. However, these importance measures almost always apply to processes or systems that can be modeled as consisting of binary state components (i.e., either "success" or "failure").

Techniques have been developed (Ref. 1) to measure the importance of components whose functionality is continuous. These measures were based on risk. In comparison, traditional importance measures are based on frequency of failure. The risk-based measures are more suitable to systems comprised of components with behaviors more easily and naturally represented as continuous, rather than binary. These importance measures appear to be able to evaluate systems comprised of both continuous and binary behavior components.

Based on reactor risk studies, importance measures are calculated for more than the top 20 dominant contributors to ensure a good understanding of dominant contributing component failure effect on core damage frequency. For proliferation resistance analysis, the extent to which importance measures are performed depends on the underlying risk associated with the particular activity and the number and complexity of the systems and components involved in the particular process or facility. In any event, the effort for importance calculation should provide good understanding of important systems and components and their contributions to total calculated risk, so that risk management for the evaluated process or facility can be planned accordingly.

Potential Applications to Non-proliferation Assessment

There is much literature on PRA (Ref. 11) that documents the applications of importance analysis of complex systems in a scenario analysis approach. This technique, carried over to the proliferation area, can highlight and focus on the significance of the intrinsic and extrinsic components of proliferation resistance.

Importance analysis can also be performed in a MAU barrier analysis. It would be helpful for the analyst and decision maker to know the relative importance of the various barriers that comprise the proliferation-resistant system.

9.9.3 Uncertainty Analysis

A nonproliferation assessment is made on the basis of incomplete information. Best estimate results can yield useful information with regard to the proliferation resistant features of a facility. At the same time, the degree of uncertainty in the results should also be assessed and presented to the policy maker. This is not an easy task, but fortunately much work has been done in this area in the context of risk prediction. Typically, uncertainties are quantified at the system level and aggregated mathematically to attain the final results in terms of an uncertainty distribution.

There are two types of uncertainties (Ref. 7) that should be examined: aleatory uncertainty and epistemic uncertainty. Aleatory uncertainty is uncertainty associated with physical phenomena that cannot be reduced by model improvements. For instance, the uncertainty associated with the enrichment of nuclear fuel is aleatory due to allowable tolerance in the manufacturing process. Epistemic uncertainty represents the modeling uncertainty associated with the human understanding of a particular process or physical phenomenon. As the knowledge base increases, our understanding of the physical phenomenon is also enhanced thereby reducing the uncertainty associated with the model. Epistemic uncertainty is reducible as the modeling aspects are refined. In practice, the probability of a scenario may be regarded as representing an aleatory uncertainty and the probability of parameters and models as representing epistemic uncertainties. However, such distinctions are not absolute. For example, in calculating consequences of disruptive geologic events (fault movement, igneous activity), the time of such an event may be chosen as model parameter, but clearly represents an aleatory uncertainty (Ref. 6).

Sources of uncertainties should be carefully considered to ensure all uncertainties associated with initiating events, scenario modeling, physical characterization and data employed are included, properly characterized and propagated through the attribute or the scenario analysis model. Some uncertainty is associated with the way the analyst applies the methods and the skill or accuracy achieved to represent the process or system with the adopted modeling method. These uncertainties can be addressed by training the analyst, using ~~of~~ consistent procedures and providing proper guidance and review. Modeling uncertainties can also be reduced by making models as realistic as possible with compensating assumptions and modeling constraints.

An important source of uncertainties involves human performance, which should be adequately addressed in any risk model. The following sources of uncertainties associated with human performance should be considered (Ref. 8), as a minimum:

1. Human motivation;
2. The dearth of data available on human performance;
3. The inexactness of human performance models that purport to describe how people act in various situations and conditions;
4. The identification of all relevant performance-shaping factors and their interactions and effects;
5. The skill and knowledge of the human-reliability analyst;
6. The variability in the performance of a given individual and among the performances of different individuals.

9.9.4 Propagation of Uncertainties

As suggested above, if the final result of the analysis, $F(x_1,\ldots, x_n)$, is comprised of the set of inputs $x_1,\ldots, x_n$, and if each xi is characterized by a probability distribution, then F can be expressed as a probability distribution, P(F). There are various techniques for computing the probability distribution for F. In some simple cases, P(F) can be computed in closed form from the distributions for the x_i. However, it is often the case that numerical integration/ simulation must be used to evaluate P(F). A straightforward Monte Carlo sampling (Ref. 9) of the distributions for the x_i can be performed. This approach works best for smooth, slowly varying distributions. For distributions with long-range tails, such as those encountered in systems reliability, Monte Carlo will sample preferentially from the more likely parts of the distribution and thus tend to not reflect the information contained in the tails. One approach to resolving this problem is the Latin Hypercube Sampling technique (Ref. 10). In this approach, the sampling is forced to include sufficient information from the tails to give a more representative characterization of the overall distribution.

Potential Applications to Non-proliferation Assessment

There is much literature (Ref. 1) on PRA that documents the applications of uncertainty analysis of complex systems for a scenario analysis approach. This technique can be carried over to the proliferation area to highlight and focus on the significance of the intrinsic and extrinsic proliferation resistance components.

It was clearly recognized from the early applications (Refs. 2 & 11) of multi-attribute decision analysis to proliferation analysis that due consideration must be given to uncertainties in the predicted results.

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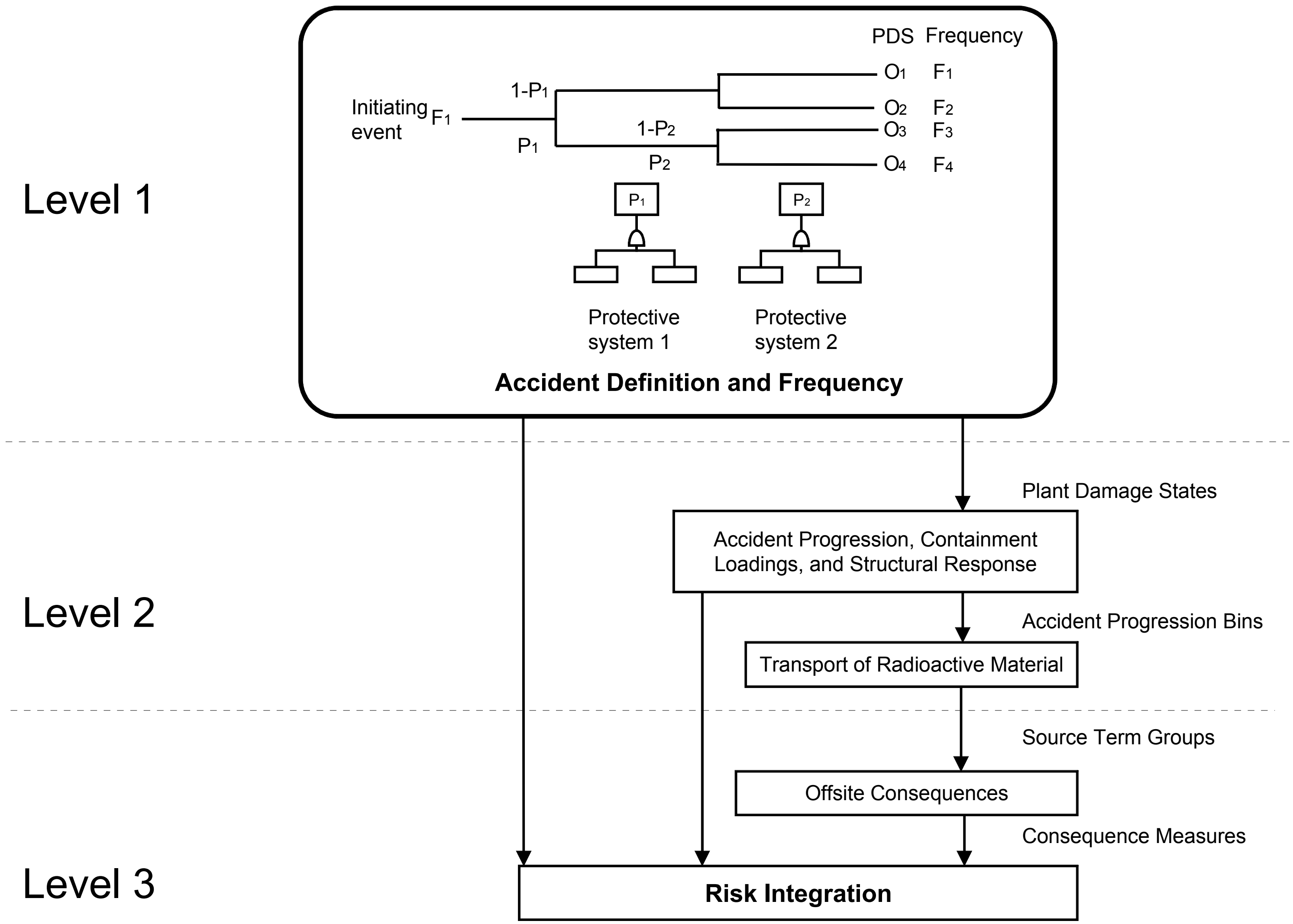

Figure 9-1. PRA

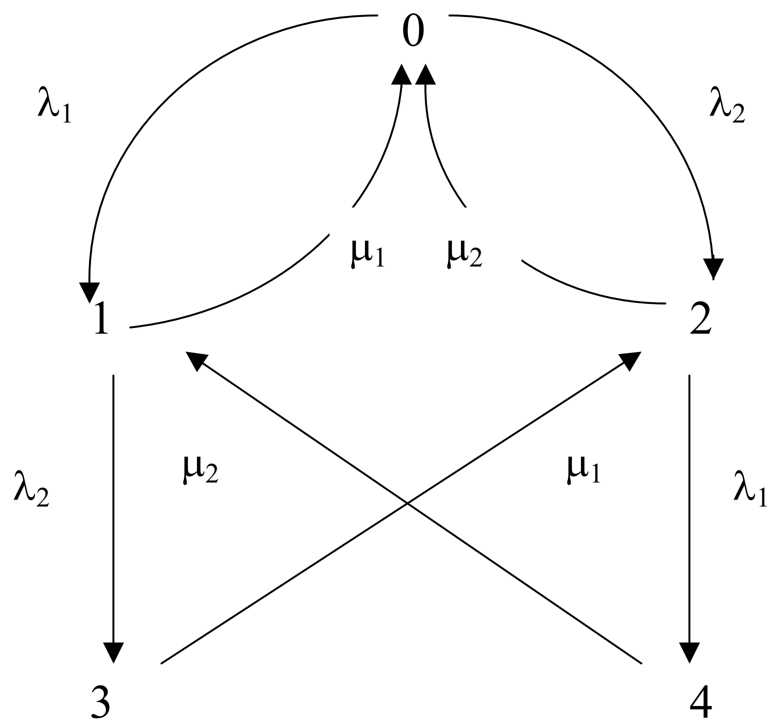

Figure 9-2. Markov Chain for Redundant Monitoring System

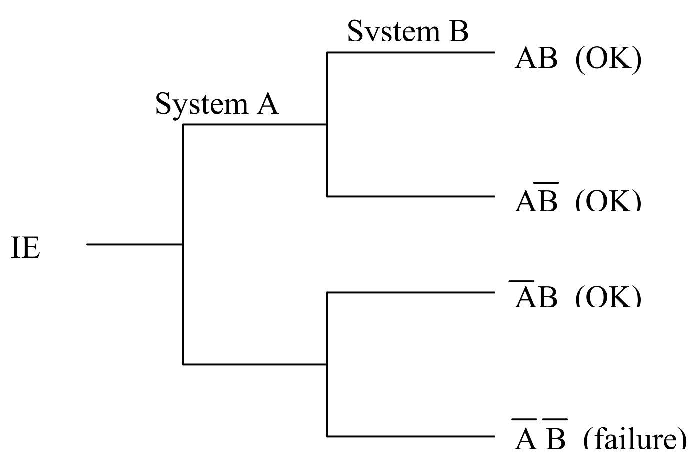

Figure 9-3. Simple Event Tree

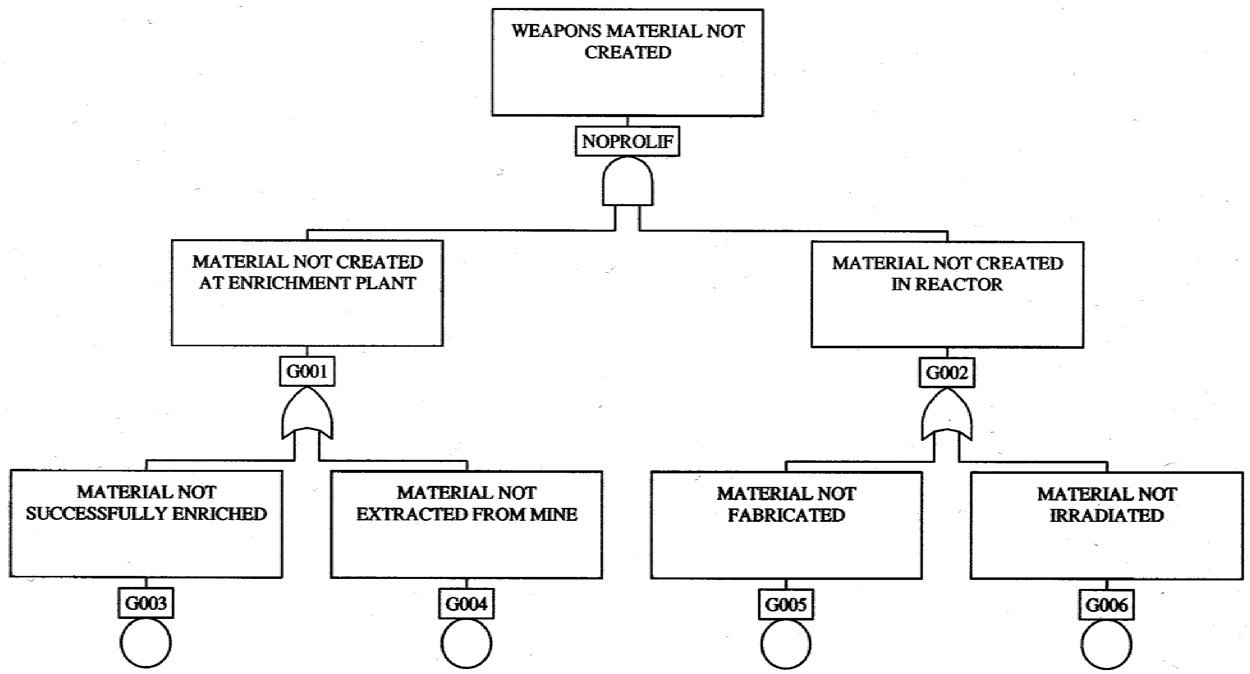

Figure 9-4. A simplified fault tree

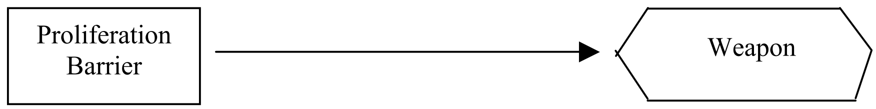

Figure 9-5a. Minimal Influence Diagram

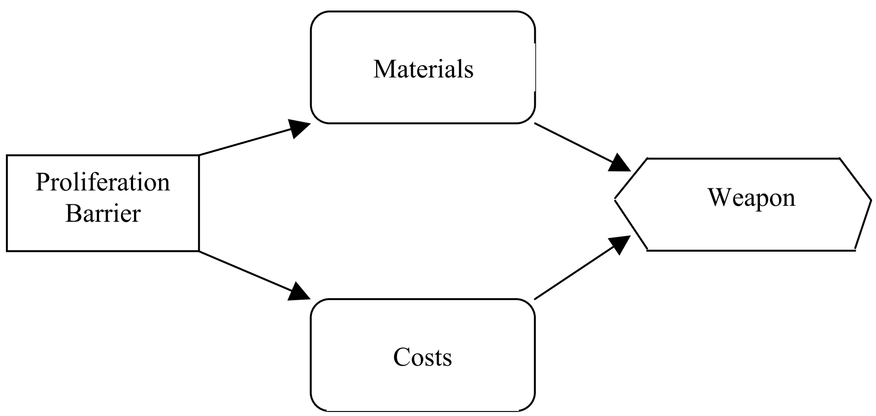

Figure 9-5b. Expanded Minimal Influence Diagram

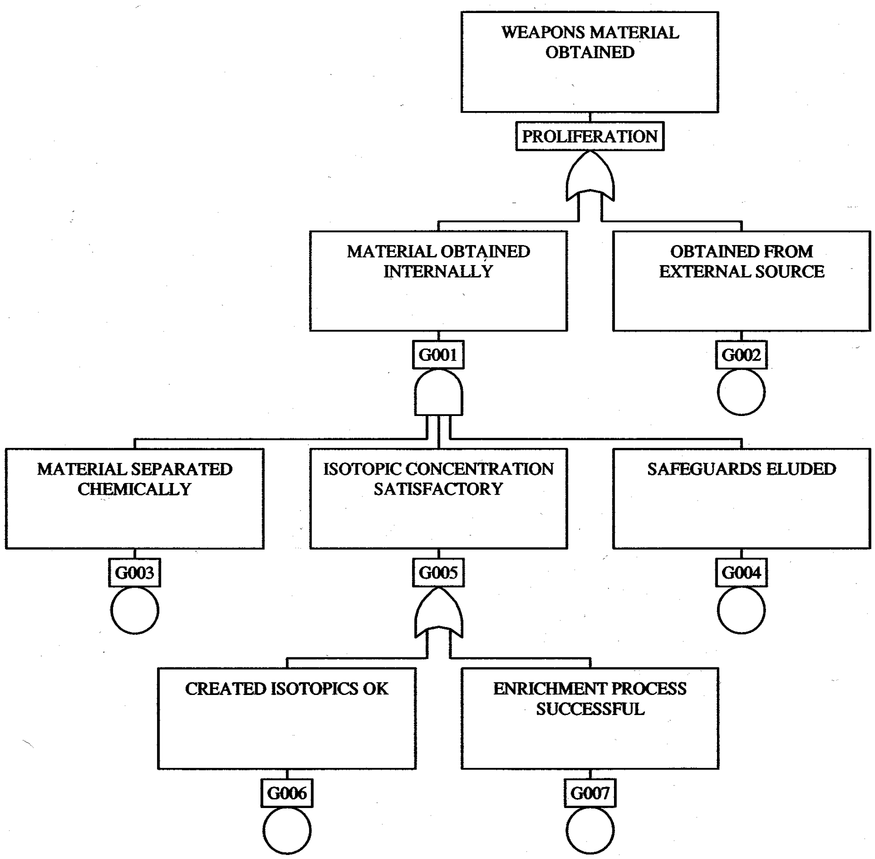

Figure 9-6. Master Logic Diagram

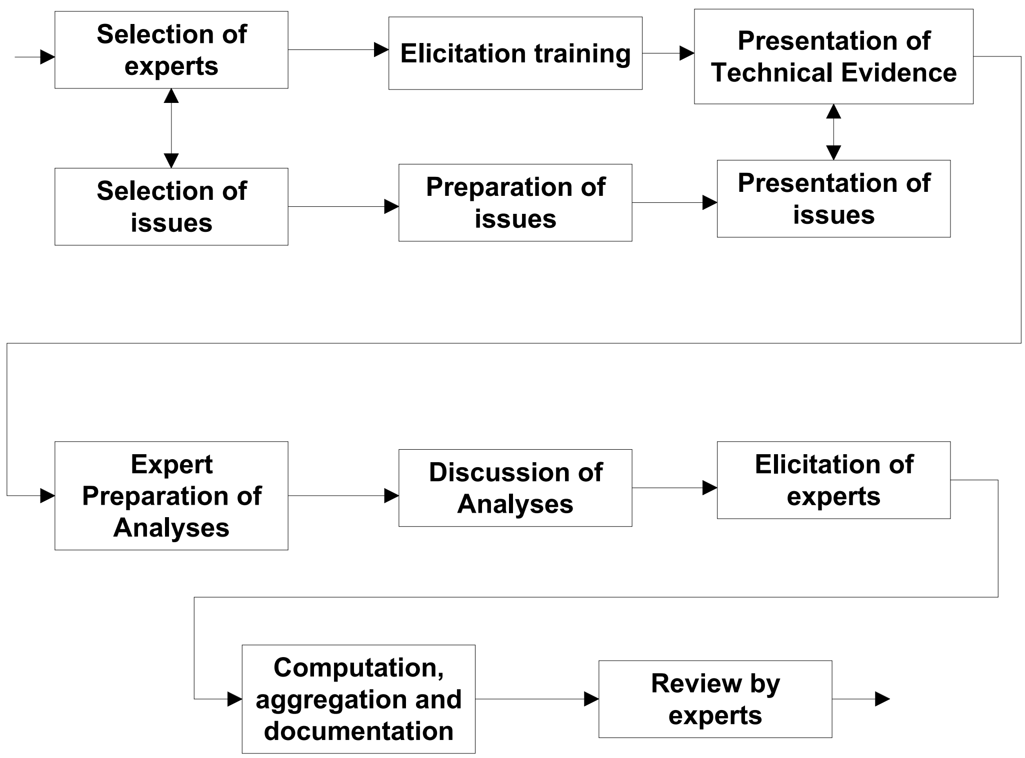

Figure 9-7. Principle Steps In Expert Elicitation Process

10.0 Integrated Methodologies for Nonproliferation Assessment

As discussed in Section 5 and illustrated in Figure 5.5, the typical nonproliferation assessment involves the evaluation of proliferation resistance measures or a system's proliferation risk by means of a complex analysis of threats, facilities, and barriers. To assist in the development of nonproliferation policy, the analysis is performed for alternatives that can be related to policy decisions. The policy maker favors alternatives with high proliferation resistance or low proliferation risk. No fully mature methods have been developed to perform these integrated assessments in a routine manner. Two promising approaches that have been partially developed to perform integrated assessments are described in Appendices C and D. MAU Barrier Analysis, an attribute analysis method, and Risk-Informed Proliferation Analysis, a scenario analysis method, require additional development before either could be used routinely.

Prior to regular use, the integrated method will have to be tested and further developed through the performance of application studies. Scenario analysis and attribute analysis approaches have different strengths and weaknesses, which make one or the other preferable for a given application. It is possible the two methods can be used effectively together for certain applications.

11.0 Integration and Presentation of Results

As discussed in Section 5, the nonproliferation problem must first be decomposed into manageable elements. At the end of the analysis, results obtained from the decomposed problem must be reassembled in a manner that can be interpreted by the user. A nonproliferation assessment produces large quantities of information. Some aggregation of results must occur to aid the policy maker in understanding the analysis messages. This aspect of nonproliferation assessment requires additional consideration and development.

The following discussion addresses an assessment of the proliferation resistance of a fuel cycle system. However, the problem of the aggregation and presentation of results is generic. In the decomposition of the problem, the fuel cycle system is segmented into elements, proliferation barriers identified, metrics defined, and a set of threats selected. Typically, the lowest level metrics are evaluated for each threat and for each segment of the fuel cycle. In the MAU Barrier Analysis approach described in Appendix D, the lowest level metrics are attributes of the barriers to proliferation. The proliferation resistance of the system is assessed by determining a value for each metric for each threat and for each segment of the fuel cycle system. For presentation and evaluation purposes, the values of each of the metrics can be multiplied by weights and summed to obtain a measure of the proliferation resistance of a segment of the fuel cycle for a specific threat. Instead of rolling up to the highest level measure, proliferation resistance, the analyst could also develop weights applicable to an intermediate level measure, such as the probability of undetected material acquisition (See Figure 8.1), which might have greater meaning to the policy maker. Care must be taken, whenever aggregating, to assure that important information is not lost and that metrics being weighted are not dependent, which could lead to a double counting or an undercounting.

Within the context of a specific threat and a specific segment of the fuel cycle, the type of weighted summing of metrics described above is probably necessary to assist the policy maker in drawing meaningful conclusions about the relative merits of policy alternatives. The benefits of weighting across threats and across segments of the fuel cycle are less clear. Fuel cycle systems can be expected to have substantially different proliferation resistance to different threats. The vulnerabilities of a fuel cycle system to the subnational threat are likely to be different from vulnerabilities to an advanced nation state. The policy analyst probably wants to keep the results for these different types of threat separate in developing logic for policy alternatives. Similarly, a simple weighting scheme might not be appropriate for aggregating across segments of the fuel cycle. One key vulnerability of a fuel cycle system would be much more important than many results indicating that the rest of the fuel cycle has outstanding proliferation resistance. Selecting the proliferation measure for the most vulnerable segment of the fuel cycle system may be the most appropriate means of measuring the vulnerability of the entire fuel cycle system.

The development of a simple, understandable approach to the display of nonproliferation results is a major challenge to the analyst. The aggregation and display of results is further complicated by the need to convey the uncertainty in the results. Reference 1 explores a number of approaches to the display of uncertainty in results. The manner in which the uncertainty is displayed may depend on the type of uncertainty analysis. In a very detailed uncertainty analysis using Monte Carlo techniques, it may be possible to display the 5^{th} percentile, 95^{th} percentile, mean and median of a distribution. More typically, a range of uncertainty is displayed without necessarily a rigorous interpretation of its meaning.

It should be assumed that the study will undergo independent review. Sufficient material should be provided within the report or within appendices and reference citations that would allow the independent reviewer to reproduce results using the information provided. Similarly, intermediate and low level results should be provided to allow the policy maker to trace the underlying reasons for high level results.

References

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12.0 Conclusions

This study has advanced the process of developing integrated methodologies to address nonproliferation issues. Building upon previous work, the study has taken the next step towards achieving a hierarchy of methodologies that can be employed with confidence and will be credible to a wide range of nonproliferation analysts and policy makers.

Nonproliferation problems tend to be complex and have defied the development of a universally agreed upon assessment methodology. However, there have been a number of attempts to apply rigorous methodologies to proliferation assessment problems. A number of promising techniques were identified during this activity. These analytical tools, often developed for analysis of other problems, can potentially be applied to nonproliferation assessments. Many of these tools will also be helpful in the development of integrated methodologies.

The study identified three general categories of analytical approaches with excellent potential for use in nonproliferation studies: attribute analysis, scenario analysis, and two-sided methods. Attribute analyses evaluate the effectiveness of barriers to proliferation, scenario analyses assess the pathways through those barriers, and the two-sided approaches explore the human interplay between adversaries. The three categories of approach are complementary in addressing the spectrum of nonproliferation issues that may be examined by NNSA and others.

Scenario analysis and attribute analysis methods can be used as the basis for integrated analysis approaches to the evaluation of the proliferation resistance or proliferation risk of nuclear systems. Two-sided methods, in particular wargames, can be used to examine proliferation issues that involve the interplay of adversaries with opposing objectives. Each of these general approaches can employ one or more of the analytical tools identified in the study. For example, the scenario analysis and attribute analysis methods could each employ an analytical hierarchy process to systematically incorporate expert opinion into the weighting of metrics.

Mature, integrated methods have not fully been developed to assess proliferation risk or proliferation resistance. Some methods have been partially developed or proposed as potential integrated methodologies. Two very promising approaches, an attribute-based approach and a scenario-based approach, are described in this report. The MAU Barrier Analysis method and the Risk-Informed Proliferation Analysis methods have been partially developed but would require additional development effort to be used in a study. Although wargames are widely used in other fields, there are only limited examples of their use in examining nonproliferation issues. The Working Group recommends that application studies be undertaken in which an attribute analysis method, a scenario analysis method, and wargames could be more fully developed and demonstrated.

A significant challenge to the development and application of integrated assessment methodologies is the selection of appropriate metrics. This report presents a hierarchy of metrics that can be used to convey the results of the assessment. There is a great deal of information produced in a nonproliferation study that must be presented to the policy maker and stakeholder in a manner that can be properly interpreted. Some aggregation of analysis results must be performed to make the results interpretable. This presents a challenge for any of the methods that have been surveyed. The aggregation of metrics must be done in a manner that avoids loss of information, minimizes interdependencies, is traceable and provides useable information to the policy-makers. Although results must be aggregated to allow the policy maker to visualize and interpret the primary messages of the assessment, detailed results must be documented to enable the policy maker to be able to trace higher-level results back to their lower-level causes.

Appendix A. NPAM Working Group Membership

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Appendix B. Glossary of Terms and Acronyms

Term	Definition
Agent-based Simulation	A simulation made up of agents, objects, or entities that behave autonomously. These agents are aware of (and interact with) their local environment through simple internal rules for decision making, movement, and action.
aleatory uncertainty	The uncertainty associated with physical phenomena that cannot be reduced by model improvements. For instance, the uncertainty associated with the enrichment of nuclear fuel is aleatory due to the allowable tolerance in the manufacturing process.
Analytical Hierarchy Process (AHP)	A systematic method for modeling and assessing otherwise unstructured problems where absolute measurement is not possible, i.e., for comparing a list of objectives or alternatives.
attribute	Refers to a general property such as cost, development time, or radiation level.
barrier	Anything that restrains or obstructs progress or access.
Barrier Analysis	Methodology used to evaluate the effectiveness of a system of barriers.
Bayes' Theorem	A theorem describing how the conditional probability of each of a set of possible causes, given an observed outcome, can be computed from knowledge of a probability of each cause and of the conditional probability of the outcome given each cause.
Boolean Algebra	A mathematics used with logical relations, such as AND and OR, in which false is 0 and true is 1. The mathematics involves rules for logical expressions which are analogous to the rules used for common mathematics.
conditional probability	The probability that an event will occur under the condition that another event occurs first; equal to the probability that both will occur divided by the probability that the first will occur.
criteria	Rules or principles for evaluating or testing something.
Declared Nuclear Weapons State	see Nuclear Weapons State
deductive approach	A logical process in which the conclusion follows necessarily from the stated premises. Inference by reasoning from the general to the specific.
Defacto Nuclear Weapons State	Although not a legal designation recognized by the United States Government or authoritative international bodies such as the International Atomic Energy Agency (IAEA), the term Defacto Nuclear Weapon State is generally understood to refer to states that are widely believed to either possess assembled nuclear weapons, or that could quickly assemble nuclear weapons from existing components. India, Pakistan, and Israel are often-n described using this terminology. These three states are not signatories of the NPT.

development time	Refers to the time required to complete a step, from initial idea to functional unit.
efficient frontier	The locus of points in a decision analysis that are not inferior to others.
epistemic uncertainty	Represents the modeling or data uncertainty associated with the human understanding of a particular process or physical phenomenon.
event tree	An inductive logic method for identifying the various possible outcomes of a given initiating event involving branching (usually binary) at decision points or key events.
Expert Delphi Group Method	Based on a structured process for collecting and distilling knowledge from a group of experts using a series of questionnaires interspersed with controlled opinion feedback. The objective is a reliable and creative exploration of ideas or the production of suitable information for decision making.
expert elicitation	Use of a group of knowledgeable individuals during problem solution to estimate systems responses, data values, consequences, etc., when those described in a problem are unknown.
extrinsic barrier	An institutional or other external measure that lowers the risk of proliferation of nuclear materials, such as physical security measures, monitoring techniques, and IAEA inspections.
fault tree	A deductive logic method in which events are subdivided into contributing events using simple logical relationships (such as And, Or, etc.). These relationships permit a methodological building of a structure that represents the system.
fertile material	An isotope that is not itself fissioned by thermal neutrons but can be converted to a fissile isotope either directly or after a short decay process following absorption of a neutron.
fissile material	An isotope that is capable of undergoing nuclear fission with low or high energy neutrons. See also the definition of "weapon useable material."
fissionable material	An isotope that is capable of undergoing nuclear fission only with high energy neutrons. Some fertile isotopes, such as U-238 and Pu-240, are fissionable, but are not fissile.
fuel cycle	The steps required to supply, use and process fuel for nuclear reactors. That is, the set of chemical and physical operations needed to prepare nuclear material for use in reactors. This includes mining, which starts at the front end of the cycle, through the disposal of nuclear wastes, which ends at the back end of the cycle.
Fuzzy Set	A generalization of a classical set with the property that each member of a population of objects has associated with it a number (usually from 0 to 1) that indicates the degree to which the object belongs to the set.
Game Theory	A mathematical theory that deals with strategies for maximizing gains and minimizing losses within prescribed constraints, such as the rules of a card game.

importance analysis	Identifies the important initiating events or causes, scenarios, system failures, subsystem failures, and human errors that are the primary contributors to the results. Importance measures are usually calculated in a hierarchical fashion to allow tracing from the important sequence/scenario to the system failures to the importance subsystem failures or human errors contributing to the system failure.
inductive approach	A logical process in which a conclusion is proposed that contains more information than the observations or experience on which it is based. The truth of the conclusion is verifiable only in terms of future experience and certainty is attainable only if all possible instances have been examined.
INFCE	International Nuclear Fuel Cycle Evaluation - A major evaluation convened by the International Atomic Energy Agency in 1978 that attempted to compare the nonproliferation characteristics of different nuclear fuel cycles and nuclear systems that would lead to recommendations on steps that nations could take to help strengthen the nonproliferation regime.
influence diagram	A variation of event trees which display interdependencies in a more transparent and intuitive way.
institutional barrier	see extrinsic barrier
integrated methodology	A set of computer tools that have been interfaced to enable the undertaking of a complete nonproliferation assessment.
international safeguards	Actions taken by the IAEA to verify that commitments made by States under safeguards agreements with the IAEA are fulfilled. The objectives of these safeguards are the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities, the deterrence of such diversion by the risk of early detection, and the detection of undeclared nuclear material and activities.
intrinsic barrier	A quality of reactor materials or the fuel cycle that is inherent to the design and operation that reduces the desirability or attractiveness for use in a nuclear weapon, makes it difficult to gain access to the materials, or makes it difficult to misuse facilities and/or technologies for weapons applications. These qualities include high level of radioactivity, chemical processing, isotopic composition, mass and bulk, sealed systems, and high burnup fuel.
Latin Hypercube Sampling technique	Sampling method that forces sufficient information from the tails of a distribution to be included in order to give a more representative characterization of the overall distribution.
Level 1 PRA	Identifies potential accident initiators and models possible sequences of events that could occur as the plant responds to these initiators. Level 1 accident sequences are classified into plant damage states according to those factors that determine the potential severity of the consequences.

Level 2 PRA	Analyzes the thermal-hydraulic progression of the accident in the reactor coolant system, interfacing systems, the containment, and, where relevant, surrounding buildings. These analyses yield estimates of the frequencies and magnitudes of potential radiological source terms.
Level 3 PRA	Estimates the potential health and economic consequences associated with the source terms from the Level 2 PRA. The consequence-weighted risks of early fatalities, latent cancers and other health and economic consequences are estimated.
Markov Chain	The depiction of consecutive events of a Markov process in which future values of a random variable are statistically determined by present events and dependent only on the immediately preceding event.
master logic diagram	A type of fault tree that is useful in identifying initiating events.
material attractiveness	A measure of the desirability of a material for nuclear weapons use.
material barriers	Those qualities that make it more difficult to produce a nuclear explosive from a particular source material. This includes the isotopic composition of the material (percentage and weight), isotopic separation or chemical processing required to retrieve or produce a weapons-usable substance, the radiation hazard and signature associated with the material at each step in the civilian system and in any process to generate weapons-usable material, and the detectability and difficulty of movement of the mass and/or bulk of the material.
measure	Refers to the high-level comprehensive variables for expressing proliferation risk or resistance.
metric	Refers to the lower-level, more concrete, proliferation-related characteristics of materials, facilities, processes or actions.
Monte Carlo Analysis	A technique for numerically approximating the solution of a mathematical problem by sampling from the distribution of some random variable, often generated by a computer.
MPC&A	Material Protection, Control and Accounting. The system implemented by a State to provide an integrated system of physical protection, material accounting, and material control measures designed to deter, prevent, detect, and respond to unauthorized possession, use or sabotage of nuclear materials.
Multi-attribute Utility Analysis (MAU)	A decision analysis technique that allows diverse attributes to be compared and combined on a common basis.
NASAP	Nonproliferation Alternative Systems Assessment Program - A study conducted in 1980 that evaluated how the U.S. light water reactor once-through fuel cycle compared to other options.
nonproliferation	Absence of the spread of nuclear weapons.

Nonproliferation Treaty	Signed in 1968, the Treaty on the Nonproliferation of Nuclear Weapons (NPT) provides that signatory nations without nuclear weapons will not seek to build or acquire them and will accept safeguards to prevent diversion of nuclear material and technology from peaceful uses to weapons programs. States possessing nuclear weapons at the signing of the NPT agreed not to help non-nuclear states gain access to nuclear weapons, but to offer them access to peaceful nuclear technology. All States agree to work towards the eventual elimination of nuclear weapons. As of the issuance of this report, there were 188 parties to the agreement. The only States that are not parties are India, Israel, Pakistan, and the Democratic Peoples Republic of Korea. The NPT also provides for review conferences at five-year intervals.
nuclear proliferation transparency	A measure of the ability to provide confidence between governments that each is abiding by its nonproliferation agreements. Methods used include the exchange of information, access to facilities, and cooperative arrangements.
nuclear weapon states	As defined by Article IX, paragraph 3 of the NPT, these are the five states that detonated a nuclear device prior to January 1, 1967 - China, France, Russia (which succeeded to the Soviet Union's nuclear status in 1992), the United Kingdom, and the United States.
ordinal utility function	Also called preference function or worth function. A scalar-valued function defined on the evaluation space with the property that v(x1, . . ., xn) is preferred or indifferent to v(x'1, . . ., x'n) if and only if (x1, . . ., xn) is preferred or indifferent to (x'1, . . . , x'n).
pathway	A description of the potential series of steps that could be taken when going from point A to point B. In nonproliferation assessment, a pathway is the specific set of steps taken to defeat barriers and to obtain weapons useable material.
pathway analysis	An evaluation of the potential pathways from point A to point B
peer review	A critical evaluation of the quality of an activity (typically the report of a study) by a group of experts.
physical protection	Comprised of those measures applied to prevent or deter the theft of nuclear material during use, storage and transport, and to preclude the sabotage of nuclear facilities by sub-national entities. Measures include isolation, containment, detection of penetration, response with force and neutralization.
Possibility Theory	A common approach to represent imprecision and uncertainty in dealing with complex systems.
PREM	Proliferation Resistance Evaluation Methodology
Probabilistic Risk Assessment or Analysis (PRA)	Science of studying the amount of risk associated with doing something. In the commercial nuclear arena it traditionally refers to a comprehensive decision making tool involving the use of event trees and fault trees by which safety can be measured and modifications can be evaluated regarding their contribution to safety. Internationally, often referred to as Probabilistic Safety Assessment.

probability distribution	A characterization of the likelihoods of different values of a variable.
production time	The time required to manufacture a product, from set-up to final disposition. In nonproliferation assessment, the analyst may use the term to either represent the total time from the start of proliferation to the achievement of nuclear weapons or the period from the acquisition of material to the production of weapons.
proliferation	Acquisition of one or more nuclear weapons by a nation or sub-national group that currently does not have them (because this definition includes theft, it is broader than the IAEA definition).
proliferation resistance	Degree of difficulty that a nuclear material, facility, process, or activity poses to the acquisition of one or more nuclear weapons.
proliferation risk	The likelihood of a nation or sub-national group acquiring one or more nuclear weapons within a given time period.
proliferant	Refers to a State, sub-national group, or a combination of the two with an active program to develop or to help to develop a nuclear weapons capability.
roll-up	The inclusion of subparts in a higher level part description.
safeguards	An integrated system of physical protection, material accounting, and material control measures designed to deter, prevent, detect, and respond to unauthorized possession, use or sabotage of nuclear materials. In addition, the term includes the concept of international safeguards defined above.
scenario	An imagined or projected sequence of events that could result in an undesirable consequence.
scenario methods	Solution techniques developed for use with problems designed using scenarios, i.e., a series of steps or activities.
screening tool	A means of eliminating events that do not significantly contribute to the final result and thus allow a problem to be simplified.
security	The condition of immunity from theft, diversion, sabotage, loss or damage in the face of malice, mischance, or error.
sensitivity analysis	Variation of a parameter to determine the magnitude of the effect on the result.
stakeholder	A person or group that has an investment, share or interest in something.
states of proliferation concern	Replaced "rogue" states. Refers to countries regarded as hostile to the U.S. and its allies and suspected of developing or deploying nuclear weapons. U.S. officials currently use this term in reference to North Korea, Libya, Syria, Iran and Iraq.
stochastic	Of or pertaining to a process involving a randomly determined sequence of observations each of which is considered as a sample of one element from a probability distribution.
stochastic uncertainty	Reflects the inherent variability in processes uncertainty analysis
sub-national threat	Proliferant below the State level, includes terrorist groups and organized crime.

technical barrier	An intrinsic barrier. In the TOPS Report, refers to facility unattractiveness; facility accessibility; available mass; diversion detectability; skills, expertise and knowledge; and, time.
threat	see proliferant
TOPS	Technical Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems. Refers to the Department of Energy TOPS Task Force which developed a set of attributes with which to both define and qualitatively assess proliferation resistance.
Two-Person Zero Sum (TPZS) Game	A competition between two players where each player selects an action, and based on these selections, the two players receive rewards. In all cases, what one player wins the other loses, so the sum of the rewards to the players is 0.
Two-Sided Approaches	Methods that consider the interplay between adversaries with opposing objectives.
uncertainty analysis	Methods for characterizing the variability or potential error in results.
utility function	The characterization of the relative importance of the magnitude of an attribute or consequence in terms of a unitless measure that reflects the preferences of the analyst.
value function	Same as ordinal utility function.
vulnerability analysis	Evaluation of the susceptibility of a system to defeat through various means, including force, deception or circumvention.
Wargame	A role-playing exercise where human participants make sequential decisions to allow a scenario to unfold. Models, simulations or lookup tables are used to determine the consequences of the decisions and to advance time. Wargames are characterized by the active and central involvement of human beings, often with opposing goals, and making sequential decisions.
warning time	The time elapsed between when a proliferant initiates actions to proliferate and the intent is discovered.
weapon-grade	Fissile material used in the fission energy elements of deployed nuclear weapons, generally understood to be limited to plutonium containing 93% or more of the isotope Pu-239 and high enriched uranium containing 90% or more of the isotope U-235.
weapon-useable material	Fissile or fissionable material suitable for use in the fission energy element of a nuclear weapon or other nuclear explosive device, including all combinations of plutonium isotopes except those containing 80% or more of the isotope Pu-238, all high enriched uranium containing 20% or more of the isotopes U-233 or U-235, and certain actinides including Neptunium and Americium.
weight	Relative importance of an attribute.

Acronyms

ABS	Agent-Based Simulation
AHP	Analytical Hierarchy Process
CDF	Cumulative Distribution Function

CCDF	Complementary Cumulative Distribution Function
IAEA	International Atomic Energy Agency (IAEA)
IE	Initiating Event
INFCE	International Fuel Cycle Evaluation
LEMUF	Limit of Error on Materials Unaccounted For
LWR	Light Water Reactor
MAU	Multi-attribute Utility Analysis
MAUD	Multi-attribute Utility Decision
MLD	Master Logic Diagram
MOX	Mixed Oxide
MPC&A	Material Protection, Control, and Accounting
NASAP	Nonproliferation Alternative System Assessment Program
NA-24	Office of Nonproliferation and International Security of NNSA
NFC	Nuclear Fuel Cycle
NNSA	National Nuclear Security Administration
NPAM	Nonproliferation Assessment Methodology
NPT	Nonproliferation Treaty
PRA	Probabilistic Risk Analysis (or Assessment)
PREM	Proliferation Resistance Evaluation Methodology
RIPA	Risk-Informed Proliferation Analysis
SERs	State Evaluation Reports
TOPS	Technological Opportunities to Increase the Resistance of Global Civilian Nuclear Power Systems
TPZS	Two-Person Zero-Sum
UO2	Uranium Oxide
WGU	Weapons Grade Uranium

Appendix C. Multi-Attribute Utility Barrier Analysis

The DOE TOPS Task Force (Ref. 1) developed a set of attributes with which to both define and qualitatively assess proliferation resistance. These attributes became known as the "barriers to proliferation" and were an expansion of a concept developed by the National Academy of Sciences to examine the risk and disposition of excess weapons plutonium (Refs 2-4). Since the TOPS charge was to identify technical approaches to improve proliferation resistance, the TOPS barriers (see Table 8.1) concentrated on attributes that could be directly impacted by the introduction and/or implementation of technical approaches. These barriers do not attempt to capture the non-technical, but very important, aspects of proliferation resistance or risk, such as "political will", "social, economic and military stability", etc.

Brief Description of the TOPS Barriers

There are advantages to building on the National Academy classification scheme rather than inventing a new one. Although the materials and facilities involved here are far more extensive, and the options for proliferation therefore much more varied, that work is applicable to deriving attributes of proliferation resistance of any fuel cycle or component. Attributes are first and easily used qualitatively, but their utility is greatly enhanced if they can be transformed into quantifiable metrics that can then be readily and objectively compared with different systems or subsystems.

Barriers to developing or acquiring a nuclear weapon are not absolute, but are challenges that may be overcome by a combination of technology, engineering skills and time. More effective barriers require greater resources and effort to overcome than lower, less effective barriers. Material qualities, technical impediments, and institutional arrangements, including the complex of measures known as material protection, control, and accounting (MPC&A) present barriers that make it difficult for proliferants to exploit nuclear systems. These barriers were shown as higher-level base metrics in Chapter 8 (Figure 8.1). The form and significance of the attributes of such barriers vary depending on the specific system under consideration.

Ideally, barriers should be defined so as to be completely independent indicators of proliferation resistance. Dependency may not always be obvious and every effort must be taken to ensure unintended dependencies do not creep into the analysis. An example of potential overlap of barriers is where a chemical process becomes difficult because of a high level of inherent radiation and the operation must be performed remotely. Care must then be taken to ensure that the impact of the radiation barrier is not counted twice. In the case where complete independence is not possible, the dependency must be made explicit and accounted for. In addition, the cumulative effect of barriers is not necessarily linear: the effect of multiple barriers might be greater (or less) than the sum of their individual effects.

There are three classes of barriers, Material barriers that deal with the attractiveness of the material itself, Technical barriers that deal with facilities and processes in the fuel cycle and are directly involved with the containment of material, and Institutional barriers that deal with administrative measures to secure material, facilities and processes and which compensate for weaknesses in the Material and Technical barriers. Material and Technical barriers are considered intrinsic in that they are inherent to technical and related elements of a fuel cycle, and its facilities and equipment.

Institutional barriers are extrinsic to the system and depend on implementation details that are intended to compensate for weaknesses in the intrinsic barriers.

Material barriers are those qualities that make it more difficult to produce a nuclear explosive from a particular fissile or fertile material. They include the isotopic composition of the material (percentage and type), chemical processing required to retrieve or produce a weapons-usable substance, the radiation hazard and signature associated with the material at each step in the civilian system and in any process to generate weapons-usable material, and the detectability and difficulty of movement of the mass and/or bulk of the material.

Technical barriers (not delineated by the National Academy of Sciences -the problem they considered only involved materials themselves) are those associated with the facilities and equipment of the fuel cycle. These barriers make it difficult to gain access to materials or misuse facilities to obtain weapons-usable materials. These technical impediments, can affect the proliferation potential of a system in a number of important ways. For example, access to irradiated fuel in the core of a Light Water Reactor (LWR) is protected by the technological complications inherent in physically opening the pressure vessel and gaining access to the fuel inside. This barrier is inherent in the technology underlying the LWR fuel cycle and is not related to either the physical attributes of the fuel itself or to external institutional issues demanding restricted access to fuel materials. This barrier is one reason that LWR systems are considered by some to be more proliferation-resistant than reactors that can be fueled online.

Other examples are the difficulty and/or time delay associated with potentially modifying or reconfiguring a facility or process to produce weapons-usable material, and material throughput (at least to the extent that processes with low throughputs may be less attractive to proliferants or may offer an increased probability of detection of diversion). It is more likely that a diversion of 1 kg of material will be noticed from a process treating 100 kg/day than from one treating 1,000 kg/day. Overcoming these facility barriers requires specialized skills, tools, materials, and supplies.

Institutional barriers are those administrative practices, controls, and arrangements designed to protect against various threats, thereby compensating in whole or in part for weaknesses of intrinsic material or technical barriers, or for the potential of other aspects of the nuclear energy system to contribute to proliferation. These include international safeguards, the complex of measures known collectively as MPC&A, and other measures such as controls over sensitive information, export controls, and the like. The work done by the National Academy of Sciences defines the attributes for the institutional barriers.

Intrinsic barriers can have a significant impact on the effectiveness of safeguards and on physical protection, security, and accountability. Thus, those extrinsic institutional barriers that can be affected by material and technology choices are part of the overall framework, recognizing that requirements for specific extrinsic barriers can only be realistically defined following an evaluation of the effectiveness of the intrinsic barriers.

Evaluation of Barriers as a Method for Assessment

The TOPS barriers were developed to represent a reasonably complete set of independent attributes to describe and qualitatively assess proliferation resistance and the potential effectiveness of proliferation resistant technologies. As such, the TOPS barriers can be seen as an appropriate set of attributes for use in a MAU analysis.

Use of barriers to proliferation in a MAU analysis requires a series of steps:

1) A utility function (See Section 9.1) for each of the barriers must be developed.
2) A set of representative threats for analysis must be selected
3) The barriers utility functions must be evaluated for each considered technology/fuel cycle at each step in the fuel cycle as appropriate.
4) The weights of the various barriers (their quantitative importance to proliferation resistance) must be established for each defined threat.
5) The weights for each defined threat must be combined with the utility functions for each technology/fuel cycle in such a way as to allow a realistic evaluation of the proliferation resistance at each step in the fuel cycle.

Barrier analysis is an approach in success space because it directly addresses the barriers that need to be in place to thwart proliferation. It characterizes the barriers by utility functions

$$U_1 (A), U_2 (B), \ldots\ldots U_n (X),$$

where A,B, ….X are a series of n barriers. U provides figures of merit for each barrier n. The utility functions are developed through expert elicitation. The overall system metric M is determined by weighting each $U_1, U_2 \ldots\ldots U_n$ and summing for the specific threat as in

$$M = w_1 U_1 + w_2 U_2 + \ldots\ldots w_n U_n$$

Here w_n are weights for each barrier to a specific threat and are determined by expert elicitation. Metrics may be summed over each class of barrier (i.e., Material, Technical or Institutional, or for all barriers to obtain the overall proliferation resistance metric). This latter is the system utility function described in Section 9.1.

This process is complicated by the large number of technical options and fuel cycle steps, combined with the number of possible threats and threat agents. The process can be simplified due to several factors:

1) The utility functions for each of the barriers can be considered independent of the threat. The value of the utility function then depends only on technical considerations (e.g., the isotopic composition of the material) while the weight of the barrier depends on the threat (e.g., does the proliferant have the capability to enrich material?).

2) It is intuitively obvious that some barriers will be more important than others and also that some will be more important in discriminating between systems. To this end a qualitative comparison of the barriers for a number of fuel cycle options was performed as an outgrowth of the TOPS effort (Ref. 1). Review of that comparison shows that effective discrimination among the various technologies for the threat considered occurs only for a relatively few barriers and at a relatively few elements in the fuel cycle. This

suggests that considerable effort in determining metrics can be saved by prioritization of the barriers and focusing on those that are most important and/or differentiate among various options.

In addition to mining and milling and other processes through transport at the beginning of the cycle, three barriers offer little or no discrimination among the fuel cycle options considered, which include the once-trough LWR cycle in common use today. These barriers are Facility Detectability, Skills, Knowledge and Expertise, and Time. This is not to say that these barriers are unimportant, but that they do not allow much differentiation among fuel cycle systems.

The most discrimination was observed for the Isotopic and Mass/bulk barriers. Considerable discrimination among fuel cycle options was also observed for the Facility Accessibility and Available Mass barriers, as well as some limited discrimination observed for the Facility Attractiveness barrier.

Putting these principles and observations to use in an MAU Barrier analysis, the following approach will facilitate integration and roll-up to high-level measures (e.g., Figure 8.1).

- Review existing studies to determine which barriers show most discrimination between fuel cycle systems.
- Interrogate[5] stakeholders and experts to review barriers and make modifications as appropriate. Also determine current wisdom on which are the appropriate threats.
- Develop prototype MAU functions and then interrogate specialists to refine these utility functions for each barrier.
- Quantify the barriers for each selected fuel cycle system concept using the utility functions established above in preparation for weighting implementation below.
- Expert elicitation for weighting barriers.
- Integrate barriers with weights for overall metrics.

Stakeholders and specialists would use pairwise comparisons (see Analytical Hierarchy Process, Section 9.4) to establish utility functions and weights and if a web-based system is used, integrated weights are immediately available to all participants. This would speed the discussion of variations in thinking among stakeholders and experts. Furthermore, with the barriers (i.e., utility functions) already quantified for the steps in the fuel cycles of interest, the preliminary analysis of the various systems against the various threats can also be made immediately available and further discussed among stakeholders.

Benefits of MAU Barrier Analysis Approach

MAU Barriers Analysis provides a straightforward method for assessing and quantifying the overall proliferation resistance of a wide variety of fuel cycle systems and options. It provides a convenient mechanism to assist in identifying the strengths and weaknesses of different fuel cycle systems. It also provides an approach for ranking of the various options. This approach allows for incorporation of non-technical components, enumerates in depth the overall defense

[5] Expert elicitation accomplished in either workshop or web-based virtual mode.

that a nuclear system possesses, and does not require a highly developed level of detail to determine the effectiveness of the barriers. Elucidation of attributes using the framework described helps to identify and then address relevant issues.

Once developed, the MAU Barrier Analysis can be implemented quite easily, and lends itself to simple adaptation to a computer application. Determination of the utility functions for a given fuel-cycle system or option is a relatively straightforward technical assessment that is performed independent of consideration of the threat. The development of the weights for the various threats is the most subjective aspect of the analysis. Different interests and viewpoints will likely reflect themselves in different weightings of the various barriers for various threats.

Even if the results of the weight determination demonstrate substantial differences among stakeholders in the weights, the overall assessment will likely reveal actions that all agree will improve proliferation resistance. This is not to suggest that all will agree that any technology improves proliferation resistance "enough", but there will likely be some technologies or actions that, independent of viewpoint, will be viewed as enhancing the proliferation resistance of the system.

It is also possible that careful review of the results, with attention to the scores of individual barriers and/or individual elements of the fuel cycle will help reveal where the most significant improvements in proliferation resistance occur, as well as where barriers and/or elements of the fuel cycle are essentially insensitive to significant improvements in technology. Such observations will give valuable insight into both defining better technical options, as well as to helping suggest areas for prioritizing R&D.

Finally, a detailed assessment of the barriers to proliferation can serve as an important input into a scenario analysis, as discussed in Section 9.2.1 and Appendix D.

Limitations of the MAU Barrier Analysis Approach

The barrier approach is not well suited to examination of the specific threats or pathways a proliferant may choose to exploit a particular fuel cycle system or element. It is defensive in nature. Although detailed phenomenological analysis must be pursued using other methods, the barriers approach can help identify where attention should be initially focused by revealing where (in the various fuel cycle systems and options) proliferation resistance appears low.

The accumulation of the weighted barriers for a single step in the fuel cycle appears straightforward, but it is not obvious how to compare and combine the resulting scores among the various steps of the fuel cycle in a balanced manner. Thus, the barriers approach in its TOPS configuration appears best suited to defining a "proliferation resistance vector" for a given fuel cycle as opposed to an individual "proliferation resistance score". The limiting (i.e., the least proliferation resistant) step or steps of the fuel cycle is an overall indicator.

MAU Barrier Analysis is recognized as being highly subjective because with the lack of historical data one must rely on expert opinion. Nevertheless, when applied to assessment of proliferation from a nuclear fuel cycle there are firm technical underpinnings to this application of the method. The expert opinions reflect the consensus of the stakeholders rather than lengthy experience with proliferation within a system. Proliferation resistance has both technical underpinnings (such as the utility of materials for weapons applications) and subjective elements (such as assessments of how easily particular proliferants can overcome the various barriers). This approach is capable of capturing both aspects. The technical underpinning of proliferation resistance is found in the utility functions describing each of the barriers. The more subjective elements are reflected in the weights assigned to the barriers.

Further work to devise a rigorous and reproducible methodology to accumulate weighted barriers in terms of various threats needs to be undertaken.

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Appendix D. The Risk-Informed Proliferation Analysis Methodology

Risk-Informed Proliferation Analysis (RIPA) attempts to address the proliferation issue by examining the proliferation act, as a project that can be optimized in terms of the proliferant's goals. It is theoretically possible to model this proliferation project from motivation to deployment. However, due to the difficulty of modeling motivation, the RIPA methodology has limited the problem, at this time, by defining the proliferant's intent (or goals) and identifying the measures key to achieving deployment.

The goal of the RIPA analysis is to provide a quantifiable measure of the risk of proliferation for a particular nuclear technology. Though quantifiable measures may not always be possible, the methodology strives to push the subjective inputs to the lowest levels of the analysis and the greatest level of detail where the uncertainty is believed to be better understood.

The following discussion has been taken from reference to provide a description of the RIPA methodology, which includes: (1) influence diagrams and resulting proliferation pathways, (2) proliferation scenarios, and (3) the proliferation measures. The RIPA methodology uses techniques derived from PRA to identify and prioritize pathways that a potential proliferant might exploit while developing nuclear weapons capabilities either from existing nuclear materials or from basic raw materials. These pathways vary according to the goals and capabilities of a postulated proliferation threat. The methodology considers factors such as the estimated cost of a pathway (evaluated against a proliferant's resources), the probability of non-detection of the proliferant on the pathway (evaluated against a proliferant's tolerance for "getting caught"), the materials throughput of the process (evaluated against a proliferant's weapon development goals and schedule), and the pathway's likelihood of achieving technical success (evaluated against a proliferant's tolerance of failing). Proliferant motivation leading to intent and the effects of interdiction are factors that have not yet been developed.

Influence Diagrams and Proliferation Pathways

The RIPA methodology begins by using deductive reasoning similar to that used for fault tree analysis to construct an influence diagram that encompasses all major activities proliferants might use to accomplish their objectives. The influence diagram represents proliferation as a network of steps and paths. The network consists of interconnecting steps that represent a set of pathways to proliferation. These influence diagrams vary depending on the proliferant objectives being analyzed. The first step in the RIPA methodology is to establish the logical relationships among the potential proliferation tasks.

Influence diagrams represent the tasks and their relationships. An influence diagram can be constructed using either inductive (cause → effect) or deductive (effect → cause) reasoning or a combination of the two. To use inductive reasoning, a list of tasks that might be involved in proliferation are assembled and then arranged in an influence diagram using arcs to denote their interdependencies. Inductive reasoning is most valuable when an analyst wants to determine the consequences of particular initial events as they relate to proliferation.

Influence diagrams present the steps (nodes) that must be followed in order to succeed in building a nuclear weapon. For example, in an analysis designed to assess the effectiveness of a particular technological barrier, the influence diagram would model the major steps, tactics, and pathways available to a proliferant to defeat that barrier. For an analysis designed to assess the nuclear weapons proliferation risk posed by a potential country, the influence diagram would model the important tasks involved (including the aforementioned barrier) in developing and producing one nuclear weapon or a serial weapons production capability.

It is convenient to construct the influence diagram with the nodes as separate facilities. This enables easier application of security measures. However, each node can be further detailed with another influence diagram to identify specific technologies and materials within the node. Again this more detailed view of the plant describes the steps that must be taken to obtain the material or technology. At this level, detailed analyses can be made of barrier performance and safeguards effectiveness.

The nodes in the influence diagram represent the tasks to be accomplished for a proliferant to have success, while the arcs in the diagram represent the interdependence among those tasks. Parallel tasks represent "or" logic conditions and serial tasks represent "and" conditions. OR conditions are frequently encountered when multiple technological options exist for each task. AND conditions indicate tasks that must be performed for successful conclusion of the pathway. The proliferant need not accomplish *all* tasks in the influence diagram in order to be successful. The conditional logic built into the model through AND and OR conditions determines the particular combinations of nodes that must be successfully completed in order for the proliferation activity to be successful. Thus, the influence diagram embodies a number of potential proliferation pathways, and shows the interrelationships between the various tasks and pathways. An individual pathway is derived from the logic embodied in the influence diagram model.

The RIPA methodology relies on influence diagrams to visualize the proliferation project. At the highest level, the influence diagram represents the primary logic from which all subsequence influence diagrams are developed. An example is shown in Figure D-1. Each of the nodes of the diagram can be further described as either a chain of events or options as shown in Figure D-2. The lines connecting the nodes represent interfaces through which information and material are exchanged between the nodes.

At this level, it is possible to break the analysis apart into modules for further analysis and to focus on specific issues. For example, the node of fissionable material can be broken out as shown in Figure D-3.

With the previous level of detail, it is convenient to focus on each of the aspects independently. For example, weapons-grade uranium (WGU) can be broken out as shown in Figure D-4.

The RIPA methodology has, to this point, generally used relatively high-level tasks in the influence diagram model. Examples include "Enrichment of UF_6 to weapons grade using gas centrifuge technology" and "Chemical extraction of ^{239}Pu from spent nuclear fuel." Given the high-level nature of these tasks, it is clear that each node in the influence diagram could potentially be accomplished in a variety of ways. These options for completing the node's task have a variety of technological, programmatic, cost, schedule, throughput, and observability characteristics, some of which might be more appealing to a terrorist group, while others might appeal more to a nation state. In order to ensure that the RIPA model is useful for the assessment of a variety of potential proliferants, a set of options is developed for each node that represents the entire spectrum of possible ways to accomplish the node task. The possibilities should cover the range of technologies; costs, capabilities, and throughputs (material flow rates) that enable a proliferant to successfully accomplish the task. These options, which are developed through a combination of expert judgment and engineering analysis, are ultimately used in the computation of metrics for the scenarios that are derived from the proliferation pathways. Ideally, the characterization is sub-divided until it is at a level of detail that a peer-reviewed engineering analysis is adequate to establish metric values with uncertainties.

Proliferation Scenarios

Once the influence diagram is completed, it can be solved using techniques similar to those used in event tree analysis to obtain the complete set of possible proliferation pathways that are represented in the diagram. Each pathway traverses one or more nodes, which represent tasks that must be accomplished or conditions that must exist if the pathway is to be realized. The method by which each of the tasks is performed creates a proliferation scenario.

A proliferation scenario is developed when a proliferation threat is defined and applied to influence diagram to identify one unique pathway. The uniqueness of the pathway is formed by selecting one condition from every OR condition and coupling it with every node in the AND conditions. Each task has been modeled in terms of the proliferation measures valued for that specific task. Each proliferation scenario can then be characterized in terms of the proliferation measures by performing the appropriate mathematics to combine the individual task measures. Finally, each proliferation scenario is then characterized by a final set of measures conditioned by the threat definition.

The proliferation pathways described previously represent the general ways that a proliferant might accomplish the proliferation objective. This is demonstrated in Figure D-5. A proliferation scenario embodies a specific option for accomplishing each task or node in the proliferation pathway. Because the options for accomplishing each such task were developed within pathways in the influence diagram, one option can be selected from each task or condition (node) to obtain one credible proliferation scenario that implements the given pathway. Thus, there can be a large number of possible proliferation scenarios for each proliferation pathway.

Scenarios can be viewed as potential "project plans" to be used by proliferants to attain a desired goal. On a smaller scale, scenarios can be viewed as a list of the steps required to accomplish part of a nuclear proliferation objective, such as the steps required to steal spent fuel from a reactor site. Regardless of the scale, a scenario is, basically, a project to be carried out that the implementer believes has a reasonable likelihood of success. Thus, some of the metrics defined for proliferation scenarios are similar to those used in project management – cost, schedule, and successful completion of goals.

The successful completion of goals is somewhat subtler in its application to nuclear proliferation assessment and is more easily defined in the context of scenarios. For now, it is defined as the likelihood that a scenario has been successfully completed. Another metric to consider in nuclear proliferation, which is not of concern to most projects, is that of detection. The detection aversion metric is defined as the likelihood that a scenario will not be detected and responded to in such a way that the response results in a catastrophic disruption to the program (e.g., air strikes). There are subtleties in the definition of detection aversion – it is NOT defined as the likelihood that a project will be detected BUT as the likelihood that a project will not be detected and interdiction as a result of a catastrophic intervention. The four metrics that have been defined as the key elements of nuclear proliferation scenarios are: cost, schedule, likelihood of success, and likelihood of detection.

Proliferation Measures

Proliferation measures are the basic values that characterize the proliferation scenario and provide a basis of comparison between scenarios. The RIPA methodology has identified four proliferation measures that can be used to characterize a proliferation scenario:

1. Production Time – Period of time required to achieve the goal
2. Cost – Monetary resources required to achieve the goal
3. Probability of Non-Detection – the cumulative conditional probability that a proliferation activity will not be detected in a scenario.
4. Probability of Success – the cumulative conditional probability that given all acquired technology and material that a proliferant can achieve the desired goal.

When a scenario is calculated, these measures are accumulated along every step of the pathway. Comparisons are made between the scenarios on the basis of these measures. The analyst should determine threshold values for these measures to streamline the analysis and eliminate scenarios that are not important.

Once the pathways (scenarios) have been defined, the next step is the development of a representative list of options that might be available for implementing the events, conditions, or tasks represented by each node (step) in the influence diagram. A key attribute of the RIPA methodology is the ability to select options for multiple steps within the influence diagram and to aggregate a proliferation scenario based on those options. In order for the method to be successful, it must be able to aggregate the proliferation scenario's metrics, such as the total cost, duration, likelihood of success, and likelihood of detection. Thus, the entries in the option list tables must be structured in such a way that computation of these metrics is possible.

Each step in the influence diagram could potentially be accomplished using a number of options, each with a specific set of metrics possibilities. Choosing viable options in the metrics table develops a multitude of viable proliferation scenarios. This results in numerous pathways with a unique set of tasks to accomplish a proliferant's goal. Once all the potential proliferation scenarios have been identified, the next step is to combine the metrics for each task in a pathway to obtain a risk evaluation. The most viable pathways can be mapped to the proliferant's available resources. Unfortunately, this requires combinatorial analysis, which is notorious for its computational intensity.

As part of the development of RIPA, efficient truncation techniques have been identified that allow large portions of the combinatorial search space to be neglected because the scenarios they represent are incompatible with the proliferant's objectives. These techniques allow elimination of portions of the search space as the tasks within a pathway exceed the proliferant's available capital or time or become too detectable or unlikely to result in successful attainment of the proliferant's goals. Using these techniques can accelerate computations by orders of magnitude. Other nonlinear optimization computational techniques, such as genetic optimization and ε-optimal shortest path methods, may also provide opportunities to improve the method's computational performance.

Once a scenario is defined, its characteristics can be computed by combining the characteristics of the underlying step options. Table D.1 has provided the combination of steps that are required to make up a proliferation pathway. Using the proliferant's objectives (e.g., desired number of weapons and production rate), the cost and time required to accomplish those objectives can be determined based on the options defined in the scenario. Also possible are estimates of the likelihood that the scenario can be accomplished successfully and without being detected (if a covert program is required). This process can be repeated until all combinations of options have been selected to form scenarios either for a selected proliferation pathway or for all such pathways.

Given the specific details of a single proliferation scenario (as defined by the specific options selected to embody the various nodes in the proliferation pathway), important information about the scenario can be inferred, such as the types of facilities that would need to be constructed, the production rates of those facilities, the research tasks to be accomplished, and other characteristics. From this information, it is relatively easy to estimate a wide variety of project management characteristics for the scenario. Because the development of nuclear weapons is really a proliferant's "project", a major part of the proliferant's value and utility structure will be based on project management-related metrics, such as total cost, project duration, and likelihood of ultimate success.

The two most straightforward metrics to compute for a particular proliferation scenario are its cost and schedule. For a multi-step proliferation project, a first-order approximation of the cost (represented by $ and t, respectively, in Table A-1) is obtained by simply summing the costs over all steps. Schedule can be approximated based on required planning and construction times, combined with the time required to produce enough product to meet the proliferant's objectives (based on the throughput for that step). These can be readily computed by automated algorithms that can be embedded in scenario generation software.

Table D.1. Example Step Options.

Path steps $S_1 \rightarrow S_2 \rightarrow S_3 \rightarrow S_4$

Each Option can have sub-options

Step 1	Step 2	Step 3	Step 4
$, P_D, t, P_S	$, P_D, t, P_S	$, P_D, t, P_S	$, P_D, t, P_S
Option 1	Option 1	Option 1	Option 1
Option 2	Option 2	Option 2	Option 2
Option 3	Option 3	Option 3	Option 3
.	.	.	.
.	.	.	.
Option n	Option m	Option o	Option p

Development of the likelihood of detection (P_D in Table D-1) for each scenario (or even each step in the scenario) is somewhat more difficult. It is possible to look at the various steps in the scenario with respect to their observable characteristics (e.g., size, personnel requirements, specialized technologies, effluents) and compare those characteristics with the observation capabilities of modern reconnaissance and intelligence techniques. However, a more simplistic "relative observability" approach may yield adequate results by allowing the analyst to compare observability on a common basis between various scenarios and step options. The quantification of observability for an individual scenario step would likely be obtained via expert judgment. Estimation of a combined observability over an entire scenario is straightforward if one assumes that discovery of any *one* step in the scenario means that the proliferation activity has been effectively discovered (the *response* to discovered proliferation activities is fundamentally a political process, and is subject to vagaries that are beyond the scope of engineering analysis).

Perhaps the most difficult metric to estimate for any scenario is its likelihood of success (P_S in Table D-1). The goal of this metric is to ascertain the "degree of difficulty" for each scenario, with more difficult scenarios and technologies having a lower likelihood of success. This metric could also account for a proliferant's indigenous natural resources, technical talent and nuclear infrastructure. It may be necessary to use a simplistic "relative success likelihood" that assesses the relative likelihood of success among the various scenarios rather than computing an absolute likelihood for each scenario (which would likely be much more difficult to defend). If the goal is simply to compare the characteristics of various scenarios, this approach will likely produce adequate results. The quantification of success likelihood for an individual scenario step would likely be obtained via expert judgment. Estimation of the combined success likelihood over an entire scenario is straightforward if the assumption is made that technical failure at any *one* step in the proliferation activity means that *this* proliferation scenario is prevented. However, it does not preclude all proliferation as other scenarios and pathways may exist for which this particular step would not be required.

As seen above, the RIPA methodology does rely on expert judgment, but poses issues to the experts in a more "bite size" form than traditional proliferation studies using MAU analysis. This enables experts to more thoroughly and confidently assess each issue than was previously possible. Estimation of uncertainty is also possible at appropriately low levels where details are available or can be easily assumed. Because expert judgment is gathered for specific activities rather than entire proliferation pathways, it can be reused for multiple analyses without going back to the experts, thus ensuring consistency between analyses.

The result of the analysis is then a set of proliferation metrics for each scenario with the calculation bounds of the problem. These data can then be presented to the policy maker for further analysis.

Benefits of the RIPA Methodology

The current state of the RIPA methodology provides the following benefits:

1. Quantified tangible measures.
2. Visualization of the physical relationships in and across the nuclear fuel cycle.
3. Models the proliferation pathways from proliferant intent to weapon deployment.
4. Compartmentalized model construction allows for reutilization of component models in other analyses.
5. Provides reproducible and reviewable results for the decision maker given the same input.

Limitations of the RIPA Methodology

The current state of the RIPA methodology has the following limitations:

1. The methodology is untested except for a few simple examples.
2. While the logic appears to be applicable, a study is required to determine if the resulting measures are meaningful to the decision maker and allow effective comparison of options.
3. The level of effort required for developing meaningful quantitative values is uncertain. The quality of these measures is dependent upon the level of detailed analysis.
4. Currently lacks a computational tool to facilitate calculations.

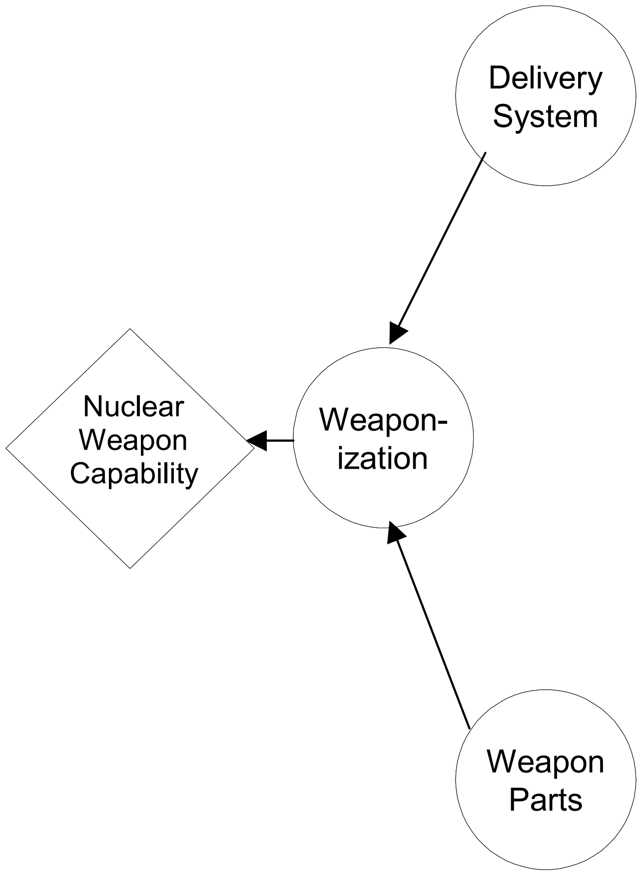

Figure D-1. Top-Level Influence Diagram For Production Of Nuclear Weapons.

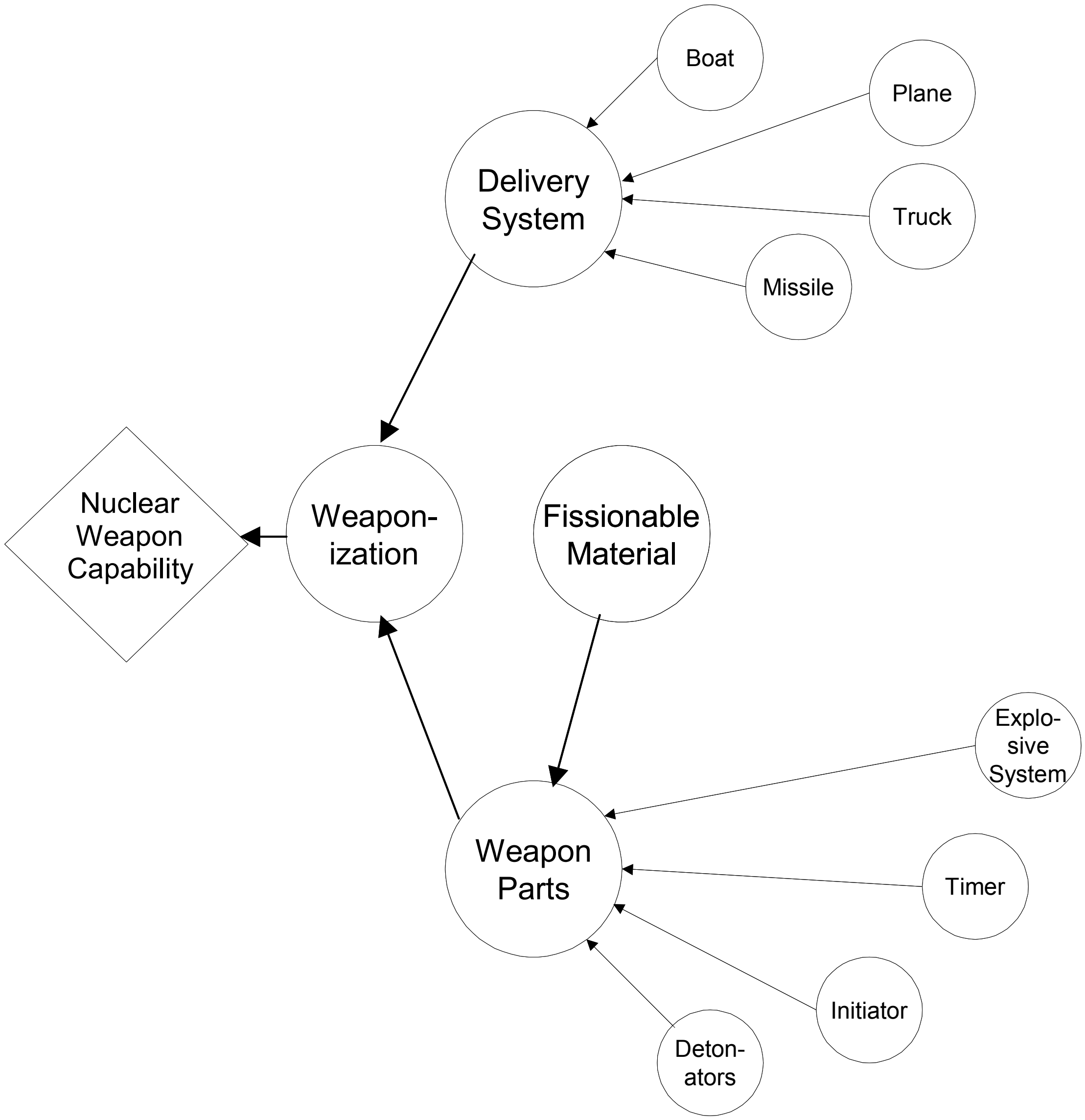

Figure D-2. Example of a Level 2 Influence Diagram of a Nuclear Weapons "Construction Project."

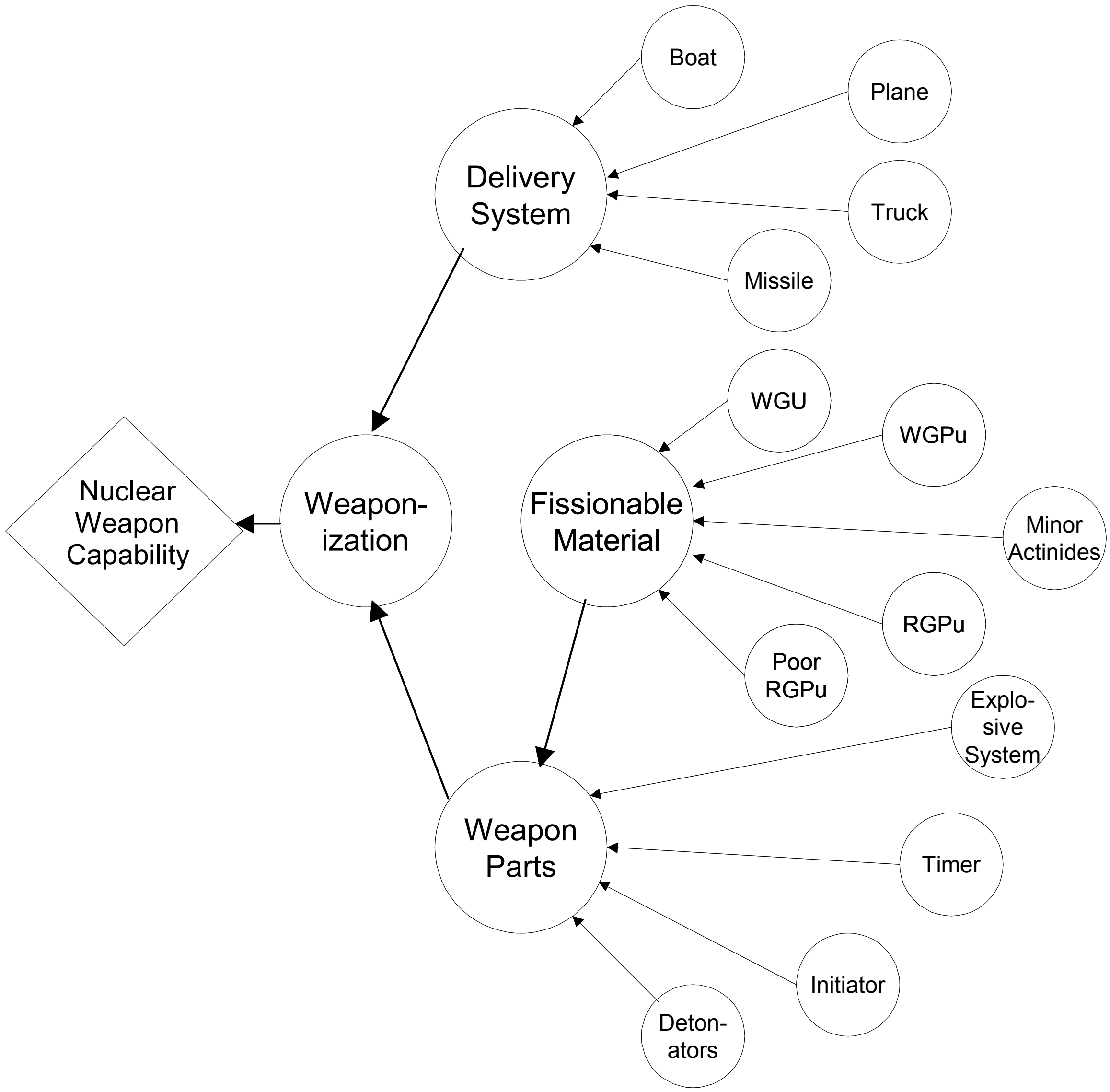

Figure D-3. Example Level 3 Influence Diagram.

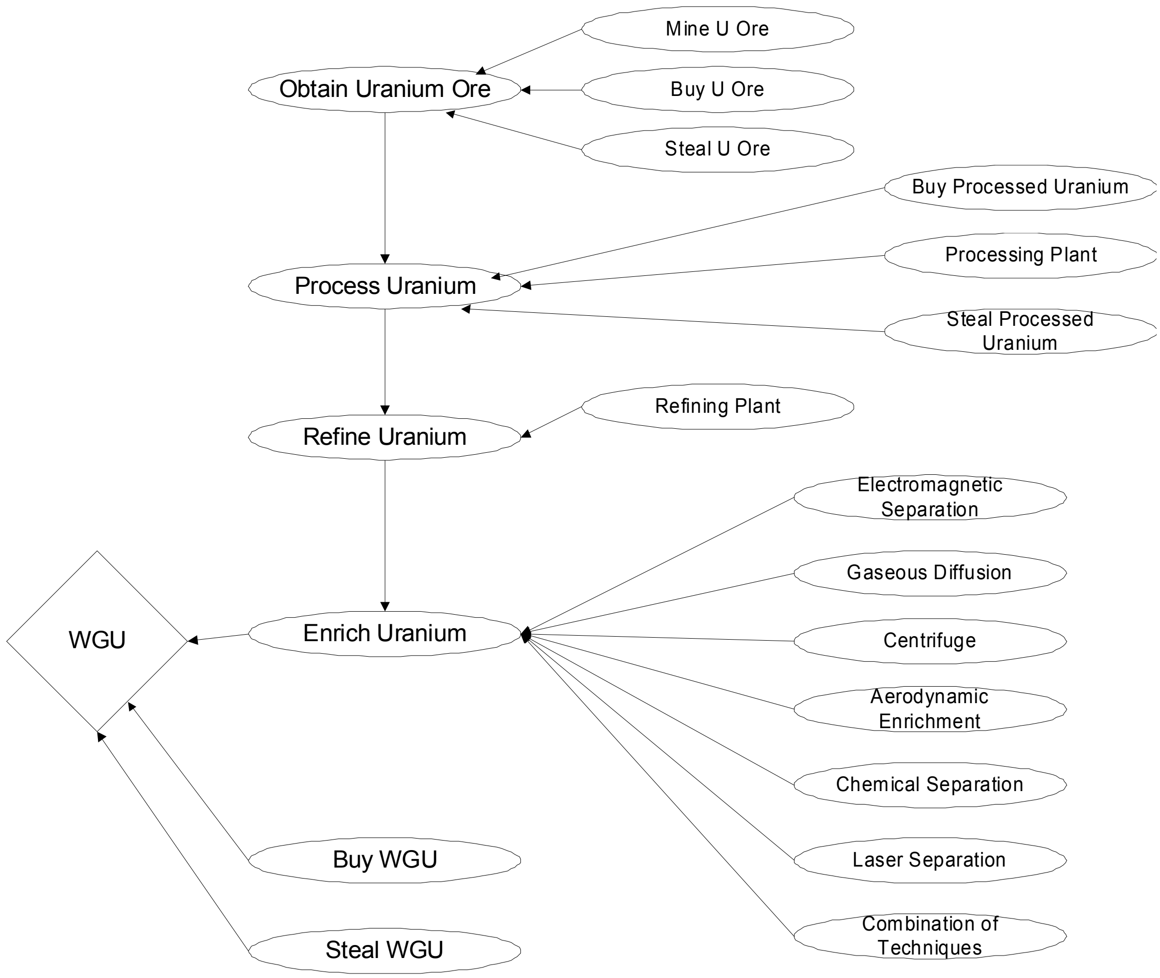

Figure D-4. Influence Diagram for Obtaining Weapons-Grade Materials (Pathway A)

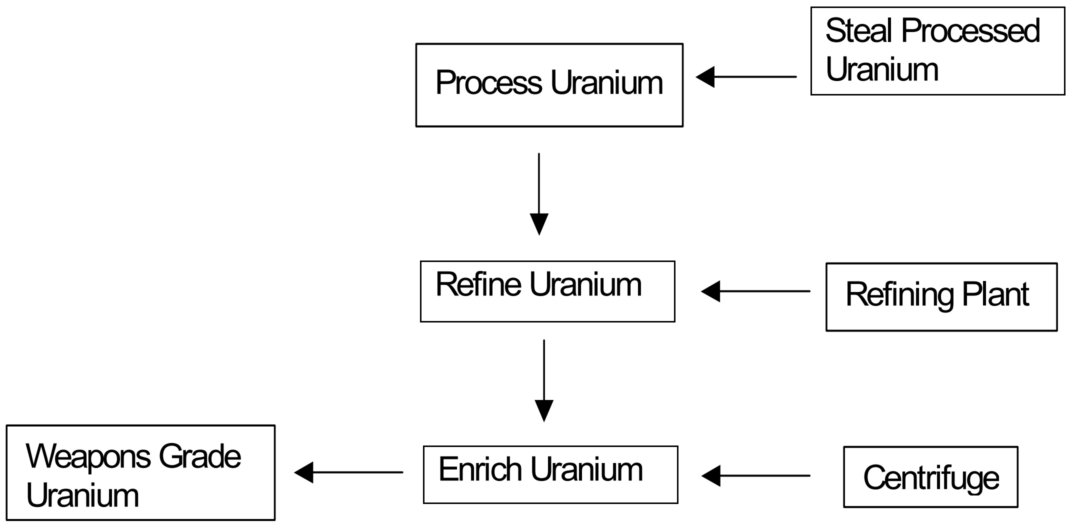

Figure D-5. Example of a Proliferation Scenario.

Appendix E. Results of Peer Review

Introduction

A structured peer review process was established to help ensure the quality of this document. A procedure (Attachment E-1) for performing a documented peer review was prepared and a team (Table E-1) qualified (Attachment E-2) to perform the peer review selected.

Table E-1. Peer Reviewers

Peer Reviewer	Organization
Dennis Bley	Buttonwood Consulting, Inc.
Burrus Carnahan	Department of State
Michael Golay	MIT
Dave Hill	ORNL
Michael Modro	ANL
Per Peterson	UC
Tom Shea	IAEA

Peer Reviewers were instructed to review the entire document with special emphasis on their areas of expertise, to record their comments on a Peer Review Record, and to forward electronic copies of the completed Peer Review Records (cf. Attachment E-1) to the Peer Review Manager, Michael D. Zentner of PNNL. The Peer Review Manager prepared an inclusive database of reviewer's comments for resolution.

Comment discussion

Approximately 220 comments (some comments addressed several issues) were received. About half were "philosophical" requiring no change to the document. A quarter of the comments were grammatical or editorial. A quarter either added information or suggested revisions to the document.

The "philosophical" comments addressed some important issues and will be summarized below.

The reviewers recognized the document's value. For example:

i. "The document provides an authoritative survey and description of the state-of-the-art of assessment methodologies that are potentially applicable to different types of proliferation analyses. The document provides an excellent starting point for the Gen IV consideration of proliferation resistance and physical protection."

ii. "…provides an excellent aggregation of available information on nonproliferation assessments, an excellent discussion of the distinction between proliferation "risk" and "resistance," as well as new and original work on how proliferation resistance assessments can be performed."

iii. "The Report's main strength is presentation of a large set of analytic methods, which might be used for nonproliferation analysis. This presentation provides a foundation from which the Program for the Development of Non-Proliferation Assessment Methodology may work."

iv. "An additional advantage of developing systematic methods for performing nonproliferation assessments can be mentioned. As the methods become more formalized, it will also become easier to document and catalog and analysis in such a way that a larger body of assessment information is generated. These reports will have common formats and organization of information. In the longer term, as with safety assessment, this growing body of knowledge will enable increasingly sophisticated assessments."

However, a number of issues and possible areas of improvement in the report were identified and are summarized below.

An important issue was the concept that the document presents *guidelines* for performing proliferation assessments. Several reviewers didn't agree. For example:

i. "The title of the document does not accurately reflect its contents. It presents thoughts on the methodological aspects of assessments, and on the relative merits of the candidate techniques considered, but 'guidelines' suggest specific criteria and procedures to be employed."

ii. "The Guidelines are a good overview document, however they provide little help and methods on how to judge which of all the tools, methods and information are best suitable for specific application."

iii. "The document … failed to truly provide guidelines. It is more an encyclopedia of methods."

Another issue concerning reviewers was the differentiation between the "attribute analysis" and "scenario analysis" methodologies. Many reviewers thought that the two approaches could be profitably combined. For example:

i. "Section 6 could be enriched by a discussion of combination of attribute analysis and scenario analysis as potential approach. It seems that the combination of these two methods will have the most utility in assessments."

ii. "The conclusions could be stronger by indicating that of the methodologies that exist today, a combination of attribute and scenario methods appear to be the most useful."

iii. "The overall impression of competing methods disturbs me. Despite statements that the methods are complementary and that an integrated methodology may be possible, the overall impression is one of competition among methods. … The methods are really not in competition; they cannot all solve the entire problem; each offers advantages for parts of the overall problem and, given the requirements of each specific application, the best (in terms of cost, rigor, fit to the issue, ease of use, accuracy of results, etc.) one for the particular situation can be selected."

iv. "The NPAM document … suffers from not being able to agree upon the integrated methodology that appears best suited for addressing … (potential) applications. It often seems more in the nature of promotional arguments being put forward by the advocates of the individual methods, of the "methodologists" driving the assessments, rather than vice-versa."

v. "The hierarchy of methods seems to suggest that certain types of assessments would best be carried out according to the methods suggested, but the guidelines do not specify any criteria for selection, nor any consideration of transitioning from one technique to another, nor any means to resolve conflicting results."

Several of the reviewers were concerned about how the document would be used. A general opinion was that the document was "too academic". For instance:

i. "The study approaches the subject by asking experts in the various methodologies to describe how the various techniques could be applied to this specific subject. It thus appears long on the side of the technologies involved, but short in the sense of assessment needs of potential users. … As a result, the study appears more academic than practical in nature."

ii. "NPAM risks being another, albeit, excellent, academic treatise that only academics and near-to academics will be inclined to learn and use. While well suited to answer the TOPS call for improved methods for proliferation resistance in nuclear fuel systems on the ten years and over horizon, foreign policy decisions addressing tactical issues take place on a time line that appears to exclude any significant application of the NPAM discipline, and individual analysts are more inclined to rely on past experience for their methodology. In retrospect, would the DPRK/KEDO policy have had a different look if the NPAM had been applied to the problem?"

Reviewers wanted to ensure that approaches from countries or organizations were included:

i. "The approach adopted does not appear to take sufficient account of the proliferation-related standards and metrics already developed and accepted in conjunction with the IAEA safeguards system. …To the extent that accepted standards and metrics are not integrated into all appropriate aspects of the study, we stand in danger of reinventing the proverbial wheel"

Finally, reviewers wanted to know what the next step would be and how the methodologies would be used:

i. "It is important that the methods be field-tested and guidelines established for the applicability in different cases (e.g., is one method more suitable for helping understand how to build PR into a facility or technology and internal use, and another in assessing an existing facility on technology)."

Comment resolution

After the comments were collected and entered into the database, the Task Manager with the assistance of the Peer Review Manager prepared proposed resolutions for each comment whether philosophical grammatical or editorial. The proposed resolutions were documented in the Peer Review Records.

The completed Peer Review Records with the proposed comment resolutions were then distributed to the NPAM Working Group for review.

After reviewing and incorporating proposed changes by the NPAM Working Group members, the revised Peer Review Records were approved by the Task Manager and the document was modified accordingly.

Final Document Approval

After the document was modified, it was sent to a technical editor and then to NA-241 for final approval.

Attachment E-1

"Guidelines for the Performance of Nonproliferation Assessments"

Peer Review Procedure

1.0 INTRODUCTION

This document describes the procedure for performing a documented peer review of "Guidelines for the Performance of Nonproliferation Assessments".

2.0 RESPONSIBLITIES

Personnel with responsibilities for implementing this procedure are:

- Task Manager responsible for approval of document (R.S. Denning)
- Peer Review Manager (M.D. Zentner)
- NNSA Project Manager (S. McGuire)
- Peer Reviewers
- NPAM Working Group

3. PROCEDURE

Copies of Attachment A: Peer Review Checklist; Attachment B: Peer Reviewer Qualifications; and Attachment C: Peer Review Record (PRR), of this procedure shall be kept as a record of the review.

3.1 Review Performance

The review process shall be documented according to Attachment A.

Reviewers' qualifications shall be documented per Attachment B; a current resume, which addresses the same requirements, may be used.

The Peer Reviewers shall be provided with a statement of the scope, objectives and schedule for the peer review. They shall also be provided with a copy of the report and procedures for its review.

Peer Reviewers shall review the entire document with special emphasis on their areas of expertise, record their comments on a Peer Review Record, and forward electronic copies of the completed Peer Review Records to the Peer Review Manager. The Peer Review Manager will prepare a database of reviewer's comments for resolution.

3.2 Comment Resolution

The Peer Review Manager, with the assistance of the Task Manager and other appropriate Working Group authors, shall determine a proposed resolution for each comment on the Peer

Review Records. The proposed resolution shall be documented in the column provided on the Peer Review Records adjacent to the subject comment.

The completed Peer Review Records with proposed comment resolutions shall be distributed to the NPAM Working Group for review and proposed modifications.

After incorporating proposed modifications by the NPAM Working Group members, the revised Peer Review Records will be signed by the Task Manager and submitted to the NNSA Project Manager for review and approval.

3.3 Document Revision

The Peer Review Manager shall ensure that the document is revised in accordance with the approved Peer Review Records. The Peer Review Manager shall develop a summary of the peer review process and results to be included as an appendix to the Guidelines document.

4.0 REQUIRED RECORDS

Records that are created as a result of this procedure include:

- Peer Reviewer Qualifications
- Peer Review Checklist
- Peer Review Records and attachments

5.0 ATTACHMENTS

Attachment A - Peer Review Checklist
Attachment B - Peer Reviewer Qualifications
Attachment C - Peer Review Record

ATTACHMENT A

GUIDELINES AND CHECKLIST FOR PEER REVIEW

PEER REVIEW MANAGER SHALL INITIAL AND DATE EACH OF THE FOLLOWING ITEMS WHEN COMPLETED:

Review Step	Initial and Date Completed
1. Complete preparation of review scope, objectives, and schedule	
2. Transmit review scope, objectives, and schedule to reviewers	
3. Transmit draft of "Guidelines for the Performance of Nonproliferation Assessments" to peer reviewers	
4. All reviewer comments have been received and entered into review database	
5. Proposed resolutions submitted to Working Group for review	
6. Revised proposed resolutions submitted to NNSA Project Manager for approval	
7. Document modified based on resolved comments	
8. Peer Review completed and all records to the Task Manager	

The above peer review was completed in accordance with the review purpose, scope, and objectives prepared in Step 1.

Review Manager Signature and Date: ___________________
Task Manager Signature and Date: ___________________

ATTACHMENT B
PEER REVIEWER QUALIFICATIONS
(SAMPLE)

NAME OF REVIEWER:

POSITION:

ORGANIZATION:

NAME

ADDRESS:

PHONE NO:

EDUCATION:

MEMBERSHIP IN RELATED COMMITTEES:

SCIENTIFIC PUBLICATIONS AND PROFESSIONAL LICENSES:

RELATED EXPERIENCE, INCLUDING WORK ON SIMILAR PROJECTS/PROGRAMS (IF APPLICABLE):

THE PERFORMANCE OF NONPROLIFERATION ASSESSMENTS
PEER REVIEW RECORD

Peer Reviewer Name: __________________________ Date Provided: ________________

Comment Number	Page/Para	Comments	Resolution

(1) Reviewers comments shall be entered into a Microsoft Word table as above. An electronic copy of the PRR will be provided to the Peer Review Manager. Comments will be numbered sequentially for each reviewer.
(2) Any additional material used to substantiate comments shall be fully referenced. Copies of references not readily available to Peer Review Manager shall be attached.
(3) The reviewer may indicate whether the comment is editorial, analytical, or addresses logical issues that would affect document conclusions.

Approved:
Date
Task Manager:____

NNSA Project Manager____

Attachment E-2

Reviewer: Dennis C. Bley

Position: Principal, Buttonwood Consulting, Inc.

Education

Ph.D., Massachusetts Institute of Technology, Nuclear Reactor Engineering, 1979
U.S. Navy Nuclear Power School, 1968
B.S.E.E., University of Cincinnati, 1967

Summary of Professional Experience

Dr. Bley has over 30 years experience in nuclear and electrical engineering, reliability and availability analysis, plant and human modeling for risk assessment, decision analysis, expert systems, and technical management. He is recognized for development and application of probabilistic risk assessment (PRA) to a wide range of engineered facilities.

Dr. Bley is co-developer of "A Technique for Human Event Analysis" (ATHEANA) for the U.S. Nuclear Regulatory Commission, a new method for human reliability analysis in support of probabilistic risk analysis (PRA). It is a process that brings together the diverse fields of engineering, PRA, operations, human factors engineering, and behavioral science.

He has been a member of the Evaluation Methodology Group for the Department of Energy Generation IV Reactor Roadmap Project, developing methods and guidance for use by the Technical Working Groups in evaluating proposed next generation nuclear energy systems. He is also a member of the Risk and Safety Crosscut Group and the Proliferation Resistance and Physical Protection methodology group.

Reviewer: Burrus M. Carnahan

Position:

Foreign Affairs Officer, Bureau of Nonproliferation Assessment, U.S. Department of State

Education

Juris Doctor 1969
LL M 1974

Summary of Professional Experience

Dr. Carnahan was previously a Senior Analyst, Weapons Proliferation Analysis Division, of Science Applications International Corp., McLean, VA from 1989 to 2000. He was a consultant for the Commission to Assess the Organization of the Federal Government to Combat the Proliferation of Weapons of Mass Destruction, 1998-1999, a member of the IAEA Experts Committee on Implementation of the Conventions on Notification and Assistance in the Event of A Nuclear Accident, 1987, and a member of the U.S. delegation to the 1985 NPT Review Conference.

Reviewer: Michael Warren Golay

Position:

Professor of Nuclear Engineering, Fission Faculty Chairman, Massachusetts Institute of Technology

Education:

Ph.D., Nuclear Engineering, Cornell University, June 1969
B.S., Mechanical Engineering, University of Florida, April 1964

Summary of Professional Experience:

For over thirty Dr. Golay has been involved in the nuclear industry as a professor and researcher. His special areas of interest are risk and reliability, decision analysis, and nuclear power performance improvement. He has acted as a consultant to the Department of Energy, the Nuclear Regulatory Commission, Sandia National Laboratories, Los Alamos National Laboratory, the Institute for Nuclear Power Operations, Korea Electric Power Research Institute, and Korea Electric Power Corporation, among others. Dr. Golay was a member of the TOPS (Proliferation Resistance) Subcommittee of the Nuclear Energy Research Advisory Committee.

Dr. Golay has written numerous papers on nuclear safety regulation, nuclear reactor thermal hydraulic analysis, nuclear power policy and management, and nuclear power innovation. He is a member of the American Nuclear Society, the American Society of Mechanical Engineers, and is a Fellow of the American Association for the Advancement of Science.

Reviewer: David J. Hill

Position:

Division Director, Nuclear Science and Technology Division, Oak Ridge National Laboratory

Education:

Ph.D., Mathematical Physics, Imperial College of Science and Technology, London University, 1974

M.B.A., University of Chicago, 1995

Summary of Professional Experience

Dr, Hill is an internationally acknowledged expert on nuclear reactor and fuel cycle issues, and has extensive experience in the area of international nuclear matters, working both with the countries of Western Europe and the countries of the Former Soviet Union, especially Russia. He has more than thirty years experience in the nuclear industry, having held positions in both the United States and the United Kingdom.

He is a member of the U.S. Department of Energy Delegation for Negotiations with the Russian Federation on proliferation-resistant fuel cycle technologies in 2000 and on advanced nuclear technologies in 2002. Dr. Hill is Chair of Science Committee's Working Party on Partitioning and Transmutation, a group within the Office of Economic Cooperation and Development's Nuclear Energy Agency. He represents the U.S. government as a member of the Nuclear Safety Advisory Group for the Korean Peninsula Energy Development Organization. Dr. Hill is a member of the Nuclear Energy Research Advisory Committee Task Force on Assessing Technology Opportunities for Proliferation Resistant Systems

Reviewer: S. Michael Modro

Position:

Manager, International Nuclear Safety Programs, Idaho National Engineering and Environmental Laboratory

Education:

M.S., Physics, University of Warsaw, Poland, 1972

Summary of Professional Experience

Mr. Modro has twenty-seven years of experience in research and engineering including twenty five years experience in nuclear reactor safety research and licensing with focus on system analysis, nuclear system analysis codes, and experimentation. He performed in-depth analyses and research related to nuclear power plant behavior during accident conditions. Mr. Modro provided assessment and evaluation of various computer codes used to simulate nuclear plant behavior. He guided development and conduct of experimental programs in support of nuclear safety needs, including small-scale experiments to complex integral nuclear powered system experiments. Mr. Modro did experimental data analyses, evaluation and post-test code analyses.

Reviewer: Per F. Peterson

Position:

Chair - Nuclear Engineering Department, U.C. Berkeley

Education:

Ph.D., University of California, Berkeley, 1988

M.S., Mechanical Engineering, University of California, Berkeley, 1986

B.S., Mechanical Engineering, University of Nevada, Reno, 1982

Summary of Professional Experience

Dr. Petersen, Chair of the Nuclear Engineering Department at U.C. Berkeley, has over twenty years experience as a professor and researcher in nuclear and mechanical engineering. He is a Fellow of the American Nuclear Society, and a member of the American Society of Mechanical Engineers. Dr. Petersen has been editor of the journals *Experimental Heat Transfer,* and the *International Journal of Heat and Mass Transfer*, and is on the Editorial Advisory Board, of *Fusion Science and Technology* and a member of the Board of Directors of Fusion Power Associates. Dr. Petersen is the Chair of the Reactor Safeguards Committee for the Aerotest Radiography and Research Reactor (ARRR). Dr. Peterson's publications include over 60 archival journal articles and 70 peer-reviewed conference proceedings.

Reviewer: Martin B. Sattison

Position:

Manager, Risk, Reliability, and Regulatory Support Department, Bechtel BWXT Idaho

Education:

B. S., Mechanical Engineering, U. S. Naval Academy, 1977.
Graduate, U. S. Navy Nuclear Power School, Orlando, FL, 1978.
Graduate, U. S. Navy Nuclear Power Training Unit - S5G, Idaho Falls, ID, 1978.

Summary of Professional Experience

Mr. Sattison is a mechanical engineer with twenty-five years of professional experience in the nuclear power operation and risk assessment fields, including eighteen years in probabilistic risk assessment (PRA) of commercial nuclear power plants for the utility industry and the U.S. Nuclear Regulatory Commission (NRC), two years in experiment safety assessment for the Advanced Test Reactor and five years in naval nuclear power plant operations, maintenance, and testing. His background includes principal investigator and project manager for several large PRA projects, technical oversight of the NRC's PRA software projects, and technical consultant to the International Atomic Energy Agency and other international organizations.

Reviewer: Thomas E. Shea

Position:

Head, Trilateral Initiative Office, Department of Safeguards, International Atomic Energy Agency, and Consultant, Pacific Northwest National Laboratory

Education:

PhD (Nuclear Science) and MS (Nuclear Engineering), Rensselaer Polytechnic Institute
BSEE (Engineering Physics), University of Massachusetts

Summary of Professional Experience

Dr. Shea was responsible, as the Head of the Trilateral Initiative Office, for development of a new IAEA verification system for weapon-origin and other fissile material released from defense programs in the Russian Federation and the United States. The Offices activities included special technical measures related to progress towards nuclear disarmament, including verification provisions to be carried out in high security sites on classified and unclassified forms of plutonium and highly enriched uranium. Dr. Shea's legal activities included drafting, with legal counsel, new bilateral IAEA verification agreements for consideration by Russia and the US. His financial activities included estimation of resource requirements out to 2010, taking into account the verification obligations arising from the US-Russian Plutonium Management and Disposition Agreement (PMDA) signed last year, and the financing arrangements to support obligatory inspections under the new regime.

As the Section Head, Division of Operations A, Department of Safeguards Dr. Shea was responsible for IAEA safeguards implementation in Japan, India, Indonesia, Australia and other countries. Under his direction, the group developed and implemented innovative safeguards arrangements in plutonium facilities in Japan and India.

Dr. Shea is a Fellow of the Institute of Nuclear Materials Management.