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Utility of Social Modeling for Proliferation Assessment

PRELIMINARY ASSESSMENT

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June 2009

Pacific Northwest
NATIONAL LABORATORY

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Summary

This Preliminary Assessment report presents the results of a literature search and preliminary assessment of the body of research, analysis methods, models, and data deemed to be relevant to the Utility of Social Modeling for Proliferation Assessment research. This report provides: 1) a description of the problem space and the kinds of information pertinent to the problem space, 2) a discussion of key relevant or representative literature, 3) a discussion of models and modeling opportunities judged to have promise to the research, and 4) the next steps of this research that will be pursued based on this preliminary assessment. This report represents a technical deliverable for the NA-22 Simulations, Algorithms, and Modeling program. Specifically this report is the Task 1 deliverable for project PL09-UtilSocial-PD06, Utility of Social Modeling for Proliferation Assessment.

This project investigates the use of social and cultural information to improve nuclear proliferation assessment, including nonproliferation assessment, proliferation resistance assessments, safeguards assessments, and other related studies. These assessments often use and create technical information about the State's posture towards proliferation, the vulnerability of a nuclear energy system to an undesired event, and the effectiveness of safeguards. This project will find and fuse social and technical information by explicitly considering the role of cultural, social, and behavioral factors relevant to proliferation. The aim of this research is to describe and demonstrate if and how social science modeling has utility in proliferation assessment.

The primary aim of this report is to summarize the references that have been collected for this research and present our initial assessment of their implications for proliferation assessment. For the sake of providing an organized overview of the body of literature relating to this research, the review was divided into five topics: 1) Theories of State-level proliferation, 2) Proliferation resistance assessment (of technologies), 3) Safeguards analysis, 4) Non-State proliferation and 5) Social and cultural modeling. Abstracts are provided for the key references used in the discussions of each topic.

Based on the literature search we have concluded that there are opportunities to use social models to improve understanding and assessment of proliferation-related problems. In fact, for decades analysts have theorized about the factors that dictate whether a State pursues the development of nuclear weapons–these factors are primarily social factors or are factors that are intimately related to social factors (e.g., national identity, leadership, politics, domestic security, economic capability). Social modeling offers a way to formalize or leverage this body of analysis and theory. This report identifies opportunities for social modeling specifically related to overarching kinds of assessments. These include proliferation resistance assessment of a nuclear energy system, or the assessment of a set of safeguards. In addition to overarching assessments, there seems to be an untapped potential to augment, support, inform, or complement assessments having a specific modeling or research focus, such as social modeling to support the use of satellite imagery to identify proliferation activity, specific technologies for detection of clandestine facilities, or computerization of a safeguards analysis decision process. In the area of geospatial modeling more explicit use of social modeling might be used to help identify activities or social patterns that correlate to proliferation activity.

A goal of this research is to investigate modeling proliferation using inference models–evidence mathematics. Proliferation theories could be incorporated into a Bayesian network. We present a simplified example model in this report. The model attempts to capture some salient factors relevant to a

state's decision to proliferate; such as, technical capability and the regional political situation. Preliminary results in using the model to compare a state that is not a recognized proliferation threat and a state that is are promising. Our intention is to expand this state proliferation model in more detail and potentially add factors relevant to non-State proliferation.

Various approaches and methodologies have been proposed to assess the proliferation resistance of nuclear energy system facilities. An international approach being developed and supported by the Generation IV International Forum Physical Security and Proliferation Resistance working group uses defined proliferation measures and incorporates structured expert elicitation. This methodology uses pathway analysis to evaluate different scenarios in nuclear energy system facilities that could result in nuclear proliferation by considering five potential host-State proliferation strategies: concealed diversion, overt diversion, concealed facility misuse, overt facility misuse, and independent clandestine facility use.

Before pathways can be defined for analysis, the facility's Material Balance Areas and Key Measurement Points are identified, along with the safeguards and physical protection measures and nuclear material targets. Pathways are specific scenarios that can be described by a proliferation strategy and target and is divided into three major stages: materials acquisition, material processing, and weaponization. The Generation IV International Forum evaluates each pathway using six measures, the first four of which are intrinsic features of the system, and the last two of which are both intrinsic and extrinsic features. The measures are: 1) technical difficulty, 2) proliferation cost, 3) proliferation time, 4) fissile material type, 5) detection probability, and 6) detection resource efficiency.

Despite the primarily technical nature of this approach, the six proliferation resistance measures have social aspects to them. Proliferation theories can be used to identify behavioral, social, and cultural factors that explain the motivation of a country or organization to develop nuclear weapons. Consideration of the behavioral, social, and cultural factors can be more explicitly integrated into consideration of the proliferation measures against proliferation pathways. In this way social factors could be used to inform nuclear energy system design (i.e., intrinsic characteristics) and safeguards (i.e., extrinsic characteristics) improvement. Bayesian networks and other analytical methods could be used to integrate the social and technical models.

Yet another opportunity for social modeling is the area of non-State proliferation, particularly as it relates to what some analysts call the "supply-side." The supply-side substructure of nuclear proliferation might be considered to include manufactures, scientists, middlemen, transporters, opportunists, and violent groups who contribute to proliferation by supplying technology, knowledge, and material to the world. The interconnection of these groups is of interest because globalization has produced a large number of organizations that operate across State borders. Analysis of social networks that show the connections, characteristics, and goals of the groups in this substructure may yield interesting clues about proliferation and the role of non-State actors. Consideration of State and non-State proliferation together may lend to novel approaches to proliferation modeling and additional insights.

Opportunities exist for social modeling in proliferation assessment. The challenge of this research is to identify opportunities where social modeling can have a significant impact and demonstrate its utility. Our approach will be to select a social modeling opportunity related to an overarching type of assessment that has promise to be used in other or in more specific kinds of applications. We intend to leverage research at PNNL by using Bayesian networks to model applicable social science or theory. Validation of these models will be an important step to demonstrating utility and will be built in parallel, based on the modeling application developed.

Acknowledgments

This report represents work funded by the DOE/NNSA Office of Nonproliferation Research and Development (NA-22).

Acronyms and Abbreviations

AFCI	Advanced Fuel Cycle Initiative
BN	Bayesian Network
CA	Complementary Access
CBRN	chemical, biological, radiological or nuclear
C/S	containment and surveillance
DA	Destructive Analysis
DE	Detection Resource Efficiency
DOE	U.S. Department of Energy
DoD	U.S. Department of Defense
DP	Detection Probability
ESFR	example sodium fast reactor
ESS	environmental sampling for Safeguards
FSU	Former Soviet Union
GDP	gross domestic product
GIF	Generation IV International Forum
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
INMN	Institute of Nuclear Materials Management
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IOS	individual, organizational and societal (model)
ISEM	Integrated Safeguards Methodology
JAEA	Japan Atomic Energy Agency
KAERI	Korean Atomic Energy Agency
LBIMS	Laser-Based Item Monitoring System
LEU	low-enriched uranium
LISSAT	safeguards system analysis tool
LWR	light water reactor
MAUA	multi-attribute utility analysis
MOX	mixed oxide (fuel)
MT	Fissile Material Type
NDA	Non-Destructive Analysis
NES	nuclear energy systems
NMA	nuclear material accounting
NNSA	National Nuclear Security Administration
NPAM	Nonproliferation Assessment Methodology
NPT	Nuclear Nonproliferation Treaty

NRC	U.S. Nuclear Regulatory Commission
NVS	Nuclear Verification Series
ORNL	Oak Ridge National Laboratory
PC	Proliferation Cost
PT	Proliferation Time
PR&PP	Proliferation Resistance and Physical Protection
PWR	pressurized water reactor
RTS	Reference Threat Set
RIPA	Risk-Informed Probabilistic Analysis
SAM	Simulation, Algorithms & Modeling
SAPRA	Simplified Approach to the Proliferation Resistance Assessment of Nuclear Systems
SKI	Swedish Nuclear Power Inspectorate
SNAP	Safeguards Network Analysis Procedure
SNL	Sandia National Laboratories
SNM	special nuclear material
TD	Proliferation Technical Difficulty
TOPS	Technical Opportunities to Increase Proliferation Resistance of Civilian Nuclear Power Systems
V&V	verification and validation
VV&A	verification, validation, and accreditation
WMD	weapons of mass destruction

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1.0 Introduction and Scope

This Preliminary Assessment report presents the results of a literature search and preliminary assessment of the body of research, analysis methods, models, and data deemed to be relevant to the Utility of Social Modeling for Proliferation Assessment research. This report provides: 1) a description of the problem space and the kinds of information pertinent to the problem space, 2) a discussion of key relevant or representative literature, 3) a discussion of models and modeling opportunities judged to have promise to the research, and 4) the next steps of this research that will be pursued based on this preliminary assessment. This report represents a technical deliverable for the NA-22 Simulations, Algorithms, and Modeling program. Specifically this report is the Task 1 deliverable for project PL09-UtilSocial-PD06, Utility of Social Modeling for Proliferation Assessment.

This project investigates the use of social and cultural information to improve nuclear proliferation assessment, including nonproliferation assessment, proliferation resistance assessments, safeguards assessments, and other related studies. These assessments often use and create technical information about the State's posture towards proliferation, the vulnerability of a nuclear energy system to an undesired event, and the effectiveness of safeguards. This project will find and fuse social and technical information by explicitly considering the role of cultural, social, and behavioral factors relevant to proliferation. The aim of this research is to describe and demonstrate if and how social science modeling has utility in proliferation assessment.

2.0 Description of Problem Space

A variety of definitions are used for the term "nuclear proliferation." From the viewpoint of the International Atomic Energy Agency (IAEA) and the Treaty on the Non-Proliferation of Nuclear Weapons (Nuclear Nonproliferation Treaty [NPT]), proliferation is State diversion or undeclared production of nuclear materials from facilities operated within a State. A broader definition is sometimes used at the domestic level that includes the theft of nuclear materials by a sub-national group or other States. In the most general sense, the term "nuclear proliferation" is used in open literature to describe the spread of nuclear weapons, fissile material, or weapons-applicable nuclear technology and information to entities that are not recognized as "nuclear weapons States" by the NPT.

For the purpose of this research we differentiate the terms "State-sponsored proliferation" and "non-State proliferation." For this research State-sponsored nuclear proliferation is defined as:

> *State sponsorship of material acquisition, processing, and weaponization activities with the intention to develop at least one nuclear weapon.*

Non-State proliferation is a sufficiently distinct type of threat that may include a greater focus on theft or illicit transfer of nuclear material or technology. The A.Q. Khan network falls into the middle ground between State-sponsored and non-State proliferation. Albright and Hinderstein [1] describe the Khan network as a profit-making "one-stop shop" for proliferation and weaponization information. The growth of underground networks performing nuclear technology transfer for profit forms a new risk of proliferation not traditionally addressed. We define non-State proliferation as:

> *Attempts by non-State-sponsored actors to acquire, process, and weaponize nuclear material with the intention to develop at least one nuclear weapon that may involve collaboration with other groups or States.*

Given these definitions of proliferation then, proliferation assessment and related studies are assessments that pursue the answer to any number of questions related to why, when, how, or if nuclear material, technology, or information could be spread in a way that results in a nuclear weapon being acquired by a State or terrorists. A range of nonproliferation studies, identified by the Nonproliferation Assessment Methodology (NPAM) working group[1] in PNNL-14294 [2], are included in Table 2.1 as an example of the kinds of studies considered to be, or supporting assessment of, proliferation. The NPAM working group list builds on earlier national and international efforts [3][4] to address concerns about the proliferation implications of different fuel cycles.[2]

[1] The National Nuclear Security Administration (NNSA) established the NPAM working group composed of representatives from U.S. Department of Energy (DOE) laboratories and academia that developed and published guidelines in 2003 for the nonproliferation assessment methodologies.
[2] During the Carter administration concern about plans for recycle of plutonium in commercial nuclear power plants led to the national and international assessment of different fuel cycles.

Table 2.1. Types of Nonproliferation Studies

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?

Assessment of the proliferation implications of fuel cycle advancements
- Detailed design-level support:
  - What is the relative proliferation risk of multiple 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?
  - What is the proliferation implications of United States support of 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?
  - What is the proliferation implication of legacy material disposal in the United States?
  - Should the United States 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?
  - Should the United States 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 United States support a renewed domestic uranium enrichment R&D program?
- What is the proliferation risk related to the United States providing advanced technologies for safeguards to the IAEA?

Physical Security Assessment
- What is the proliferation risk associated with physical security of a nuclear energy system?

Regional Security Studies:
- Should the United States 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?

Different types of studies attempt to answer different proliferation-related questions. Some of these questions include:

- What is the level of resistance of a facility or nuclear energy system[1] to nuclear proliferation?
- What is the adequacy of international or domestic safeguards to prevent proliferation?
- What is the adequacy of international or domestic export controls to prevent proliferation?
- How well does the physical security of a nuclear energy system protect against theft or sabotage of nuclear material?
- What are the factors related to a country's decision to develop nuclear weapons?
- What is the likelihood that a country would decide to develop nuclear weapons?
- How do domestic policies affect a State's ability to develop nuclear weapons?
- What is the likelihood that a non-State-sponsored group would decide to develop or support development of nuclear weapons?

In general, two types of analysts study nuclear proliferation issues: technical analysts and policy analysts. Technical analysts focus on evaluation of nuclear technologies, safeguards systems, physical protection systems, and other technical means used to deter, detect, assess, and prevent the theft, undeclared production or diversion of nuclear materials as well as indicators that a State may be pursuing nuclear weapons. Policy analysts focus on international treaties and agreements in place to protect against proliferation, and policies that impact social, political, and economic conditions underlying a State or group's decision to pursue, or not pursue, nuclear weapons.

Export control clearly plays an important part in preventing the spread of nuclear material or technologies, and export-control assessment is important in gauging the effectiveness of this system in monitoring or predicting intent to proliferate. Export control does not play as central a role, however, as direct controls (i.e., safeguards) placed on the nuclear energy system facilities themselves. Furthermore, a parallel effort exists that addresses the use of social modeling in export-control assessment. Project NN2001-6, a Simulation, Algorithms & Modeling (SAM) project, entitled *Predicting Intent from Real-World Datasets* addresses the use of social modeling as a complement to current assessment process for detection and prediction of export-control violations. Therefore, a literature search of export-control-related research was not performed as part of this study.

Physical security also plays an important part in preventing the theft or sabotage of nuclear material and assessment of physical security is important in gauging their effectiveness of those controls and in monitoring or predicting intent to acquire nuclear material. Literature related to physical controls was examined but only from the perspective of non-State proliferation. It was not considered a factor in State-sponsored proliferation.

[1] A nuclear energy system includes a nuclear power-producing plant and the facilities necessary to implement its related fuel cycle.

The literature review needed to begin researching the questions defined above is considerable. For the sake of providing an organized overview of the body of literature relating to these questions, the review was divided into five topics:

1. Theories of State-level proliferation
2. Proliferation resistance assessment (of technologies)
3. Safeguards analysis
4. Non-State proliferation
5. Social and cultural modeling.

The following sections discuss each of these topics in turn.

References

[1] Albright D and C Hinderstein. 2006. "The A. Q. Khan Illicit Nuclear Trade Network and Implications for Nonproliferation Efforts." *Strategic Insights* V(6). Accessed April 15, 2009, at http://www.ccc.nps.navy.mil/si/2006/Jul/albrightJul06.pdf

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[3] USDOE/NASAP. 1980. *Nonproliferation Alternatives System Assessment Program*. USDOE/NE-001, U.S. Department of Energy (DOE), Washington, D.C.

[4] International Atomic Energy Agency (IAEA). 1980. *International Nuclear Fuel Cycle Evaluation* IAEA, Vienna, Austria.

2.1 Theories of State-Sponsored Proliferation

For the last few decades there has been much debate over how to explain what motivates State-sponsored nuclear proliferation and whether future nuclear proliferation can be predicted or not. Over that period of time a significant number of theories have been advanced that define factors that impact nuclear proliferation. Development and articulations of these theories have spawned a shared vocabulary and conceptualizations that analysts have used to discuss their theories and differentiate their ideas from each other.

In general, these theories involve evaluating the capabilities and willingness of State proliferators to attempt to acquire a nuclear weapon or undertake a nuclear weapons development program. These theories attempt to define key causes, factors, or determinants that impact the decision of a country to develop nuclear weapons. These factors are organized and described differently depending on the theory espoused, but generally can be classified into one the following groups:

1. Technical capability
2. National and international security
3. Domestic politics
4. National identity and psychology.

On the one hand, it is clear that social concepts and social modeling have a role in theories that explain the spread of nuclear weapons; there has been no shortage of academic theories. On the other hand, there is a lack of agreement on the validity or the ability to forecast using the various postulations. Singh claims that "*Authors frequently find existing explanations unable to account for the details of a case of particular interest and then seek to redress the shortcoming by offering yet another alternative*."[1] Concepts, such as the Technological Imperative and the Motivational Hypothesis, debated in 1984 by Stephen Meyer in his book [2] and the security versus domestic and norm models described by Scott Sagan in his 1996 article [3] have been debated, are still being debated, and some cases are being either further elaborated on or even discredited. Tanya Ogilvie-White concludes in an 1996 article [4] that when the "*…complexities of the nuclear proliferation process are considered, it is not surprising to find that none of the existing theories of nuclear proliferation provide a satisfactory explanation of the proliferation dynamics, although many provide important pieces of the puzzle.*" Table 2.2 adapted from that article illustrates her point by summarizing the strengths and weaknesses of the models she investigated.

Table 2.2. Explanatory Powers/Limitations of Existing Proliferation Theories (from Ogilvie-White [4])

Theory or model	What it is	Strengths as a theory of nuclear proliferation	Weaknesses as a theory of nuclear proliferation
Classical realism	Acquisition of nuclear weapons is rational response to protect national interests.	Explains role of security considerations.	Ignores domestic determinants.
Neo-realism	Variant of classical realism to include power structure of international politics (whether unipolar, bipolar, or multipolar).	Presents an elegant, logically deduced explanation of nuclear proliferation, but side-steps empirical difficulties.	Explains systemic outcomes, not unit-level outcomes. Predictions and explanations are misleading and inaccurate.
Neo-liberal institutionalism	Democratic states pursuing liberal economic policies may decide that it is not in their interests to develop an overt arsenal, due to their extensive reliance on the global economy.	Explains domestic determinants, such as economic and political factors.	Leaves decision-making out of analysis.
Organizational theory	Emphasizes the role of organizations in nuclear decision making.	Analyzes implementation of decisions. Explains role of organizations in irrational behavior.	Underestimates impact of individuals and new information.
Belief systems theory	Actions are linked to beliefs which are fundamental to understanding foreign policy decision making.	Focuses on role of individuals and groups and explains irrational decisions.	Difficult to quantify. Cannot explain causes of beliefs.

Learning models	Beliefs can change as a result of learning shared technical information, leading to new policies	Explains impact of new information.	Cannot explain what lessons are likely to be learned under what circumstances.
SCOT theory	Uses organizational theory to challenge idea that states are unitary and rational actors that act in the interests of the state.	Explains role of technology. Places nuclear proliferation in historical and social contexts.	Very descriptive.

Investigation of this literature finds that the role of culture, groups, and individuals play an important part in the theories that have been crafted. It was been argued by some that the nuclear proliferation process itself must be viewed as the consequence of a combination of internal and external pressures and constraints, involving influential organizations, groups, and individuals, and their ideas, beliefs, and interests [4]. Despite the importance of these social factors in the theoretical literature on proliferation, there have been few attempts at integration of social modeling with technical modeling and only a few attempts at quantifying social factors for the purpose of carrying out quantitative tests of theories.

Theories of proliferation are an important part of this problem space. The fundamental questions that characterize this problem space are the same underlying questions of the aforementioned debate: What are the factors related to a country's decision to develop nuclear weapons and what is the likelihood that a country would decide to develop nuclear weapons. Equally important, how and to what extent is country motivation related to proliferation risk of a facility? These are not questions that can be answered definitively. Uncertainty will always be a part of the equation. In no case have we identified attempts at building models to answer these questions in a manner that explicitly considers uncertainty as integral to the modeling process.

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[2] Meyers S. 1984. *The Dynamics of Nuclear Proliferation*. The University of Chicago Press, Chicago, Illinois.

[3] Sagan S. 1997. "Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb." *International Security* 21(3):54-86.

[4] Ogilvie-White T. 1996. "Is There a Theory of Nuclear Proliferation? An Analysis of the Contemporary Debate." *The Nonproliferation Review* (Fall Issue):43-60.

2.2 Proliferation Resistance Assessment

The term "proliferation resistance" is term that is widely used but lacks a universal definition. The definition used by the IAEA [1] and by the Generation IV International Forum (GIF) is as follows:

> *"That characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by States in order to acquire nuclear weapons or other nuclear explosive devices."*

Proliferation resistance assessment consists of evaluating a nuclear energy system (or a sub-system) to determine a measure of its resistance to diversion, misuse, theft, or other activities that would contribute to nuclear proliferation. This assessment can be done in the context of a particular threat or as a general assessment. The measures of proliferation resistance assessment focuses on both intrinsic (i.e., design of facility or system) and extrinsic (i.e., safeguards and other institutional features) barriers to proliferation. The degree of proliferation resistance results from a combination of technical design features, operational modalities, institutional arrangements, and safeguards measures. [2]

Intrinsic measures are those technical design features that reduce the attractiveness of nuclear material for use in a nuclear weapon, makes it difficult to gain access to material, makes it difficult to misuse facilities and technologies for weapons development, and facilitates nuclear material accountancy and verification [1][3][4]. Extrinsic measures consist of control and verification measures commitments, obligations, and policies of States to agreements such as the NPT and the IAEA safeguards agreements, and export- and import-control agreements [1][4].

Although proliferation assessment can be performed in the context of a general or specific threat, a comprehensive analysis requires the assessment of a full suite of potential proliferation threats. The Generation IV [1] Proliferation Resistance and Physical Protection (PR&PP) working group recommends that the assessment be performed across a Reference Threat Set (RTS), which is defined as "…*a collection of well-defined threats that is to be consistently considered and is the foundation for any level of PR (proliferation resistance) or PP (physical protection) assessment….*" [5] They also suggest that the RTS should be developed at the design stage of a system and that it be re-evaluated once the facility is constructed. Threat characterization provides an avenue to infuse country-level social and cultural information.

A spectrum of qualitative and quantitative forms of proliferation resistance assessment approaches and analysis techniques have been proposed. Currently, the two most prominent proliferation resistance assessment methodologies are those used by DOE: (1) the Generation IV International Forum, PR&PP working group methodology (hereafter referred to as the GIF methodology), and (2) the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles[2] (INPRO); (referred to hereafter as

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[1] The GIF was chartered in July 2001 to lead the collaborative efforts of the world's leading nuclear technology nations to develop next-generation nuclear energy systems to meet the world's future energy needs. The nine GIF founding members were joined by Switzerland in 2002, Euratom in 2003, and most recently by China and Russia at the end of 2006.

[2] The INPRO methodology was launched in the year 2000, based on resolutions of the IAEA General Conference. The INPRO methodology intends to help ensure that nuclear energy is available in the 21st century in a sustainable manner, and bring together all interested Member States, both technology holders and technology users, to jointly consider actions to achieve desired innovation.

the INPRO methodology).. Many of the approaches define proliferation resistance measures. Based on our initial assessment, we believe that many of these measures represent opportunities to more fully integrate social information or modeling.

Even though much has been written on proliferation resistance assessment in the last three decades, it is still an evolving discipline. The material that currently exists is primarily a set of proposed proliferation resistance assessment methodologies with example applications, rather than actual applications using real-life facilities or designs. The guidance [3] written by the NPAM working group,[1] for example, presents a range of potential approaches for assessing proliferation assessment. According to Pomeroy, "*Considerable work remains in refining proliferation resistance analysis and interpreting results.*" [2]

Proliferation resistance assessment is an important aspect of the proliferation assessment. The fundamental issue relevant to proliferation resistance assessment is: What is the level of resistance of a facility or nuclear energy system[1] to nuclear proliferation? Social modeling presents an opportunity to more accurately characterize the level of resistance. Relevant questions that highlight the potential benefit of social modeling might be:

- How and to what extent is the proliferation resistance of a nuclear energy system impacted by the social and cultural environment of the country in which it resides?
- What assumptions are made in the process of threat characterization regarding social and cultural factors that could be better analyzed through objective analysis?

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[1] IAEA STR-332. 2002. *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems.* International Atomic Energy Agency (IAEA), Vienna, Austria.

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[1] A nuclear energy system includes a nuclear power-producing plant and the facilities necessary to implement its related fuel cycle.

2.3 Safeguards Analyses

The term "safeguards" can have a general or specific meaning depending on its context. The following is a general definition from an IAEA TECDOC-1434: [1]

"An extrinsic measure comprising legal agreements between the party having authority over the nuclear energy system and a verification or control authority, binding obligations on both parties and verification using, inter alia, on-site inspections."

Often the term "safeguards" refers to IAEA international safeguards implemented under Safeguards Agreements between each State and the IAEA. However, safeguards can refer to regional safeguards based on regional agreements, such as the Euratom Treaty or the Brazilian Argentine Agency for Accounting Control of Nuclear Materials. Regional agreements frequently implement safeguards that are, in effect, the same controls as international safeguards. Safeguards can also refer to domestic safeguards, which are defined differently than IAEA or regional safeguards. The U.S. Nuclear Regulatory Commission (NRC) defines safeguards" in the following way [2]:

"As used in regulation of domestic nuclear facilities and materials, the use of material control and accounting (MC&A) programs to verify that all special nuclear material is properly controlled and accounted for, as well as physical protection (also referred to as physical security) equipment and security forces."

"As used by the International Atomic Energy Agency (IAEA), verifying that the 'peaceful use' commitments made in binding non-proliferation agreements, both bilateral and multilateral, are honored."

The NRC definition of domestic safeguards, typical of other domestic definitions of safeguards, includes the use of physical protection equipment and security forces. Physical security provides protection against theft, so is less about compliance of a State to the NPT than it is about protecting against nuclear trafficking or actions of a non-State actor[1]. MC&A protects against insider theft, and through inventory tracking, detects and deters theft or loss. Section 2.4 provides further discussion about non-State proliferation.

International nuclear safeguards are measures and controls used to detect diversion of nuclear material from peaceful nuclear energy programs. International safeguards serve the function of verifying the peaceful use of declared nuclear materials in the State, deterring diversion through the risk of early detection, and verifying compliance with safeguards agreements, including completeness of a State's declarations regarding its nuclear program [3]. Table 2.3 illustrates how the objectives of safeguards interact with different inspection goals.

Traditional IAEA safeguards approaches that focus on prevention of the diversion of nuclear material include [3]:

- Audit of nuclear material accounting records or reports
- Material verification that includes a physical inventory verification of all nuclear material

[1] This research defines non-State actors as sub-national or multi-national groups that include terrorists.

- Surveillance and real-time monitoring system
- Containment measures such as seals, shipping casks, and tamper analysis.

Newer approaches include a focus on information analysis, remote monitoring, and environmental sampling.

The types of facilities under IAEA Safeguards or containing safeguarded material are[1]: power reactors, research reactors and critical assemblies, conversion plants, fabrication plants, reprocessing plants, enrichment plants, separate storage facilities, and miscellaneous facilities, such as laboratories containing safeguarded material. The objective of IAEA safeguards are to:

1. Detect the diversion of a significant quantity of nuclear material from a declared facility in a timely fashion.
2. Detect the undeclared production of nuclear material in a declared facility, or the misuse of a declared facility (such as enriching uranium to higher-than-declared levels).
3. Detect the presence of undeclared nuclear material or facilities.

Table 2.3. Comparing Safeguards Objectives (from Doyle [3])

	Safeguards Objective	Scope	Role of "Quantity" Goal	Role of "Timeliness" Goal	Primary Safeguards Measures
Verification	Verify that all declared material remains in civilian use.	Declared materials	Determines measurement level; establishes target values[(a)]	Not particularly important; verify inventory with some frequency[(b)]	Materials accounting augmented by containment/ surveillance (for efficiency)
Deterrence (through risk of timely detection)	Establish the ability to detect all credible proliferation pathways.[(c)]	Undeclared actions at both declared and undeclared sites	Not a focus per se, only part of throughput consideration in pathway definitions	A major focus; objective is to detect pathway use prior to path completion	Surveillance/ unannounced inspections/new measures to detect undeclared activities
Assurance of completeness of a State's declarations	Find evidence of use of any plausible proliferation pathways.	Undeclared actions at both declared and undeclared sites	Not particularly important	Not particularly important	Information analysis[(d)] State-specific review of the IAEA's physical model[(e)]

(a) For uncertainties
(b) Establishes the frequency of verification based on the ease of conversion of material to weapons-usable form
(c) This reference [3] defines the term "pathway" to be "Representation of the minimum set of activities that a State must undertake to produce weapons-usable material."
(d) Environmental sampling
(e) Complementary access

[1] From Table A28. Facilities under Agency Safeguards or Containing Safeguarded Material on 31 December 2007 at http://www.iaea.org/Publications/Reports/Anrep2007/table_a28.pdf

It is worth noting that safeguards analysis and proliferation resistance assessment are interrelated. Proliferation resistance assessments address intrinsic and extrinsic barriers to proliferation. Safeguards are the primary means by which the extrinsic measures are implemented. So, to a certain extent, the proliferation resistance assessment of a nuclear energy system provides a measure of the corresponding safeguards effectiveness. According to Haas, "*Effective and efficient implementation of international safeguards will remain essential for the proliferation resistance of a nuclear energy system, regardless of the level of effectiveness of proliferation resistance intrinsic features*."[4]

There is another kind of safeguards analysis which IAEA refers to as safeguards effectiveness evaluations [5]. The IAEA considers safeguards evaluation a key element of planning the safeguards activities in a State. The IAEA defines safeguards effectiveness evaluation [5] to be the process of evaluating the extent to which the IAEA's implementation of safeguards is able to achieve the safeguards objectives.

Safeguards analyses and evaluation are an important part of the problem space. A couple of fundamental questions that characterize this problem space are: What is the adequacy of international or domestic safeguards to prevent proliferation and how do these two components of safeguards reinforce one another to that end? A relevant question that highlights the potential benefit of social modeling question might be:

- How and to what extent is the adequacy of international or domestic safeguards impacted by the social and cultural environment of the country in which it resides?

References

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[2] U.S. Nuclear Regulatory Agency (NRC). 2009. Glossary. Accessed March 24, 2009, at http://www.nrc.gov/reading-rm/basic-ref/glossary/safeguards.html.

[3] Doyle J. 2008. *Nuclear Safeguards, Security and Proliferation*. Elsevier – Butterworth-Heinemann.

[4] Haas E. 2007. *Proliferation Resistance and International Safeguards*. Japan Atomic Energy Agency/International Atomic Energy Agency (JAEA-IAEA). JAEA/IAEA Workshop, November 13-15, Tokai, Japan.

[5] International Nuclear Verification Series No. 3. 2002. *IAEA Safeguards Glossary*. 2001 Edition, International Atomic Energy Agency (IAEA), Vienna, Austria.

2.4 Proliferation by Non-State Actors

Traditionally, non-State proliferation has not been considered a plausible threat. Non-State actors were seen as potential thieves of material, but unlikely to develop the capability to produce nuclear material suitable for use in a weapon weapons [1]. Pomeroy states that: *"...proliferation threats posed by the host State are carefully distinguished from the potential security threats posed by non-host-State actors. The latter are treated separately as a part of physical protection rather than under proliferation resistance."* [2] This focus on State sponsorship as a requirement for proliferation separates terrorist activities, such as theft, from development of nuclear weapons programs. A Sandia report about proliferation argues: *"Although a successful effort by any actor, non-State or otherwise, to steal nuclear material or technology may result in a nuclear weapon; it is a sufficiently distinct type of threat deserving separate consideration. Evaluating the performance of features to address theft-type threats may require a different approach (most notably one which considers physical protection characteristics), as technology features and characteristics which aid or impede host State-type threats may have not always have a consistent relationship to theft-type threats."* [3] In addition to physical protection, thwarting theft demands measures to address the insider threat, such as material control, procedural controls, and surveillance.

These authors argue that non-State threats should be evaluated in terms of physical protection systems –that is, as break-in or sabotage scenarios. This view, however, dismisses the relevance of development by non-State actors of clandestine proliferation or an insider threat of a non-State actor. This research will not limit itself to this view.

Potential non-State actors include sub-national groups, multi-national groups, and corporations. These groups may be interested in proliferation for use in nuclear terrorism or for profit via blackmail or sale via the black market. Although attempts by non-State actors to proliferate, as it is defined in this research space, is speculative at this point, it is imaginable that these groups could seek to work alone or in collaboration with other groups (e.g., including States or sub-national groups) to attempt to achieve nuclear weapons capability.

Proliferation by non-State actors is an important part of the problem space. The fundamental question that characterizes this problem space is: What are the factors related to a non-State actor's decision to develop nuclear weapons and what is the likelihood that a non-State actor would decide to develop nuclear weapons? Post [4] details psychological motivations and constraints, differentiating the continuum between rational thought and goals related to non-State actors, to the irrational, psychotic, end of-the-world thinking. A relevant question that highlights the potential benefit of social modeling question might be:

- How and to what extent is non-State-actor motivation related to proliferation risk of a facility?[1]

References

[1] Willrich M and TB Taylor. 1974. *Nuclear Theft: Risks and Safeguards A report to the Energy Policy Project of The Ford Foundation*. Accessed May 14, 2009, at http://www.fordfound.org/archives/item/0154

[1] A State working on a nuclear weapons program could also use the excuse of non-State actors' thefts to hide material diverted to the secret weapons program.

[2] Pomeroy G, R Bari, E Wonder, M Zentner, E Haas, T Killeen, G Cojazzi, and J Whitlock. 2008. "Approaches to Evaluation of Proliferation Resistance of Nuclear Energy Systems." In: The 49th Annual Meeting: Institute of Nuclear Materials Management, July 13-17, Nashville, Tennessee.

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[4] Post JM. 1987. "Prospects for Nuclear Terrorism: Psychological Motivations and Constraints." *Conflict Quarterly* 7 (Summer 1987): 47-58.

2.5 Contribution from Social and Cultural Modeling

Because this research is about the utility of social modeling to proliferation assessment, social modeling is a key part of the problem space. How to model the likely behavior or decisions that might be made by individuals, groups, cultures, or countries is of primary interest as it pertains to nuclear proliferation. Modeling in the social sciences has been an integral part of social science research in understanding, explaining, and predicting social phenomena. Modeling, in its early stages, began as qualitative descriptions, but the use of mathematical models in social science has evolved from a desire to be more precise in describing phenomena, predicting behavior, and testing theories. So mathematical modeling emerged as an extension of qualitative descriptions of social science due to its greater precision than narrative descriptions and its ability to make quantitative predictions.

It is clear that social factors play a role in nuclear proliferation and relate to the four general proliferation factors introduced in Section 2.1:

- Technical capability
- National and international security
- Domestic politics
  National identity and psychology.

While at first blush the technical capability of a country would seem to be independent of social consideration, deeper consideration reveals that even it is very much related to social factors like politics, economics, leadership, and national traits. Furthermore, there are social assumptions made (even if not made explicitly) in performing related assessments, such as proliferation resistance assessment and safeguards analysis. The inherent proliferation resistance or "safeguard-ability" of nuclear energy systems are both affected by the social environment operations and management culture, and conditions of the locations where they reside.

From the areas of State-sponsored proliferation theory, proliferation resistance, safeguards analysis, and proliferation by non-State actors. Relevant questions that highlight the potential benefit of social modeling question might be:

- How and to what extent is country motivation related to proliferation risk of a facility?
- How and to what extent is the proliferation resistance of a nuclear energy system impacted by the social and cultural environment of the country in which it resides?

- How and to what extent is the adequacy of international or domestic safeguards impacted by the social and cultural environment of the country in which it resides?
- How and to what extent is the proliferation risk of a nuclear facility affected by the social and cultural characteristics of the majority nationality of its staff (regardless of the State in which the facility resides)?
- How and to what extent is non-State-actor motivation related to proliferation risk of a facility?

3.0 Proliferation Assessment Literature

This section summaries the references that have been collected for this research. As discussed earlier, for the sake of providing an organized overview of the body of literature relating to this research, the review was divided into five topics: 1) Theories of State-level proliferation, 2) Proliferation resistance assessment (of technologies), 3) Safeguards analysis, 4) Non-State proliferation and 5) Social and cultural modeling. Abstracts are provided for the key references used in the discussions of each topic.

3.1 Theories of State-Level Proliferation Literature

Literature that currently exists on theories of State-sponsored proliferation is abundant and goes back to the decades following World War II and the signing of the non proliferation treaty (NPT). Many of the theories and articulation of incentives and disincentives for countries to go nuclear were formed in the cold war era and still play a significant role in the ongoing debate. However, in the cold war era there was a clear emphasis on international security as the dominant factor. Epstein says in his article, "Why States Go–And Don't Go –Nuclear" [1] in 1977: "*The dominant positive and negative incentives to go or not to go, nuclear are those involving a country's military security. Problems of military security are paramount questions for all governments, and in the absence of any other satisfactory way of ensuring it, defense based on military force is the customary preferred path*." In other literature this concept has been referred to as the "realist view" or the security model. In the cold war era many thought that ability to be in a secure alliance to one of the two nuclear super powers was the decisive factor of whether a country would pursue nuclear weapons [1]. However, even in this era it was acknowledged that political and economic motivations were also important factors, such as strengthening independence and increasing status and prestige in the world.

One of the early books written on why States decide to pursue nuclear weapons is *The Dynamics of Nuclear Proliferation* [2] by Stephen Meyer in 1984. Meyer contradicts the then popular deterministic notion that the pace of nuclear proliferation is controlled only by a Technological Imperative[1] and suggests that other factors account for the past decisions of nations to acquire or forgo development of nuclear weapons. He espouses a Motivational Hypothesis that sees latent capacity[2] as a necessary, but not sufficient, condition. It assumes some specific politico-military condition is necessary to motivate a deliberate proliferation decision.

From the perspective of the Motivational Hypothesis, decisions to initiate nuclear weapons programs can be understood in the context of three categories of incentives: 1) international political power and prestige incentives, 2) military and security incentives, and 3) domestic politics incentives. Based on these categories, Meyer compiles a list of proliferation incentives from literature available at the time (i.e., 1962-1982) by identifying factors that would answer the hypothesis: "*From a decision-making perspective, the possession of atomic weapons could be helpful if the government wishes to….*" This list was then translated from incentives into motive conditions. Meyer came up with a list of 15 motive conditions (i.e., predictor variables):

[1] The Technological Imperative assumes that once a country has acquired the technical capacity to manufacture a nuclear weapon that it's only a matter of time before it does.

[2] Meyer defines latent capacity as sufficient technical, industrial, material, and financial resources to support a wholly indigenous nuclear weapons program.

1. Nuclear threat
2. Latent capacity threat
3. Overwhelming conventional threat
4. Regional power status/pretensions
5. Global power status/pretensions
6. Pariah status[1]
7. Domestic turmoil
8. Loss of war
9. Regional nuclear proliferation
10. Defense expenditure burden
11. Nuclear ally
12. Legal treaties enforce
13. Risk of unauthorized seizure
14. Possible nuclear intervention
15. Peaceful reputation

Meyer elaborates on these motive conditions and defines indicators for them. Consider for example, "domestic turmoil." He argues that increased domestic turmoil due to civil strife, ethnic hostility,or labor unrest might be a motive for acquiring nuclear weapons. Meyer identifies general strikes, riots, and antigovernment demonstrations as indicators of domestic turmoil and defines criteria to indicate when domestic turmoil has reached a level of concern. Another example is "loss of war" as a motive condition. He argues that raising the concern of a country's defense establishment might be a motive for acquiring nuclear weapons and speculates that Pakistan's response to its dismemberment in 1971 may be related to initiation of a weapons program.

Meyer tested his motivational hypothesis using historical data. Cases in which there may be motive present and dissuasive conditions absent were examined to see if there was a systemic relationship between proliferation decisions and motive conditions. The percentage of proliferation decisions for countries where a motive was present was compared to the average. Proliferation decisions significantly higher than the average of the entire set were taken to support the motivation hypothesis. In this process Meyer defines a term he calls "nuclear propensity":

> *"…the extent of a nation's explicit (but time varying) predisposition towards initiating the manufacture of nuclear weapons."*

Meyer generates estimates of nuclear propensity as a function of motive conditions. When calculating the nuclear propensity for a country to go nuclear he accounts for multiple motive conditions and the dampening effects of dissuasive motives. Meyer defines a numerical value for nuclear propensity of a country to be between 1 and 0. He calculates this on a year-by-year basis and discusses the results for a number of countries. Figure 1 shows the nuclear propensity for Pakistan as calculated for 1960 to 1980. The figure shows a sharp increase in nuclear propensity for Pakistan beginning about 1970. In fact Pakistan began its nuclear weapons program in 1972. Other countries that have made proliferation decisions that he discusses include Britain, South Africa, France, India, South Korea, Brazil, Argentina, Taiwan, and Pakistan. The Meyer work is a significant milestone in the thinking about nuclear proliferation and is often referenced in later literature.

[1] Countries that for one reason or other have been shunned by their neighbors, if not by the international community in general, are considered to have pariah status.

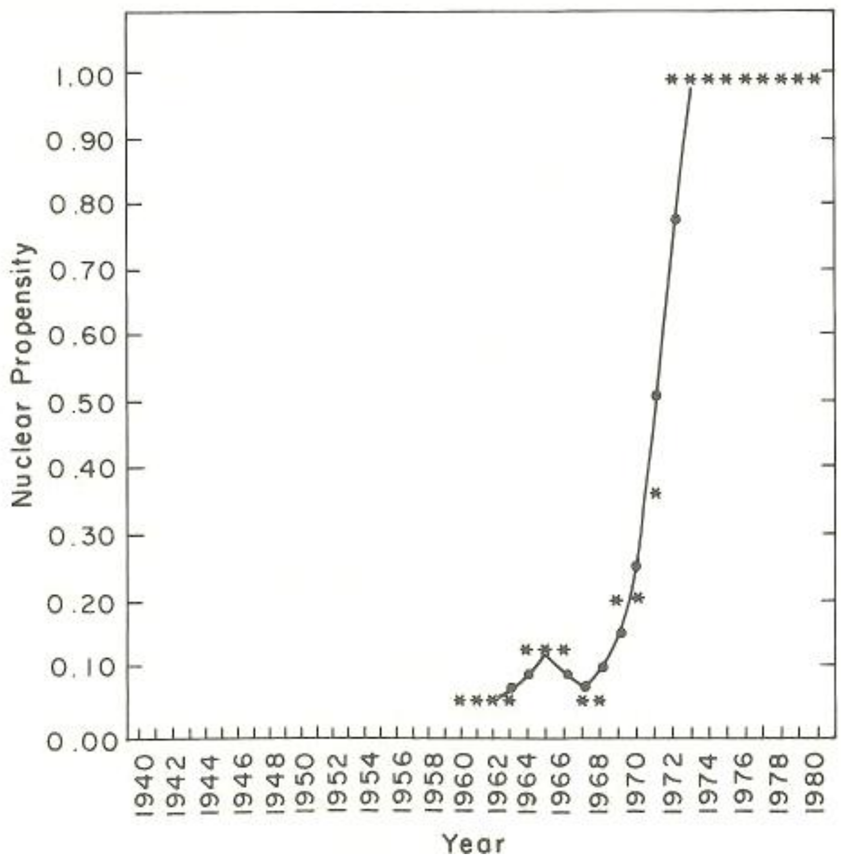

Figure 3.1. Nuclear Propensity of Pakistan (from Meyer [3])

A more recent (1996) article [3], "Why Do States Build Nuclear Weapons: Three Models in Search of a Bomb," Sagan refutes the idea that international security is the dominant factor in why countries decide to pursue nuclear weapons: "*I argue that the consensus view, focusing on national security considerations as the cause of proliferation is dangerously inadequate because nuclear weapons programs also serve other, more parochial and less obvious objectives*." Sagan goes on to say that "*Any rigorous attempt to evaluate the security model of proliferation, moreover, also requires an effort to develop alternative explanations, and to assess whether they provide more or less compelling explanations for nuclear proliferation.*" Besides the security model, Sagan goes on to describe two other theories he calls the "domestics politics model" and the "norms model."

The domestic politics model of nuclear weapons proliferation focuses on domestic actors who encourage or discourage governments from pursuing the bomb. Sagan points out that three kinds of actors typically appear in historical case studies of proliferation: 1) the State's nuclear energy establishment (which includes officials in State-run laboratories as well as civilian reactor facilities), 2) important units within the professional military (e.g., navy bureaucracies interested in nuclear propulsion), and 3) politicians in States in which individual parties or the public strongly favor nuclear weapons acquisition. When such actors form coalitions strong enough to control government decisions directly or indirectly, then nuclear weapons production can thrive.

According to Sagan, the norms model of nuclear proliferation is seeing proliferation decisions as serving important symbolic functions in both shaping and reflecting a State's identity. According to this perspective: "…*State behavior is determined not by leaders' cold calculations about the national security interests or their parochial bureaucratic interests, but rather by deeper norms and shared beliefs about what actions are legitimate and appropriate in international relations.*" [3] He says that the progress of sociologists and political scientists in the area of international norms is helpful in explaining nuclear proliferation. Sagan cites as an example the concept of "institutional isomorphism" for why organizations and institutions often come to resemble each other rather than competitive selection or rational learning.

Sagan uses the norms model to explain why Ukraine decided to eliminate its nuclear arsenal, which is difficult to explain using the security model. He points out that:

- Ukrainian politicians adapted an anti-nuclear position as a way of buttressing Kiev's claim of national sovereignty and independence from Moscow.
- Ukrainian officials wanted to enhance the State's international prestige and notes that NPT history had produced the notion that countries like North Korea and Iran were considered "rogue States" by the international community.
- Ukraine could more easily accept economic inducements, if it believed it was being supported in keeping an international commitment.

In a 1996 article [4], "Is There a Theory of Nuclear Proliferation? – An Analysis of the Contemporary Debate," Tanya Ogilvie-White analyzes dynamics of nuclear proliferation, exposing the areas where confusion has occurred due to the multifaceted and complex nature of proliferation dynamics. Ogilvie-White summarizes the power and limitation of the different proliferation theories she examined (see Table 2.2). She also presents a list of what she refers to as "Questions Remaining in the Proliferation Puzzle" in Table 3.1 that show what strong roles social factors (i.e., psychological, political, organizational, cultural, societal, and economic) play in the important questions that remain to be investigated.

Table 3.1. Questions Remaining in the Proliferation Puzzle (from Ogilvie-White [4])

Questions about psychological factors	• How much behavior can belief systems theory explain? • Why do belief systems change? • How does new information affect proliferation dynamics? • How can States be persuaded to adopt policies that are contrary to their conceptions of self interest?
Questions about political and organizational factors	• How do different domestic political structures and traditions affect proliferation dynamics? • How do bureaucratic compromises and group dynamics affect nuclear diplomacy? • What determines the nature of civil-military relations and how does this affect nuclear proliferation?
Questions about cultural and societal factors	• How are nuclear interests formed, who defines them, and how do they interact? • What impact do cultural factors, such as religion, have on proliferation dynamics? • What effect does public opinion and "world opinion" have on nuclear proliferation? • Is there a relationship between social cohesion and nuclear proliferation?
Questions about economic and environmental factors	• How do trade relations affect nuclear proliferation? • What influence does the health of the domestic economy have on nuclear decision-making? • Are States that seek economic autarky more likely to develop nuclear weapons? • What is the relationship between aid and nuclear diplomacy? • How do environmental concerns affect nuclear decision-making?

More recent work on theories of proliferation was performed by Sonali Singh and is described in a 2004 article [5] entitled “The Correlates of Nuclear Proliferation: A Quantitative Test” In this work Singh suggests that a quantitative test of theories of nuclear proliferation can provide a useful complement to the qualitative, comparative case studies that dominate this research. He points out that most qualitative studies ignore or underemphasize the large number of countries that have never pursued nuclear weapons, and thus run the risk of either underestimating the strength of casual effect or accepting relationships that do not hold up in a wider sample. Singh points out that analysts can always identify security threat contributors after the occurrence of a proliferation episode.

Singh divides theories on nuclear proliferation into three perspectives: 1) technological determinants, 2) external determinants, and 3) domestic determinants. What Singh means by the technological determinants perspective is similar to what Meyer called the Technological Imperative; that is, once a country acquires the latent capability to develop nuclear weapons, it is only a matter of time until it does. What Singh refers to as the external determinants perspective is similar what others have called the realist view or what Sagan calls the security model. What Singh refers to as domestic determinants perspective is a combination of factors related to what Sagan divides into the domestic model and the norms model. Singh’s domestic determinants perspective specifically focuses on four domestic factors: 1) democracy, 2) liberalizing governments, 3) an autonomous domestic elite, and 4) symbolic and status motivation.

Singh then defines proxy explanatory variables for each of the three proliferation perspectives. For example, Singh identifies gross domestic product (GDP) per capita, industrial capacity index and energy, electricity, and steel production and consumption as proxy explanatory variables for the technological determinants perspective.

Singh defines countries as falling into one of four categories: 1) explosion or assembly of weapons, 2) pursuit of weapons, 3) exploration of weapons, and 4) no interest. He then employs history models (also called hazard models), supplemented with multinomial logistic regressions, to test claims about the correlates of nuclear weapons proliferation. In his models the independent variables are the proxy explanatory factors and the dependent variables are the four country groups. To supplement the hazard model approach he also re-estimates using multinomial logistic regression. Multinomial logistic models supplement the hazards model approach by estimating the likelihood that the independent variable takes on one of the four (in this case) possible outcomes given the values of the explanatory variable. The coefficients represent effects related to the proliferation theory (i.e., one of the three perspectives).

Singh reports his results confirm that existing arguments do a reasonable job of accounting for the data, contrary to what scholars have suggested. To support his results Singh presents a list of countries having high predicted hazard values for some number of years that corresponds to countries that should have explored the nuclear option (according to the theories) but did not (as far as we know): Saudi Arabia, West Germany, Japan, Turkey, Bulgaria, Spain, Greece, Italy, and Syria. On the other hand, Singh reports that Libya, Brazil, Algeria, and Pakistan had relatively low hazard scores at the time they began seriously exploring the nuclear option.

As a voice representing advocacy for disarmament, David Krieger writes in a 2005 article, [6] “Why Nations Go Nuclear,” that the overwhelming majority of States in the international system have not chosen to go nuclear and cites the following reasons:

- Lack of technological capability
- Secure alliances
- The NPT
- Nuclear Weapons-Free Zone agreements
- Perception of negative consequences
- National self-image.

In a 2007 article [7], “Determinants of Nuclear Weapons Proliferation,” Jo Jong-Joon reports the results of another quantitative evaluation of explanations of nuclear proliferation not dissimilar to the Sonali Singh effort. Jo organizes his theory into measures of opportunity and willingness. Measures of opportunity include technology related to manufacture of nuclear weapons, economic capacity, and trade restrictions related to fissile material. Measures of willingness consist of factors related to international security, domestic politics, norms of international behavior, and national status.

The two dependent variables that Jo defines are countries that possess nuclear weapons in a given year and countries that have an active nuclear weapons development program in a given year. The independent variables are factors related to the measures of opportunity and willingness that he defines. Jo’s assessment results show that security and technological capabilities are important determinants of whether States form nuclear weapons programs while security concerns, economic capabilities, and domestic politics help explain the possession of nuclear weapons.

In a 2008 article [8], Maria Rost Rublee points out (like David Kreiger) that since the NPT came into force almost 40 years ago, only four States have acquired nuclear weapons. Rublee argues that social psychology can help us understand this near-universal signing and compliance with the NPT. She brings new terms to the debate: “persuasion,” “social conformity,” and “identification.” She claims that nuclear forbearance can be explained by 1) persuasion (behavior resulting from genuine transformation of preferences), 2) social conformity (behavior resulting from the desire to maximize social benefits or minimize social costs without a change in underlying preferences), and 3) identification (behavior resulting from the desire or habit of following the actions of an important other). Although these ideas are new, as postulated factors contributing to whether or not a country decides to pursue nuclear weapons, Rublee does tie them explicitly to social psychology literature. She discusses at the normative messages that international actors are being bombarded with and discusses what she calls “linking,” “activation,” and “consistency.” To explain activation she points out that “*In some cases norms are in direct competition with each other, and the norm that has been emphasized tends to win ou*t.” Her message is that through social psychology, we can specify the mechanisms by which the norm of nonproliferation has influenced policy makers.

Other major works on proliferation theory include but are not limited to: *The Nuclear Tipping Point–Why States Reconsider Their Nuclear Options* [9], a collection of writing published in 2004 by editors Kurt Campbell, Robert Einhorn, and Mitchell Reiss; *The Psychology of Nuclear Proliferation: Identity, Emotions, and Foreign Policy* [10] by Jacque Hymans, who emphasizes the impact of State leadership; *Technology and the Proliferation of Nuclear Weapons,* [11] by Richard Kokoski, who examines crucial technologies affecting nuclear weapon proliferation and their potential ramifications for the NPT regime; *Nuclear Proliferation after the Cold War*, [12] by Michell Reiss, who talks about how some of the factors contributing to proliferation have changed since the break up the Soviet Union; and *Nuclear Proliferation Technology Trend Analysis*, [13] by Mike Zentner, which describes and quantifies how long different countries took to achieve different proliferation-related technologies.

In a recent article, "The Perils of Predicting Proliferation", [14] Montgomery and Sagan provide a cautionary note and give specific warnings about the pitfalls of predicting proliferation. Among their observations are that proliferation study findings are rarely subject to a robust test, variables related to social factors like prestige and bureaucratic power are often overlooked and that it is difficult to find proxies for certain proliferation related variables like "nonproliferation regime."

This collection of literature is considered to represent this part of the problem space (i.e., theories of State-level proliferation) by the research team. Other germane literature includes actual case studies of individual countries. A representative set of those references is provided in Section 4.2.

References[1]

[1] Epstein W. 1977. "Why States Go–And Don't Go–Nuclear." *The Annals of American Academy of Political and Social Science* 430(1):16-28. Accessed March 24, 2009, at http://ann.sagepub.com/cgi/content/abstract/430/1/16.

Abstract: The incentives and disincentives for countries to go nuclear comprise a combination of military, political, and economic concerns and motivations. These vary over time for different countries. For countries allied to one of the two nuclear superpowers, concern about military security is not a predominant factor, while it is the decisive one for the non-nuclear countries who are not under the nuclear umbrella of a super power and who perceive serious threats to their security. For countries without acute security problems, the political and economics motivations are the predominant ones and these include such incentives as strengthening their independence and increasing their status and prestige in the world. The disincentives are largely political, ranging from effective security guarantees through adequate supplies of conventional armaments to assurances concerning future supplies of fissile materials. Incentives to go nuclear appear to outweigh the disincentives. Only drastic measures by the nuclear powers in the way of security assurances, nuclear disarmament, and the creation of a more just political and economic world order can serve to prevent the emergence of a proliferated world.

[2] Meyer S. 1984. *The Dynamics of Nuclear Proliferation*. The University of Chicago Press, Chicago, Illinois.

Abstract: Stephen Meyer presents a systematic examination of the underlying determinants of nuclear weapons proliferation. Looking at the current theories of nuclear proliferation, he asks: Must a nation that acquires the technical capability to manufacture nuclear weapons eventually do so? In a rigorous and accessible analysis Meyer provides the first empirical, statistical model explaining why particular countries became nuclear powers when they did. His finding clearly contradict the notion that the pace of nuclear proliferation is controlled by a technological imperative and shows that political and military factors account for the past decisions of nations to acquire or forgo development of nuclear weapons.

In contrast, the technological imperative−the motivational hypothesis that Meyer espouses−sees latent capacity as a necessary, but not sufficient, condition. It assumes some specific politico-military condition is necessary to motivate the proliferation decision. The motivational aspects are the *decision stimuli*, *decision options*, and *choice*. The motivational basis consists of the motive factors and dissuasive factors. The actual choice will result from the incentives and disincentives attached to each option.

[3] Sagan S. 1997. "Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb." *International Security* 21(3):54-86.

[1] The abstracts included here with references cited and discussed in this section were taken primarily from corresponding published abstracts, forewords, or paper or report introductions and other summary materials. However, this material was typically edited to produce abstracts of similar length and tone.

Abstract: Scott Sagan refutes the idea that international security is the dominant factor in what countries decide to pursue nuclear weapons which he call the "security model" and goes on to describe two other theories, the "domestics politics model" and the "norms model."

The Domestic Politics model of nuclear weapons proliferation focuses on domestic actors who encourage or discourage governments from pursuing the bomb. Sagan points out three kinds of actors that typically appear in historical case studies of proliferation: 1) the State's nuclear energy establishment (which includes officials in State-run laboratories as well as civilian reactor facilities), 2) important units within the professional military (e.g., navy bureaucracies interested in nuclear propulsion), and 3) politicians in States in which individual parties or the mass public strongly favor nuclear weapons acquisition. When such actors form coalitions strong enough to control government decisions directly or indirectly, then nuclear weapons incentive can thrive.

According to Sagan, the norms model of nuclear proliferation is seeing proliferation decisions as serving important symbolic functions in both shaping and reflecting a State's identity. According to this perspective, a State's behavior is determined not by leaders' cold calculations about the national security interests or their parochial bureaucratic interests, but rather by deeper norms and shared beliefs about what actions are legitimate and appropriate in international relations.

[4] Ogilvie-White T. 1996. "Is There a Theory of Nuclear Proliferation? An Analysis of the Contemporary Debate." *The Nonproliferation Review* Fall Issue 43-60.

Abstract: This article has analyzed the contemporary debate over the dynamics of nuclear proliferation, exposing the areas where confusion has occurred due to the multi-faceted and complex nature of proliferation dynamics. It has also argued that the nuclear proliferation process itself must be viewed as the consequence of a combination of internal and external pressures and constraints, involving influential organizations, groups, and individuals, and their ideas, beliefs, and interests. When the complexities of this process are considered, it is not surprising to discover that none of the existing theories of nuclear proliferation provide a satisfactory explanation of proliferation dynamics, although many provide important pieces of the puzzle. Ogilvie-White highlights this point, summarizing the strengths and weaknesses of the most significant theories and models discussed.

[5] Singh S and CR Way. 2004. "The Correlates of Nuclear Proliferation: A Quantitative Test." *Journal of Conflict Resolution* 48(6):859-885.

Abstract: Developing an adequate theory of proliferation remains a central security issue, given fears of rogue States, withdrawal of cold-war-era security guarantees, a falling technological threshold, and availability to terrorist organizations. A dataset on nuclear proliferation is constructed that identifies three different stages on the path to the weaponization of nuclear weapons technology. Hazard models and multinomial logistic regressions are used to test theories of nuclear proliferation. Results suggest that nuclear weapons proliferation is strongly associated with the level of economic development, the external threat environment, lack of great-power security guarantees, and a low level of integration in the world economy.

[6] Krieger D. 2005. "Why Do Nations Go Nuclear?" The Istanbul Workshop on Nuclear Dangers in the Middle East, November 17-21, Istanbul, Turkey. Accessed March 24, 2009, at http://www.wagingpeace.org/articles/2005/11/00_krieger-why-nations-go-nuclear.htm.

Abstract: Krieger offers as a hypothesis four principal, though often overlapping, factors: fear, security, enhancing the country's bully potential or countering another country's bully potential, and prestige. North Korea seems to be pioneering a fifth reason: to use the weapons as a bargaining chip to gain security guarantees and financial concessions. Each country that chooses to go nuclear will certainly reflect some or all of these reasons in their decision, although they may be in different combinations or proportions for different States. The reasons the current nuclear weapons States went nuclear provide insights into these dynamics.

[7] Jo D-J and E Gartzke. 2007. "Determinants of Nuclear Weapons Proliferation." *Journal of Conflict Resolution* 51(1):167-194. Accessed March 24, 2009, at http://jcr.sagepub.com/cgi/content/abstract/51/1/167.

Abstract: Diverse opinions exist about the determinants of proliferation and the policy options to alter proliferation incentives. We evaluate a variety of explanations in two stages of nuclear proliferation¯the presence of nuclear weapons production programs and the actual possession of nuclear weapons. We examine proliferation quantitatively, using data collected by the authors on national latent nuclear weapons production capability and several other variables, while controlling for the conditionality of nuclear weapons possession based on the presence of a nuclear weapons program. We find that security concerns and technological capabilities are important determinants of whether States form nuclear weapons programs, while security concerns, economic capabilities, and domestic politics help to explain the possession of nuclear weapons. Signatories to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) are less likely to initiate nuclear weapons programs, but the NPT has not deterred proliferation at the system level.

[8] Rublee M. 2008. "Taking Stock of the Nuclear Nonproliferation Regime: Using Social Psychology to Understand Regime Effectiveness." *International Studies Review* 10(3):420-450. Accessed March 24, 2009, at http://www3.interscience.wiley.com/journal/121385697/abstract.

Abstract: Since the Nuclear Nonproliferation Treaty (NPT) came into force almost 40 years ago, only four States have acquired nuclear weapons. What accounts for such near-universal compliance? This paper argues that social psychology can help us understand the puzzle of nuclear restraint in two ways. First, nuclear forbearance should be unpacked into three outcomes: persuasion (behavior resulting from genuine transformation of preferences), social conformity (behavior resulting from the desire to maximize social benefits and/or minimize social costs, without a change in underlying preferences), and identification (behavior resulting from the desire or habit of following the actions of an important other). Second, through social psychology, we can specify the mechanisms by which the norm of nonproliferation has influenced policy makers. Indeed, the case of Japan shows that both these contributions help us better understand nuclear decision-making and offer larger insights into regime compliance more generally.

[9] Campbell K, R Einhorn, and M Reiss, Editors. 2004. *The Nuclear Tipping Point – Why States Reconsider Their Nuclear Options*. The Brookings Institution, Washington, D.C. Accessed March 24, 2009, at http://books.google.com/books?hl=en&lr=&id=NvkDBNV-ks8C&oi=fnd&pg=PR7&dq=The+Nuclear+Tipping+Point+%E2%80%93+Why+States+Reconsider+Their+Nuclear+Options.&ots=srrQUwfFxH&sig=pssPxovXtfSripuoJsj2OuGmoaQ#PPP1,M1.

Abstract: Today many of the building blocks of a nuclear arsenal—scientific and engineering expertise, precision machine tools, software, design information—are more readily available than ever before. The nuclear pretensions of so-called rogue states and terrorist organizations are much discussed. But how firm is the resolve of those countries that historically have chosen to forswear nuclear weapons? A combination of changes in the international environment could set off a domino effect, with countries scrambling to develop nuclear weapons so as not to be left behind-or to develop nuclear "hedge" capacities that would allow them to build nuclear arsenals relatively quickly, if necessary.

The Nuclear Tipping Point examines the factors, both domestic and transnational, that shape nuclear policy. The authors, distinguished scholars and foreign policy practitioners with extensive government experience, develop a framework for understanding why certain countries may originally have decided to renounce nuclear weapons—and pinpoint some more recent country-specific factors that could give them cause to reconsider. Case studies of eight long-term stalwarts of the nonproliferation regime—Egypt, Germany, Japan, Saudi Arabia, South Korea, Syria, Turkey, and Taiwan—flesh out this framework and show how even these countries might be pushed over the edge of a nuclear tipping point.

[10] Hymans J. 2006. *The Psychology of Nuclear Proliferation: Identify, Emotions, and Foreign Policy*. Cambridge University Press, Cambridge, Massachusetts. Accessed March 24, 2009, at http://books.google.com/books?hl=en&lr=&id=EoNoZom3TIwC&oi=fnd&pg=PA1&dq=+The+Psychology+of+Nuclear+Proliferation:+Identify,+emotions,+and+Foreign+Policy,&ots=hwkxuIwBHN& sig=FQm_6F-9BNi7TUcqnymPswclpGU.

Abstract: Dozens of states have long been capable of acquiring nuclear weapons, yet only a few have actually done so. The author, Jacques E. C. Hymans, finds that the key to this surprising historical pattern lies not in externally imposed constraints, but rather in state leaders' conceptions of the national identity. Synthesizing a wide range of scholarship from the humanities and social sciences to experimental psychology and neuroscience, Hymans builds a rigorous model of decision making that links identity to emotions and ultimately to nuclear policy choices. Exhaustively researched case studies of France, India, Argentina, and Australia - two that got the bomb and two that abstained - demonstrate the value of this model while debunking common myths. This book will be invaluable to policymakers and concerned citizens who are frustrated with the frequent misjudgments of states' nuclear ambitions, and to scholars who seek a better understanding of how leaders make big foreign policy decisions.

[11] Kokoski R. 1996. *Technology and the Proliferation of Nuclear Weapons*. Sipri Oxford University Press, New York.

Abstract: This examination of the implementation of the nuclear non-proliferation regime focuses on critical developments, technological in particular, currently endangering the regime. Crucial technologies affecting nuclear weapon proliferation and their potential ramifications for the NPT regime as a whole are examined and potential policy options which could ameliorate or perhaps eliminate the resulting dangers are analyzed. Developments and problems raised by the nuclear programs in Iraq and North Korea receive special attention. The book contributes to the discussion and debate occurring in preparation for the 1995 NPT Extension and Review Conference.

[12] Reiss M and RS Litwak, Editors. 1994. *Nuclear Proliferation after the Cold War*. Woodrow Wilson Center Press.

Abstract: The Authors claim that the end of the Cold War fundamentally changed the calculus of nuclear threat. So, although the world no longer lives in the fear of a superpower confrontation leading to nuclear holocaust, other dangers have arisen. The authors claim that former Soviet republics threaten to gain control over nuclear weapons sited on their territories, and also report on North Korea, Pakistan, India, and Iraq reveal current or recent weapon development programs. In this climate, Nuclear Proliferation after the Cold War offers a timely assessment of the prospects for nuclear nonproliferation.

[13] Zentner M, GL Coles, and RJ Talbert. 2005. *Nuclear Proliferation Technology Trends Analysis*. PNNL-14480, Pacific Northwest National Laboratory, Richland, Washington.

Abstract: An important element in predicting and evaluating future proliferation events is to understand past events, that is, the different pathways actually taken to acquire or attempt to acquire the fissionable material (also known as Special Nuclear Material or SNM) essential for nuclear weapons. This text describes how States in the past have staged their fissile material acquisition efforts, so that by evaluating historical events in nuclear technology development, conclusions can be reached concerning: 1)The length of time it takes to acquire a technology, 2) The length of time it takes for production of SNM to begin, and 3) The type of approaches taken to acquire the technology.

[14] Alexander H. Montgomery and Scott Sagan. 2009. "The Perils of Predicting Proliferation" *Journal of Conflict Resolution* 53(2):302-328. Accessed November 20, 2009, at http://jcr.sagepub.com/cgi/content/abstract/53/2/302.

Abstract: : Studies of nuclear proliferation share five serious problems. First, nuclear programs' initiation and completion dates are ambiguous and difficult to code, but findings are rarely subjected to sufficient robustness tests using alternative coding. Second, independent variables overlook important factors such as prestige and bureaucratic power and often use poor proxies for concepts such as the nonproliferation regime. Third, methodologies and data sets should be tightly coupled to empirical questions but are instead often chosen for convenience. Fourth, some findings provide insights already known or believed to be true. Fifth, findings can ignore or gloss over data crucial for policy making and wider debates. This article reviews new quantitative research on nuclear proliferation, noting improved analysis and lingering problems. It highlights the 1999 Kargil war to explore dangers of relying on stock data sets and the need for research on statistical outliers. It concludes with a future research agenda aimed at correcting problems and a cautionary note regarding hasty application of quantitative results to policy making.

3.2 Proliferation Resistance Assessment Literature

The current body of publicly available proliferation resistance literature consists primarily of proposed proliferation resistance assessment methodologies (with example applications), as well as guidance on what makes a good proliferation resistance assessment method. There is not as much literature presenting the results of the sustained application of a particular methodology on existing facilities or proposed designs. Methodologies for use in performing proliferation resistance assessment are still evolving [1]. There is not yet a standardized approach that can be used to support global decisions to assess different reactor and fuel cycle systems. According to Wiborg, a methodology that would be universally accepted must solve a number of problems [2]:

- It must be capable of measuring tradeoffs between intrinsic and extrinsic measures.

- It must represent a wide consensus of the technical community.
- It must produce reproducible results.
- It must accommodate a range of uncertainty.
- It must be understandable by an intelligent, non-technical audience.
- It must aid in reducing proliferation risk without introducing new opportunities for proliferation.

The 2007 Sandia National Laboratories report, *Strengthening the Foundations of Proliferation Assessment Tools* [3], describes several characteristics needed for a robust proliferation resistance assessment methodology. According to the report, the methodologies should be:

1. Auditable: Assessment tools should readily allow others to review the results of their application and lend themselves to criticism and contestation.
2. Transparent: Users and reviewers should be able to easily determine what data was used, how it was obtained, and how each element or input affects the results. The existence of relationships between data inputs, which may unintentionally weight or discount particular elements, should be identifiable and their effects understood.
3. Flexible: Assessment tools need to be flexible in three primary ways. First, they should allow for sensitivity analysis to evaluate the importance of the presence or absence of individual inputs. Second, they should be applicable to any nuclear process, facility, or activity[1]. Finally, assessment tools should be applicable to multiple users.

According to the Sandia report, increased interest in proliferation risk and resistance methodologies has created a desire to use these assessments for various purposes. These purposes identified in this report are:

1. International Policy Considerations: Evaluations of the effect the acquisition of a particular nuclear energy system has on a given State's ability to develop a weapons capability while under IAEA safeguards.
2. Domestic Policy Considerations: Internal choices about the adoption of any given nuclear technology. In most cases, the primary concern of domestic policy will relate to theft-type threats and the performance of physical protection measures.
3. Technical Design and Evaluation Tasks: Design and assessment of fuel cycle and safeguards technologies; cost/benefit evaluations.
4. Technical Analysis Capabilities: Improved ability to understand how system features impact nonproliferation goals.

This Sandia document also defines critical attributes and inputs for each of the five stages of proliferation, as defined by the authors' approach: Diversion, Facility Misuse, Transportation, Transformation, and Weapons Fabrication.

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[1] However, the Sandia team warns that evaluations of specific technologies in the absence of the context of a State's nuclear energy system in which they are deployed offer only limited, and in some cases, misleading information.

A guideline on proliferation resistance assessment is presented in a work by the NPAM working group in: PNNL-14292, *Guidelines for the Performance of Nonproliferation Assessment* [4]. This guideline identifies three overall approaches to proliferation risk and proliferation resistance assessments: 1) attribute analysis approach, 2) scenario approach, and 3) the two-sided method. The attribute analysis approach (e.g., multi-attribute utility analysis) consists of identifying the characteristics of a system (e.g., barriers) that make it more or less resistant to proliferation and assigning measures to those values. The scenario, or pathway[1], analysis approach consists of identification and evaluation of specific scenarios leading to proliferation and their likelihood [4]. Probabilistic Risk Assessment is an example of a scenario analysis approach. The two-sided method consists of examining the interplay between adversaries with opposing objectives (e.g., table top and red team physical protection exercises). The methods have different areas of strength.

The guidelines document also offers a list of tools that are available for use in proliferation resistance assessments. Those tools are:

- 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 elicitations are structured techniques for obtaining expert judgment while minimizing bias.
- Uncertainty analysis, sensitivity studies, and importance measures are methods used to place the results in the context of analysis uncertainties and to indicate which factors contribute most significantly to the results.
- Dynamic models describe the time-dependence of processes, usually by the solution of differential equations.
- Multi-Attribute Utility theory is a means of assessing and aggregating widely different characteristics of a system in a common set of units.
- Probabilistic methods are 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 is an attribute analysis method that 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 is an alternative means of treating imprecise and uncertain processes in which possibilities, rather than probabilities, are assessed,
- Two-sided methods are approaches that examine the interplay between adversaries with opposite objectives.

In a 2002 IAEA report from the Department of Safeguards [5], the Agency affirms that proliferation resistance should be examined "…*from a combination of, inter alia, technical design features, operational modalities, institutional arrangements, and safeguards measures…*" and take into consideration both intrinsic and extrinsic measures. Intrinsic measures are those features that result from

[1] This reference [4] defines the term "Pathway" as "…*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.

the technical design of nuclear energy systems. Extrinsic measures are the characteristics that result from States' decisions and undertakings related to nuclear energy systems and non-proliferation. These ideas are repeated in the IAEA's proliferation resistance methodology, the INPRO methodology, discussed later.

Two proliferation resistance assessment methodologies being developed and supported by authoritative bodies are: 1) the Evaluation Methodology for Proliferation Resistance and Physical Protection of the GIF methodology[6] being developed by the GIF PP&PR[1] working group and 2) the Methodology for the Assessment of Innovating Nuclear Reactors and Fuel Cycles being developed by the IAEA-sponsored INPRO[2] methodology [7].

The GIF methodology uses pathway analysis to evaluate different scenarios in nuclear fuel cycle facilities that could result in nuclear proliferation by a State (non-State proliferation is considered by the methodology, but only through theft/sabotage scenarios evaluated in the physical protection realm). Each proliferation pathway relies on the establishment of a host-State threat definition, which encompasses the motives of the host State to acquire nuclear weapons, the urgency, type, and quantity of weapons sought, available resources, and risks deemed acceptable. The methodology considers five potential host-State proliferation strategies: concealed diversion, overt diversion, concealed facility misuse, overt facility misuse[2], and independent clandestine facility use. State capabilities are defined through general technical skills/knowledge, workforce and capital resources, uranium and thorium resources, industrial capabilities, and nuclear capabilities.

Before pathways can be defined for analysis, the fuel cycle facility's Material Balance Areas and Key Measurement Points are identified, along with the safeguards and physical protection measures to be in place at the facility. Targets–nuclear material that can be diverted, equipment and processes that can be misused to process undeclared nuclear materials, or equipment and technology that can be replicated in an undeclared facility–must also be identified. High-level pathways can be described by proliferation strategy and target. As the proliferation pathway becomes more developed, it will include the potential sequence of events or actions to be followed by the proliferator to reach its goal. The GIF methodology breaks up these sequences into three major stages: materials acquisition, material processing, and weaponization.

The GIF methodology evaluates each pathway on six measures, the first four of which are intrinsic features of the system, and the last two of which are both intrinsic and extrinsic features applied to the system. The measures are:

- Proliferation Technical Difficulty (TD)
- Proliferation Cost (PC)
- Proliferation Time (PT)
- Fissile Material Type (MT)
- Detection Probability (DP)

[1] The Generation IV International Forum (GIF) is developing next-generation energy system and nuclear reactor technologies to be deployed by 2030. Technology goals of the GIF highlight proliferation resistance and physical protection along with sustainability, safety, reliability, and economy.
[2] Sometimes referred to as "breakout."

- Detection Resource Efficiency (DE).

MT is estimated for the complete pathway, but the other measures are evaluated for the entire pathway. Social, cultural, and economic factors play a role in the TD, PC, and PT measures.

The INPRO methodology is the other major proliferation resistance assessment methodology discussed in this report. It attempts to measure the proliferation resistance of a nuclear energy system by determining the proliferation resistance provided through a combination of technical design features, operational modalities, institutional arrangements, and safeguards measures that inhibit proliferation by State actors.

The INPRO methodology addresses both technical and State-specific considerations. According to the methodology, the strength of the proliferation resistance provided by some intrinsic features can depend on State-specific information such as, *inter alia*, the presence of indigenous uranium resources or the presence of other nuclear facilities. Similarly, State-specific extrinsic measures, such as fuel supply agreements for the procurement of fresh fuel and return of spent fuel can affect the proliferation resistance of nuclear energy systems.

The INPRO methodology uses a hierarchical structure of top-level basic principles, user-requirements, indicators, evaluation parameters, and acceptance criteria. This approach is consistent with the approach used in others areas in which IAEA has oversight (e.g., waste management, environment, and nuclear safety). The approach is meant primarily for existing facilities opposed to proposed designs. The INPRO methodology proliferation resistance approach [7] identifies two *Basic Principles of Proliferation Resistance*[1] and five *User Requirements* for meeting this principle along with 17 indicators with specific criteria and acceptance limits. Assessors review the proliferation resistance characteristics of a nuclear energy system in a given State to determine how well the requirements are met. The five User Requirements are:

- UR1.1 States' commitments, obligations, and policies regarding non-proliferation should be adequate.
- UR1.2 The attractiveness of nuclear material in a nuclear energy system for a nuclear weapons program should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the nuclear energy system.
- UR1.3 The diversion of nuclear material should be reasonably difficult and detectable. Diversion includes the use of an innovative nuclear energy system facility for the introduction, production, or processing of undeclared nuclear material.
- UR2.1 Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures.
- UR2.2 The combination of intrinsic features and extrinsic measure, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.

[1] Basic Principle BP1: Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that nuclear energy systems will continue to be an unattractive means to acquire fissile material for a nuclear weapons program.
Basic Principle BP2: Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.

The GIF and INPRO proliferation resistant methodologies both rely on some social information, but utilize that information in different ways. The GIF methodology uses social information (mostly political information, based on the State's urgency, goals, and capabilities for proliferation) in the definition of the threat scenario. However, it does not directly address how to determine the threat scenario for nuclear fuel cycle facilities that are being assessed in different States. The INPRO methodology considers social information in its "extrinsic" measures, utilizing information about treaties and agreements, enforcement of safeguards and non-proliferation obligations, and other undertakings. While it would be possible to evaluate an identical technology under two distinct "extrinsic" circumstances using the INPRO methodology, it does not consider the actual motivation of a State to proliferate. As such, both methodologies could benefit from the use of social modelling to better define their threat scenarios, incorporate those scenarios into the methodology itself, and consider motivation and intent as an extrinsic feature of a State affecting the proliferation resistance of a given technology.

The Markov-modelling approach [8], developed by Brookhaven National Laboratory, is a significant contribution to the proliferation resistance methodology field. The Markov-modeling approach was developed as an application of the GIF methodology. It calculates three proliferation resistance measures: detection probability, technical failure probability, and proliferation time. The approach has three distinct features:

1. An effective detection rate has been introduced to account for the implementation of multiple safeguards approaches at a given strategic point.
2. Technical failure to divert material is modelled as an intrinsic barrier related to the design of the facility or the properties of the material in the facility.
3. Concealment to defeat or degrade the performance of safeguards is recognized in the Markov model.

There have been significant contributions to proliferation resistance assessment literature by a number of analysts. Some contributions, like LA-UR-01-0169, *Review of Approaches for Quantitative Assessment of the Risks of and Resistance* [9], by Los Alamos National Laboratory and *Review of JNC's Study on Assessment Methodology of Nuclear Proliferation Resistance* [10] by Naoko Inoue provide a review or general guidance on designing valid proliferation resistance approaches. Other contributions provide specific approaches, applications, or interpretation of results. Most assessment approaches fall into one of two of the camps identified by the NPAM working group report, *Guidelines for the Performance of Nonproliferation Assessment*: scenario analysis and attribute analysis[1].

Analyses utilizing attribute methodologies include the 1978 Massachusetts Institute of Technology (MIT) methodology [11], the Advanced Fuel Cycle Initiative (AFCI) based multi-attribute utility analysis (MAUA) [12], the Japan Atomic Energy Agency (JAEA) quantitative assessment methodology [13], and the Korean Atomic Energy Research Institute quantitative assessment methodology [14]. Scenario-based methodologies include the Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) methodology [15][16], Risk-Informed Probabilistic Analysis (RIPA)[17], and the Simplified Approach to the Proliferation Resistance Assessment of Nuclear Systems (SAPRA)[15]. For an overview of the most recognized methodologies, and their incorporation of social modelling, see Table 3.2.

[1] Limited work has been done in two-sided analyses, with the majority of the work being conducted for physical protection rather than proliferation resistance.

This collection of literature is considered to be representative of this part of the problem space (i.e., proliferation resistance assessment) by the research team but is by no means a complete compilation.

Table 3.2. Proliferation Risk/Resistance Assessment Methodologies

Methodology and Approach	Technical Attributes	Social Attributes	Qualitative/ Quantitative
MIT Methodology (1978) Attribute Analysis	• Cost: the total cost for achieving aspired nuclear weapons capability • Weapon development time: time from first proliferation action to completed weapon • Difficulty • Weapons material: proxy attribute for difficulty • Warning period: time between detection and completed weapon	Considers country-specific political and institutional frameworks: industrial infrastructure, scientific know-how, economic capability, resource sufficiency, **geopolitical** outlook. Also defines weapons **aspiration** level–quality and quantity of weapons.	Quantifies values and tradeoffs between technical measures such as cost, time, and difficulty through MAUA and expert elicitation, such as the tradeoff between the warning period (international intervention, sanctions, etc.) and difficulty and weapons material obtained, also between cost and time for weapons development. Had difficulty combining political and technical attributes into a meaningful result.
AFCI-based Multi-attribute Utility Analysis (Charlton) (1999) Attribute analysis	• Material attractiveness • Material concentration • Handling requirements • Accounting system • Accessibility to material	None. Does not address social factors, including threat characterization.	Quantitative. Results in a numeric proliferation resistance “score” based on objective and subjective measures, which are not always independent.
Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) (2000) Attribute analysis	• Material barriers: isotopic, chemical, radiological, mass, bulk • Technical barriers: unattractiveness of the facility, access controls, detectability, required skills, time • Safeguards and other extrinsic measures that prevent proliferation	Relies on definition of a proliferation threat, against which all of the barriers are measured. Institutional barriers may also have implications for social attributes (what kind of States sign the AP, etc.)	Qualitative non-linear scales: I=ineffective barrier; L=low barrier; M=medium barrier; H=high barrier; VH=very high barrier

Table 3.2. (contd)

Methodology and Approach	Technical Attributes	Social Attributes	Qualitative/ Quantitative
Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) (2000) Attribute analysis	• Material barriers: isotopic, chemical, radiological, mass, bulk • Technical barriers: unattractiveness of the facility, access controls, detectability, required skills, time • Safeguards and other extrinsic measures which prevent proliferation	Relies on definition of a proliferation threat, against which all of the barriers are measured. Institutional barriers may also have implications for social attributes (what kind of States sign the AP, etc.)	Qualitative non-linear scales: I=ineffective barrier; L=low barrier; M=medium barrier; H=high barrier; VH=very high barrier
GIF PRPP (2002) Scenario Analysis	• Technical difficulty • Proliferation time • Proliferation cost • Fissile material type • Probability of detection • Detection resource efficiency	Uses social information in the form of threat characterization. Aspects such as capability can affect time, cost, and technical difficulty, as does the actor value of human life, financial resources, willingness to get caught, etc. Social factors might influence adversary strategy, which is part of the threat characterization.	Semi-quantitative. Uses "binned" quantitative scales. Does not propose a manner to aggregate data.
Risk-Informed Probabilistic Analysis (RIPA) (2002) Scenario Analysis	• Proliferation pathway cost • Observability of elements that make up the pathway • Materials throughput of the process (schedule) • Pathway's likelihood of achieving technical success	The PRA operates within a defined threat scenario, which characterizes the proliferator's technical capabilities, know-how, fuel cycle facilities already in place, etc. Mentioned incorporating Stephen Meyer's *The Dynamics of Nuclear Proliferation* for **motivation** measure.	Quantitative. Computes each scenario metric probabilistically. Quantitative computation through fault-tree/event-tree analysis. Uses influence diagrams, fault trees. 3-D scatter plots to display results.

Table 3.2. (contd)

Methodology and Approach	Technical Attributes	Social Attributes	Qualitative/ Quantitative
JAEA Quantitative Assessment Methodology (2003) Attribute analysis	• Mass • Volume • Radiation field • Isotopic composition • Chemical composition	Considers threat characteristics and institutional barriers (facility safeguards)	Semi-quantitative. Barriers are assigned weights, and input for matrix is gathered through expert elicitation. The effectiveness of each barrier against proliferation is scored on a scale of 1-5, corresponding to the TOPS qualitative scale.
KAERI Quantitative Assessment Methodology (2004) Attribute analysis	• Isotopic content • Chemical form • Radiation field • Heat generator • Spontaneous neutron generator • Difficult to modify facility • Design features limiting access to nuclear material • Bulk/Mass • Diversion detect-ability	Considers Skills, expertise and knowledge required to divert or produce nuclear material and convert it to weapons-useable form as a specific indicator.	Semi-quantitative. Indicators for “Attractiveness of nuclear material” and “Difficulty and detectability,” Indicators are scored in one of five categories from very low to very high.
International Project on Innovation Nuclear Reactors and Fuel Cycles (INPRO) (2003) Attribute analysis	• Material characteristics • Diversion difficulty - Detectability • Defense-in-depth strategy • Robustness of barriers • Cost	State’s nonproliferation commitments, obligations, policies (such as import/export), access control to nuclear material and facilities, IAEA and regional/ bilateral/national verification measures, legal/institutional arrangements to address violations of nonproliferation. Does not consider threat characteristics.	Semi-quantitative. Some attributes are strictly quantitative, but are assigned qualifiers for different value ranges. Other attributes, specifically the extrinsic, or social, attributes are qualitative in nature.
Markov-based approach (2006) Scenario analysis	• Detection Probability • Technical Difficulty • Proliferation Time • Probability of proliferator success	Threat definition similar to GIF approach, with definition of actor characteristics and strategies.	Quantitative, Markov modeling. Uses probabilities of detection and successful diversion as a function of time.

Table 3.2. (contd)

Methodology and Approach	Technical Attributes	Social Attributes	Qualitative/ Quantitative
Simplified Approach to the Proliferation Resistance Assessment of Nuclear Systems (SAPRA) [18] Attribute	• Material barriers: isotopic enrichment, neutron emission, heat generation, radiation, dangerousness, chemical, radiological, mass and bulk, physical form, detectability. • Technical barriers: facility accessibility, available mass, diversion detectability, skill/expertise/knowledge, time, technical difficulty, collusion level, construction detectability, signature of the installation • Institutional barriers: safeguards, access control, security, location	Employs a country profile, consisting of nuclear weapons possession and NPT status, industrial development, existing reactors in operation, and open/closed fuel cycle options and their associated facilities. as well as acquisition strategy.	Semi-quantitative. Uses binned values to describe the robustness of each barrier. Scores for each barrier were summed and normalized, and then aggregated over proliferation phases (diversion, transport, conversion, weaponization). Results in a Proliferation Resistance Index .

References[1]

[1] Pomeroy G, R Bari, E Wonder, M Zentner, E Haas, T Killeen, G Cojazzi, and J Whitlock. 2008. "Approaches to Evaluation of Proliferation Resistance of Nuclear Energy Systems." In: The 49th Annual Meeting: Institute of Nuclear Materials Management, July 13-17, Nashville, Tennessee.

Abstract: Over the past several years, the Generation IV International Forum (GIF) has been developing an evaluation methodology for proliferation resistance and physical protection (PR&PP) of nuclear energy systems[2], through collaboration between the countries and international organizations that participate in GIF. Generation IV nuclear energy systems are nuclear reactor technologies that could be deployed by 2030 and would present significant improvements over currently operating reactor technologies. The technology goals for GIF highlight PR&PP as one of the four goal areas, along with sustainability, safety and reliability, and economics. The PR&PP evaluation methodology that has been developed is a result of a consensus among the GIF participants, and has been approved by GIF for broad dissemination and use.

In parallel with this multilateral effort by GIF, and over the same time period, the International Atomic Energy Agency (IAEA) has been sponsoring development of an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) to help to ensure that nuclear energy is available in the 21st century in a sustainable manner. In particular, INPRO has put forth basic principles, user requirements, and criteria for future nuclear energy systems, with similar broad goal areas to those that are being considered by GIF, including proliferation resistance and physical protection.

This paper describes an effort to address the compatibility and use of the two methodologies, starting with proliferation resistance, in order to more fully understand and articulate the range of applicability and the potential for synergy in their application. "Proliferation resistance" evaluation is in its early stages, and on-going efforts to use the methodologies to assess particular fuel cycles or facilities will shed further light on what proliferation resistance means, how best it can be assessed, and their value to policy-makers, facility designers and users of nuclear facilities. The authors of this paper report on the status of

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[1] The abstracts included here with references cited and discussed in this section were taken primarily from corresponding published abstracts, forewords, or paper or report introductions and other summary materials. However, this material was typically edited to produce abstracts of similar length and tone.
[2] A Generation IV nuclear energy system includes a nuclear power producing plant and the facilities necessary to implement its related fuel cycle.

progress on this effort, particularly with regard to the respective objectives, analysis approaches, input requirements, form of results and end uses. The views expressed herein are those of the authors, and do not necessarily reflect the views of the Department of Energy or its laboratories, the IAEA, Atomic Energy of Canada Limited, or the European Commission-Joint Research Centre.

[2] Wiborg J, R Omberg, and M Zentner. 2001 *Problems in Achieving A Quantitative Approach to Technologic Proliferation Resistance*. Pacific Northwest Center for Global Security, Pacific Northwest National Laboratory, Richland, Washington.

Abstract: The nuclear industry and the nonproliferation community have a stake in developing a standardized quantitative methodology for assessing proliferation resistance of different reactor and fuel cycle systems. The assessment framework must support global decisions. This methodology must address a number of problems inherent in any effort to quantify proliferation resistance. It must be capable of measuring tradeoffs between intrinsic and extrinsic measures. It must represent a wide consensus of the technical community. It must provide reproducible results, regardless of the analyst. It must accommodate a broad range of uncertainties. And it must aid in reducing proliferation risk without introducing new opportunities for proliferation. Ultimately these results must be easily used. The assessment framework used to compare the proliferation resistance of systems must be understandable by an intelligent non-technical audience, providing results in a manner that is useful to decision makers and technologists alike.

[3] Cleary VD, PE Rexroth, GE Rochau, DH Saltiel, WS Charlton, DG Ford, and Don Giannangeli. 2007. *Strengthening the Foundations of Proliferation Assessment Tools*. SAND2007-6158, Sandia National Laboratories, Albuquerque, New Mexido.

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

[4] PNNL-14294, *Guidelines for the Performance of Nonproliferation Assessment*. 2003. Pacific Northwest National Laboratories, Richland Washington.

Abstract: The NNSA established a n NPAM Working Group, comprised of representatives from DOE laboratories and academia, to develop guidelines for the practical application of 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.

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.

[5] IAEA STR-332. 2002. *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems.* International Atomic Energy Agency (IAEA), Vienna, Austria.

This document describes fundamentals that should apply to consideration of the “proliferation resistance” of future nuclear energy systems. It is intended to provide guidance to International Atomic Energy Agency (IAEA) programs and Member States activities related to the development of future nuclear energy systems, and is also intended to serve as the basis for considering

proliferation resistance in future IAEA safeguards implementation. Some elements might be also of use for current safeguards implementation. In addition, this document is relevant to two specific programs for developing future nuclear energy systems: (1) the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), established by the IAEA's General Conference Resolution CG(44)/RES/22, and (2) the GIF Program, sponsored by the United States and the associated GIF.

The proliferation resistance fundamentals presented in this document were agreed to at an international technical meeting convened by the IAEA Department of Safeguards in Como, Italy on 28-31 October 2002, organized in cooperation with the Centro Volta – Landau Network. The IAEA and the meeting participants express their appreciation to the Centro Volta – Landau Network for its support on this effort. The participants are identified in Annex I.

This document addresses only proliferation resistance. It does not address other security concerns arising in conjunction with peaceful nuclear power activities, such as the theft of nuclear material, the theft of other hazardous radioactive material, or the sabotage of nuclear installations or transport systems. It also does not make a link to the utilization of excess military materials. These are important topics, but they are not addressed in this document.

[6] GIF/PRPPWG/2006/005, Revision 5. 2006. *Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems. Generation IV International Forum*. Accessed March 24, 2009, at http://www.gen-.org/Technology/horizontal/PRPPEM.pdf.

Abstract: This report presents an evaluation methodology for proliferation resistance and physical protection (PR&PP) of Generation IV nuclear energy systems (NESs). For a proposed NES design, the methodology defines a set of challenges, analyzes system response to these challenges, and assesses outcomes. The challenges to the NES are the threats posed by potential actors (proliferant States or sub-national adversaries). The characteristics of Generation IV systems, both technical and institutional, are used to evaluate the response of the system and determine its resistance against proliferation threats and robustness against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of six measures for PR and three measures for PP, which are the high-level PR&PP characteristics of the NES. The methodology is organized to allow evaluations to be performed at the earliest stages of system design and to become more detailed and more representative as design progresses. Uncertainty of results are recognized and incorporated into the evaluation at all stages. The results are intended for three types of users: system designers, program policy makers, and external stakeholders. Program policy makers will be more likely to be interested in the high-level measures that discriminate among choices, while system designers will be more interested in measures that directly relate to design options that will improve PR&PP performance of the NES.

[7] IAEA-TECDOC-1434. 2004. *Methodology for the Assessment of Innovative Nuclear Reactors and Fuel Cycles. Report of Phase 1B (first part) of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).* International Atomic Energy Agency (IAEA), Vienna, Austria.

Abstract: The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was launched in the year 2000, based on resolutions of the IAEA General Conference. INPRO intends to help to ensure that nuclear energy is available in the 21st century in a sustainable manner, and bring together all interested Member States, both technology holders and technology users, to jointly consider actions to achieve desired innovations.

INPRO is proceeding in steps. In its first step, referred to as Phase 1A, INPRO developed a set of basic principles, user requirements, and criteria together with an assessment method, which taken together, comprise the INPRO methodology, for the evaluation of innovative nuclear energy systems. The results of Phase 1A were documented in IAEA-TECDOC-1362, published in 2003.

This report documents changes to the basic principles, user requirements, criteria, and the method of assessment that resulted from the second step of INPRO (referred to as Phase 1B (first part)), which started in June 2003 and ended in December 2004. During this step, Member States and individual experts performed 14 case studies with the objective of testing and validating the INPRO methodology. Based on the feedback from these case studies and numerous consultancies mostly held at the IAEA, the INPRO methodology has been significantly updated and revised, as documented in this report.

The ongoing and future activities of INPRO will lead to further modifications to the INPRO methodology, based on the feedback received from Member States in light of their experience in applying the methodology. Thus, additional reports will be issued, as appropriate, to update the INPRO methodology.

[8] Yue M, LY Cheng, and R Bari. 2006. "*Methodology for Proliferation Resistance for Advanced Nuclear Energy Systems.*" Presented at the PSAM8 – International Conference on Probabilistic

Safety, May 14-16, New Orleans, Louisiana, BNL-75428-2006-CP, Brookhaven National Laboratory, Upton, New York.

The Technology Goals for GIF nuclear energy systems highlight Proliferation Resistance and Physical Protection (PR&PP) as one of the four goal areas for Generation 1V nuclear technology. Accordingly, an evaluation methodology is being developed by a PR&PP Experts Group. This paper presents a possible approach, which is based on Markov modeling, to the evaluation methodology for GIF nuclear energy systems being developed for PR&PP. Using the Markov model, a variety of proliferation scenarios can be constructed and the proliferation resistance measures can be quantified, particularly the probability of detection. To model the system with increased fidelity, the Markov model is further developed to incorporate multiple safeguards approaches in this paper. The approach to the determination of the associated parameters is presented. Evaluations of diversion scenarios for an example sodium fast reactor (ESFR) energy system are used to illustrate the methodology. The Markov model is particularly useful because it can provide the probability density function of the time it takes for the effort to be detected at a specific stage of the proliferation effort.

Other References

[9] Krakowski RA. 2001. *Review of Approaches for Quantitative Assessment of the Risks of and Resistance*, LA-UR-01-0168, Los Alamos National Laboratory, Los Alamos, New Mexico.

[10] Inoue N, J Kurakami, and H Takeda. 2004. "*Review of JNC's Study on Assessment Methodology of Nuclear Proliferation Resistance.*" Presented at the 45th Annual Meeting of the Institute of Nuclear Materials Management, July 18-22, Orlando, Florida.

[11] Papazoglou IA, EP Gyftopoulos, NC Rasmussen, MM Miller, and H Raiffa. 1978. *A Methodology for the Assessment of the Proliferation Resistance of Nuclear Power Systems.* Topical Report MIT-EL, 78-021, MIT-EL, 78-022, Massachusetts Institute of Technology (MIT) Energy Laboratory, Cambridge, Massachusetts. Accessed March 25, 2009, at http://dspace.mit.edu/handle/1721.1/27225.

[12] Charlton WS. 2005. "Multi-Attribute Proliferation Resistance Assessment Methodology Developed for AFCI." Presented at Assessment Methodology of Proliferation Resistance for Future Nuclear Energy Systems, a Joint Workshop of the Japan Nuclear Cycle Development Institute and the Japan Chapter of the Institute for Nuclear Materials Management, Institute for Nuclear Materials Management, Tokyo, Japan.

[13] Inoue N, M Hori, and K Hori. 2003. "Methodologies of Nuclear Proliferation Resistance Assessment for Nuclear Fuel Cycle Options." The 44th Annual Meeting of the Institute of Nuclear Materials Management, July 13-17, Phoenix, Arizona.

[14] Ho DK, JH Park, WI Ko, MS Yang, and HS Park. 2004. "A Quantitative Analysis of Proliferation Resistance of DUPIC Facility Based on the INPRO Requirements." Presented at The 45th Annual Meeting of the Institute of Nuclear Materials Management, July 18-22, Orlando, Florida.

[15] TOPS. 2000. *Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS).* TOPS Task Force of the Nuclear Energy Research Advisory Committee (NERAC).

[16] Hassberger JA. 2001. *Application of Proliferation Resistance Barriers to Various Existing and Proposed Nuclear Fuel Cycles*. UCRL-ID-147001, Lawrence Livermore National Laboratory, Livermore, California.

[17] Rochau GE, D Blair, Y McClellan, C Morrow, PE Rexroth, TT Sype, and GD Wyss. 2002. "*Risk-Informed Proliferation Analysis.*" SAND200, Sandia National Laboratories, Albuquerque, New Mexico.

[18] Greneche D. 2006. A Simplified Approach for Proliferation Resistance Assessment of Nuclear Systems (SAPRA)−Final Report, French Working Group on Proliferation Resistance and Physical Protection. Presented at the European Safeguards Research and Development Association Annual Meeting,, Aix en Provence France May 22nd – 24th, 2007.

3.3 Safeguards Analyses Literature

The safeguards analysis literature identified was organized for this discussion into three categories:

1. Assessment of safeguards systems, such as the IAEA safeguards system or regional and State safeguards systems and agreements
2. Assessment of facility-specific international safeguards, which strive to achieve address the timely detection of diversion or misuse at a particular nuclear facility with specifics relating to the type and quantity of material at the facility, and the process that is being performed
3. Assessment of specific safeguards measures, which compare and contrast individual safeguards measures and techniques for their ability to detect diversion and misuse of nuclear materials.

An additional category of safeguards literature is not included in this report: State-level safeguards that are being to be implemented as part of the IAEA's State-Level Approach [1][2]. There have been only limited attempts to evaluate the effectiveness of State-level safeguards because they are relatively new and still under development. State-level safeguards means that the State has entered into force a comprehensive safeguard agreement and additional protocols[1] [2]. A State-level approach integrates a broad range of information sources in an attempt to not only detect diversion and misuse of nuclear material, but also to confirm the absence of undeclared activities. Detection of undeclared activities includes assessing import and export-control information, open-source media information, satellite imagery, environmental samples, and other information sources related to nuclear activities within a State and comparing that information to the State's declaration to identify and resolve inconsistencies or inaccuracies. As such, this evolving information-driven safeguards approach may represent an opportunity to use or further integrate social science.

3.3.1 Assessment of Safeguards Systems

Assessment of safeguards system refers to assessment of a body of safeguards controls, such as the IAEA safeguards system, and safeguards at an organizational or State level (such as safeguards approaches in the DOE complex). Some assessments, such as Bennett et al. [3], even incorporate societal-level characteristics to inform safeguards assessments and evaluations.

[1] Additional protocols (which are typically modeled after the Model Additional Protocol-INFCIRC/540) mark the culmination of major safeguards strengthening measures of the 1990s as it equips the IAEA with new tools and additional information and access to verify the correctness and completeness of a State's declarations under comprehensive agreements.

Bennett et al. describe the problems facing safeguards effectiveness evaluation, in 1975, as "…*the lack of well-defined objectives, system parameters and boundary conditions as a framework for communication.*" [3] Today, more than 30 years later, safeguards have changed considerably, especially in the last decade. The expanded scope of IAEA safeguards now includes not only the verification of correct State declarations, but also verification of the completeness of those declarations using a State-Level Approach This will change the way safeguards are planned, implemented and evaluated. Nevertheless, it is still instructive to look at historical examples of safeguards analysis approaches, if only to see how they have evolved.

In their 1975 article, Bennett et al. suggest that the ultimate level of protection provided by nuclear safeguards should be an objective measure of "societal risk." [3] The goal of safeguards, then, would be to balance that perceived societal risk, which includes *"…the expected frequency of successful occurrence of deliberate destructive acts involving nuclear materials or facilities, and the potential magnitude of the effects on society."* [3] This argument–that the effectiveness of a system should be measured against its expected threat–resonates deeply with the threat characterization used in many proliferation resistance methodologies. Bennett et al. note that *"…while the evaluation of the risk associated with a postulated or existing safeguards system requires only a consideration of the protective mechanisms included in that particular system, the design or improvement of a safeguards system requires consideration of all available protective mechanisms and their associated technical and economic characteristics."* [3]

The paper "Safeguards Systems Analysis Research and Development of the Practice of Safeguards at DOE Facilities" [4] outlines the safeguards reviews for LANL as part of the Safeguards Systems Group. As part of the reviews, the team became familiar with the safeguards-related needs typical of the DOE complex and provided proposed solutions for enhanced performance and improved techniques for meeting safeguards requirements for protecting, controlling, and accounting for nuclear material. While the article does not thoroughly explain the methodology used for the assessment, it does recommend the following improvements for safeguards systems:

- As much transparency as possible with operations personnel
- Detailed evaluations of simulation and modeling software used to detect safeguards systems weaknesses, to measure effectiveness of the tools
- Ongoing technical reviews of a facility's safeguards systems, and R&D to develop new nuclear materials control and accountability techniques.

In their article, "Incorporation of a Risk Analysis Approach for the Nuclear Fuel Cycle Advanced Transparency Framework," Cleary et al. suggest the use of process information in new automated nuclear facilities as a method for monitoring proliferation risk [5]. Cleary et al. propose to incorporate process information through an examination of two distinct types of risk: expected risk and observed risk. Expected risk is "…*the risk introduced by the existence of the facility based on planned and declared operations,"* [5] and serves as the baseline of the facility's proliferation risk dependent upon the plant's design and processing capabilities. Observed risk is *"…measured instantaneously when the plant is operating and is based on the plant process data transmitted by sensors during the completion of declared operations."* [5] The expected and observed risks for nuclear facilities contribute to an estimate of a State's probability of diversion, which is part of an overall diversion risk score. Expected risk comes, in part, from the assessment of the safeguards measures that will be implemented at a nuclear facility, with the observed risk number coming, at least in part, from the readings and other outputs from those same safeguards measures. The diversion risk "…*quantifies the probability and consequence of a host nation diverting nuclear materials from a civilian fuel cycle facility*." [5] The incorporation of advanced safeguards analysis techniques into measuring diversion risk is promoted to increase transparency as part of an advanced safeguards approach.

The Integrated Safeguards Methodology (ISEM) was designed by LANL to be a safeguards evaluation tool that can flexibly analyze proposals for integrated safeguards approaches for the IAEA [6]. ISEM is promoted for use assessment of a generic facility or State-wide integrated safeguards in support of the implementation of integrated safeguards in specific States. The approach is based on hypothetical State threat and a generic fuel cycle design. The methodology was tested from between March and September 2000 with exercises to evaluate a proposal for light water reactors (LWRs) without mixed oxide (MOX) fuel, research reactors, critical assemblies, and spent-fuel storage in a hypothetical State.

3.3.2 Assessment of Facility Safeguards

Assessments of facility safeguards analysis employ many of the same concepts as for assessment of safeguards systems, combining various factors and measures to evaluate the effectiveness of the safeguards implemented for a facility. Safeguards assessments exist for virtually all types of nuclear facilities, including centrifuges enrichment, reprocessing plants, and reactors.

The Safeguards Network Analysis Procedure (SNAP), described in *A Network Modeling and Analysis Technique for the Evaluation of Nuclear Safeguards Effectiveness* [8], proposes a standardized analysis methodology for safeguards effectiveness evaluations at nuclear facilities. The objective of SNAP is to provide a means of evaluating resistance to sabotage or theft of a safeguards system, including nuclear reactor sites, spent fuel storage sites, and fuel fabrication facilities. SNAP utilizes a network modeling approach to problem-solving. According to Grant et al., "*The SNAP analysis program is used to simulate the system of interest. Reports are generated by the program to provide information which allows the analyst to evaluate the performance of proposed or existing safeguards systems." [7]* Models such as SNAP provide a consistent approach to effectiveness evaluation, and can provide quantitative information about the performance of existing or proposed safeguards systems [7]. The SNAP modeling approach can be described on two levels: *"On the general level, SNAP employs the network modeling approach to problem-solving. On the specific level, SNAP provides a structure for safeguards system analysis by dividing safeguards systems into three interacting sub-models."* The sub-models are:

- The facility – defines various components of the safeguards at the facility and their relationships
- The defender force – guard operating policies, including a representation of the decision logic associated with guards forces as well as the physical movement of guards through the facility
- The intruder force.

The SNAP tool mirrors the barrier analysis method used in proliferation resistance assessments, as well as approaches to various physical protection system assessment methodologies.

In an attempt to analyze facility-level safeguards in a more specific manner, in 2004 Brookhaven National Laboratory and Oak Ridge National Laboratory (ORNL) published the report, *Evaluation of*

IAEA Safeguards at Medium-Sized Gas Centrifuge Uranium Enrichment Plant [8]. For this paper,[1] analysts evaluated the effectiveness (probability of detection) of the IAEA's safeguards inspection activities in detecting the production of highly enriched uranium, the diversion of uranium from the material balance, and the production of undeclared low-enriched uranium using undeclared feed material. Based on the probability of detection for each scenario, analysts provided potential improvements in the safeguards approach for medium-sized centrifuge enrichment plants. One of the IAEA safeguards goals for medium-sized enrichment facilities is the timely detection of diversion of one significant quantity of nuclear material. Timeliness is determined by the amount of nuclear material, and its enrichment, present at a nuclear facility.

The report identifies the following activities as part of the activities within the cascade areas during Limited Frequency Unannounced Inspections [8]:

1. Visual Inspection
2. Non-Destructive Analysis (NDA) Measurements
3. Environmental Sampling
4. Containment/surveillance

To determine how effective these activities are in detecting diversion, *"…one must make some assumptions in order to assign a probability of detection. First, access is sufficient to provide a high probability that an individual cascade would be selected either for visual inspection or NDA measurement during each three-month period. Second, the facility would not be able to disguise process modifications. Third, the facility could not adjust the inspectors' route to avoid the isolated cascade being used for diversion. Under these assumptions, these activities have a moderate to high probability of detecting production of HEU for the second through fourth scenarios listed above. However, these activities are not designed to detect a separate undeclared HEU production area."* [8]

The analysis yields the following recommendations for potential improvements for gas centrifuge enrichment plant safeguards [8]:

1. Enhanced inspector access inside cascade halls
2. Enhanced video surveillance inside cascade halls
3. NDA measurements on piping inside the cascade halls
4. Radiation monitors inside cascade halls
5. Installation of flow monitoring equipment at the feed/withdrawal building
6. Enhanced inspector access to buildings on the plant site
7. Application of the minor isotope safeguards technique.

[1] A full report of this work is provided in UCRL-TR-212441, "System Analysis of Safeguards Effectiveness in a Uranium Conversion Plant," by Lawrence Livermore National Laboratories but is not classified for public release (i.e., is classified as Official Use Only)

According to Gordon et al., the IAEA does not currently carry our any inspection activities that are intended to detect the production of excess LEU from undeclared feed, including the verification that all feed cylinders are declared or verification of a plant's separative work capacity [8].

In their 2004 article, Elayat, Lambert, and O'Connell discuss their methodology for evaluating the effectiveness of safeguards approaches on generic uranium conversion facilities. The team utilizes directed graphs and fault trees, with safeguards indicator probabilities based on sampling statistics or measurement accuracies [9]. They use the digraph fault trees to structure diversion scenarios in which safeguards measures and activities relevant to the diversion scenario can be evaluated, including potential failure modes of the safeguards measures. Inputs to the fault tree consist of probabilities of detection of various diversion activities. Outputs include the *"...probability of success, quantity, and value of the material removed in the diversion scenarios."* [9] The most attractive diversion scenarios are determined through a time-domain simulation. The digraph fault-tree framework can look like:

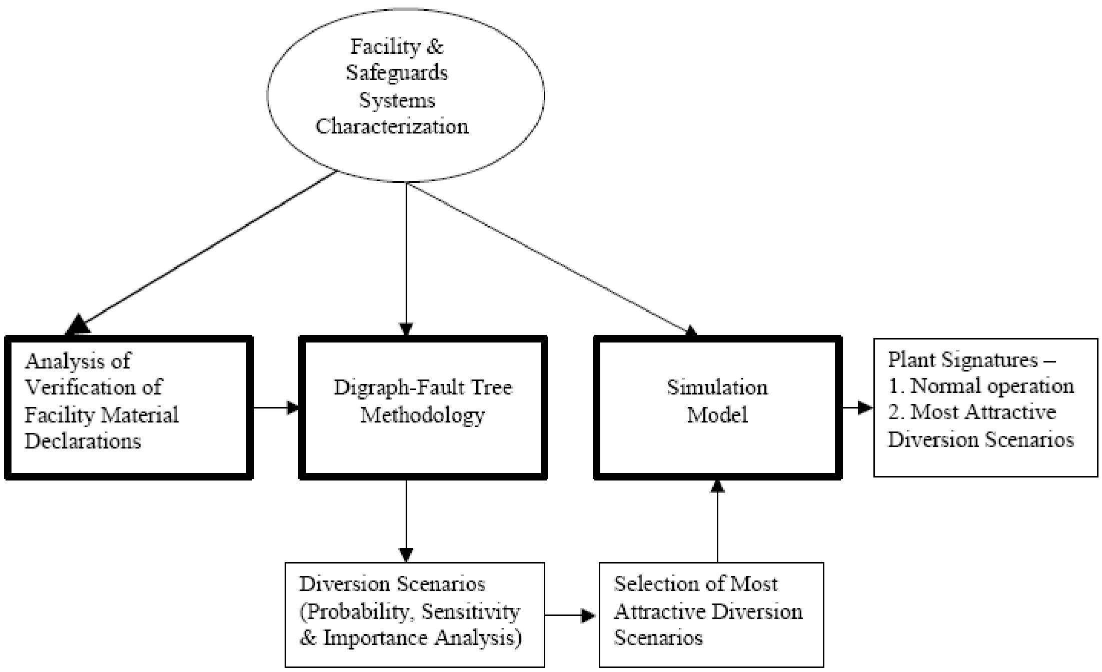


Figure 3.2. Framework for Performing Evaluation of the Effectiveness of a Safeguards System (from Elayat [9])

This framework for evaluating safeguards systems consists of eight steps [9]:

1. Describe the system to be analyzed.
2. Describe safeguards measures to be implemented by the Facility Operator and by Inspectors.
3. List removal nodes (points of diversion).
4. Define diversion scenarios for each removal node.
5. Construct a directed graph for each diversion scenario.
6. From the directed graph, construct a fault tree that describes how the diversion scenario can occur (top event is failure of safeguards system to detect the diversion).

7. Perform a fault-tree evaluation.
    a. Find the modes of failure for each diversion scenario called the min cut sets.
    b. Compute the probability of safeguards system failure for each diversion scenario.
    c. Conduct Sensitivity and importance analysis.
8. Determine the most attractive diversion scenarios for simulation.

In later literature this framework for evaluating safeguards systems is referred as an integrated safeguards system analysis tool, or LISSAT. For example, application of this approach as LISSAT on a generic centrifuge plant was published in 2007 [10].

3.3.3 Assessment of Specific Safeguards Measures

Rather than assessing an entire safeguards system, or the safeguards in place at a facility, safeguards measure- and technique-level assessments strive to analyze the effectiveness of the individual components of a safeguards system.

Jacobsson provides one such analysis in his article entitled, "Safeguards Analysis of Tomographic Data from a Measurement on a pressurized water reactor (PWR) Nuclear Fuel Assembly." Jacobsson's article compares two methods for taking tomographic measurements in support of safeguards verification activities. The data collected between the two tomographic measurement devices were compared with known values to evaluate their accuracy. From a comparison of the collected data, Jacobsson was able to conclude that the new tomographic measurement method was more accurate and that "…*even the removal of a single, central rod may confidently be detected provided that the precision can be improved*." [11] Safeguards analyses such as Jacobsson's, which evaluate a single safeguards method, technology, or technique, can be used as part of a larger-scale safeguards systems analysis, such as the barrier analysis used in the SNAP methodology [7].

Other examples of "safeguards measure" literature are: 1) the IAEA International Nuclear Verification Series document, *Safeguards Techniques and Equipment*, [12] which describes techniques and equipment used for nuclear material accountancy, containment, surveillance measures and for new safeguards of environment sampling, 2) *Computerization of the Safeguards Analysis Decision Process* [13] that assesses the challenges and opportunities related to information systems used by safeguards systems, and *Statistical Methods in Nuclear Nonproliferation Activities at Declared Facilities* [14] that describes statistical methods used in nuclear material accounting (NMA) measurements.

Still other examples of safeguards literature are specific proposals to enhance some element of a safeguards system with new technology: 1) *IAEA Safeguards: Cost/Benefit Analysis of Commercial Satellite Imagery* [15] that provides potential cost- and time-savings that could be gained by using new proposed satellite imagery, 2) *Increase in the Role of Destructive Analysis – A Strong Measure Against World Concerns on Proliferation* [16] presents a case for why destructive analysis and the high measurement accuracy it offers is an important to safeguards verification, and 3) *Safeguards Applications Options for the Laser-Based Item Monitoring System (LBIS)* [17] that proposes advantages to gain by using low-power laser transceiver to monitor the presence and position of items with retroreflective tags.

This collection of literature is considered to be representative of this part of the problem space (i.e., safeguards analysis) by the research team but is by no means meant to be a comprehensive compilation. Analysis in the area of safeguards is definitely evolving, in no small part because of the advent of strengthened safeguards and the State-level approach, which is likely to produce much more literature.

References[1]:

[1] Sylvester KB, J Pilat, and T Burr. 2008. "Evaluating International Safeguards Systems." In: *Nuclear Safeguards, Security, and Nonproliferation*. JE Doyle, Editor, Amsterdam: Elsevier Inc.

Abstract: The international safeguards system has evolved considerably since the early 1990s. Traditional safeguards measures that focus on monitoring declared materials and facilities have been augmented with new measures aimed at detecting undeclared facilities and activities. How does one integrate such disparate measures into a coherent "State-level" safeguards system and demonstrate that it is both effective and efficient? How can State-specific factors be taken into account? A comprehensive means for assessing safeguards system performance is needed. In this writing, the system of evaluation developed for traditional IAEA safeguards based on diversion pathway analysis is described and extended to include detection activities beyond declared sites.

[2] International Atomic Energy Agency (IAEA). 2009. *The Safeguards System of the International Atomic Agency*. IAEA, Vienna, Austria. Accessed March 31, 2009, at http://www.iaea.org/OurWork/SV/Safeguards/safeg_system.pdf.

Abstract: The purpose of the safeguards system of the International Atomic Energy Agency (the Agency) is to provide credible assurance to the international community that nuclear material and other specified items are not diverted from peaceful nuclear uses. Towards this end, the safeguards system consists of several, interrelated elements: (i) the Agency's statutory authority to establish and administer safeguards; (ii) the rights and obligations assumed in safeguards agreements and additional protocols; and (iii) the technical measures implemented pursuant to those agreements. These, taken together, enable the Agency independently to verify the declarations made by States about their nuclear material and activities. The nature and scope of such declarations - and of the measures implemented to verify them - stem from the type of safeguards agreement that a State has in force with the Agency. So do the specific, technical objectives of safeguards and the final product of their implementation, i.e., the Agency's safeguards conclusions, which are drawn annually and published in the Agency's Safeguards Implementation Report (SIR).

This document describes the Agency's safeguards system as it currently operates and how it is changing to respond to new challenges. It describes the legal instruments in which safeguards obligations are anchored and the measures taken, since the early 1990s, to strengthen safeguards.

[3] Bennett CA, WM Murphey, and TS Sherr. 1977. *Societal Risk Approach to Safeguards Design and Evaluation*. ERDA-7, Energy Research and Development Administration, Washington, D.C.

Abstract: Useful dialogue on this subject has been hampered by the lack of well-defined objectives, system parameters and boundary conditions as a framework for communication. This study, "Societal Risk Approach to Safeguards Design and Evaluation," provides such a framework.

Expressing the safeguards objective in terms of societal risk represents a change in focus, rather than intent, from the earlier view of safeguards as a system of protecting nuclear material against theft or diversion. The study defines both the safeguards problem and the safeguards system in terms that can be related to the general safeguards objective.

It is axiomatic that the first step to an effective solution is a careful definition of the problem. The significant and immediate value of the study lies in the rigorous definition and systematic organization of the recognized elements into a coherent pattern.

[1] The abstracts included here with references cited and discussed in this section were taken primarily from corresponding published abstracts, forewords or paper or report introductions and other summary materials. However, this material was typically edited to produce abstracts of similar length and tone.

Although the title specifically addresses design and evaluation, the framework provided by the study will be a useful management tool for safeguards implementation and administration as well.

[4] Zack NR, KE Thomas, JT Markin, and JW Tape. 1991. "Safeguards Systems Analysis Research and Development and the Practice of Safeguards at DOE Facilities". Presented at the 32nd Annual Meeting of the Institute of Nuclear Materials Management (INMM), July 28-31, New Orleans, Louisiana.

Abstract: Los Alamos Safeguards Systems Group personnel interact with Department of Energy (DOE) nuclear materials processing facilities in a number of ways. Among them are training courses, formal technical assistance such as developing management or data analysis software, and informal ad hoc assistance especially in reviewing and commenting on existing facility safeguards technology and procedures. These activities are supported by the DOE Office of Safeguards and Security, DOE Operations Offices and contractor organizations. Because of the relationships with the Operations Office and the facility personnel, the Safeguards Systems Group research and development staff has developed an understanding of the needs of the entire complex. Improved safeguards are needed in areas such as material handling procedures. This paper surveys the generic need for efficient and cost effective enhancements in safeguards technologies and procedures at DOE facilities, identifies areas where existing safeguards R&D products are being applied, and sets a direction for future systems analysis R&D to address practical facility safeguards needs.

[5] Cleary VD, GE Rochau, CM Méndez, N Inoue, T Kitabata, T Irie, and M Hori. 2007. *Incorporation of a Risk Analysis Approach for the Nuclear Fuel Transparency Framework*. SAND2007-3166, Sandia National Laboratories, Albuquerque, New Mexico.

Abstract: Proliferation resistance features that reduce the likelihood of diversion of nuclear materials from the civilian nuclear power fuel cycle are critical for a global nuclear future. A framework that monitors process information continuously can demonstrate the ability to resist proliferation by measuring and reducing diversion risk, thus ensuring the legitimate use of the nuclear fuel cycle. The automation of new nuclear facilities requiring minimal manual operation makes this possible by generating instantaneous system State data that can be used to track and measure the status of the process and material at any given time.

Sandia National Laboratories (SNL) and the Japan Atomic Energy Agency (JAEA) are working in cooperation to develop an advanced transparency framework capable of assessing diversion risk in support of overall plant transparency. The "diversion risk" quantifies the probability and consequence of a host nation diverting nuclear materials from a civilian fuel cycle facility. This document introduces the details of the diversion risk quantification approach to be demonstrated in the fuel handling training model of the MONJU Fast Reactor.

[6] Pilat JF and KB Sylvester. 2001. *Possible Roles for the Integrated Safeguards Evaluation Methodology (ISEM)*, LA-UR-01-3748, Los Alamos National Laboratory, Los Alamos, New Mexico. Accessed March 31, 2009, at http://lib-www.lanl.gov/la-pubs/00796152.pdf.

Abstract: In the future, if the nuclear nonproliferation and arms control agendas are to advance, they will likely become increasingly seen as parallel undertakings with the objective of comprehensive cradle-to-grave controls over nuclear materials and possibly even warheads removed from defense programs along with materials in civilian use. This "back to the future" prospect was envisioned in the Acheson-Lillienthal Report and the Baruch Plan, and more modestly in the Atoms-for-Peace Proposal. Unlike the grand plans of the early nuclear years, today's and tomorrow's undertakings will more likely consist of a series of incremental steps with the goal of expanding nuclear controls. These steps will be undertaken at a time of fundamental change in the IAEA safeguards system, and they will be influenced by those changes in profound ways. This prospective influence needs to be taken into account as the IAEA develops and implements integrated safeguards, including its efforts to establish new safeguards criteria, undertake technological and administrative improvements in safeguards, implement credible capabilities for the detection of undeclared nuclear facilities and activities and, perhaps, provide for a more intensive involvement in applying safeguards in new roles such as the verification of a fissile materials cutoff treaty. Performance-based approaches offer one promising way to assess and characterize the effectiveness of integrated safeguards and to provide a common means of assessing the other key areas of a comprehensive approach to nuclear controls as these develop independently and to the extent that they are coordinated in the future.

[7] Grant FH III, RJ Miner, and D Engi. 1978. *A Network Modeling and Analysis Technique for the Evaluation of Nuclear Safeguards Effectiveness*. NUREG/CR-0616, prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Washington, D.C.

Abstract: Nuclear safeguards systems are concerned with the physical protection and control of nuclear material. The Safeguards Network Analysis Procedure (SNAP) provides a convenient and standard analysis methodology for the evaluation of safeguards system effectiveness. This is achieved through a standard set of symbols which characterize the various elements of safeguards systems and an analysis program to execute simulation models built using the SNAP symbology. The reports provided by the SNAP simulation program enable analysts to evaluate existing sites as well as alternate design possibilities. This paper provides an example illustrating its use.

[8] Gordon DM, BD Boyer, JM Whitaker, and JM Younkin. 2004. *Evaluation of IAEA Safeguards at Medium-sized Gas Centrifuge Uranium Enrichment Plants*. BNL/NCT-03-002, ORNL/ESP02-102.20, Oak Ridge National Laboratories, Oak Ridge, Tennessee.

Abstract: This report provides an evaluation of the effectiveness of International Atomic Energy Agency (IAEA) safeguards at medium-sized gas-centrifuge uranium-enrichment plants. The model plant has a separative capacity of 500 metric tons of separative work units per year. This report describes the primary safeguards concerns and goals at such plants, a number of relevant diversion and undeclared production scenarios, and the IAEA's current inspection approach and activities. It provides an evaluation of the effectiveness (i.e., probability of detection) of the IAEA's inspection activities in detecting the production of highly enriched uranium (HEU), the diversion of uranium from the material balance, and the production of undeclared low-enriched uranium (LEU) using undeclared feed. It concludes by describing potential improvements in the IAEA safeguards approach for each of the three diversion/production concerns noted above.

[9] Elayat HA, HE Lambert, and WJ O'Connell. 2004. *Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility*. Proceedings of the 45th Annual Meeting of the Institute of Nuclear Materials Management (INMM), July 10-14, Orlando, Florida.

Abstract: The U.S. Department of Energy (DOE) is interested in developing tools and methods for potential U.S. use in designing and evaluating safeguards systems. For this goal several DOE National Laboratories are defining the characteristics of typical facilities of several size scales, and the safeguards measures and instrumentation that could be applied. Lawrence Livermore National Laboratory is providing systems modeling and analysis of facility and safeguards operations, diversion path generation, and safeguards system effectiveness. The constituent elements of diversion scenarios are structured using directed graphs (digraphs) and fault trees. Safeguards indicator probabilities are based on sampling statistics and/or measurement accuracies. Scenarios are ranked based on value and quantity of material removed and the estimated probability of non-detection. Significant scenarios, especially those involving timeliness or randomly varying order of events, are transferred to simulation analysis. Simulations show the range of conditions encountered by the safeguards measurements and inspections, e.g., the quantities of intermediate materials in temporary storage and the time sequencing of material flow. Given a diversion campaign, simulations show how much the range of the same parameters observed by the safeguards system can differ from the base-case range. The combination of digraphs, fault trees, statistics, and simulation constitute a method for evaluation of the estimated benefit of alternate or additional safeguards equipment or features. A generic example illustrates the method.

[10] Lambert HE, HA Elayat, WJ O'Connell, L Szytel, and M Dreicer. 2007. LISSAT *Analysis of a Generic Centrifuge Enrichment Plant*. Proceedings of the 48th Annual Meeting of the Institute of Nuclear Materials Management (INMM), July 8-12, Tucson, Arizona.

Abstract: The U.S. Department of Energy (DOE) is interested in developing tools and methods for use in designing and evaluating safeguards systems for current and future plants in the nuclear power fuel cycle. The DOE is engaging several DOE National Laboratories in efforts applied to safeguards for chemical conversion plants and gaseous centrifuge enrichment plants. As part of the development, Lawrence Livermore National Laboratory has developed an integrated safeguards system analysis tool (LISSAT). This tool provides modeling and analysis of facility and safeguards operations, generation of diversion paths, and evaluation of safeguards system effectiveness. The constituent elements of diversion scenarios, including material extraction and concealment measures, are structured using directed graphs (digraphs) and fault trees. Statistical analysis evaluates the effectiveness of measurement verification plans and randomly timed inspections. Time domain simulations analyze significant scenarios, especially those involving alternate time ordering of events or issues of timeliness. Such simulations can provide additional information to the fault tree analysis and can help identify the range of normal operations and, by extension, identify additional plant operational signatures of diversions. LISSAT analyses can be used to compare the diversion-detection probabilities for individual safeguards technologies and to inform overall strategy implementations for present and future plants.

Additionally, LISSAT can be the basis for a rigorous cost-effectiveness analysis of safeguards and design options. This paper will describe the results of a LISSAT analysis of a generic centrifuge enrichment plant. The paper will describe the diversion scenarios analyzed and the effectiveness of various safeguards systems alternatives.

[11] Jacobsson S. 2002. *Safeguards Analysis of Tomographic Data from a Measurement on a PWR Nuclear Fuel Assembly*. STU-YTO-TR 189–Annex, Uppsala University, Uppsala, Sweden.

Abstract: In March 2001, tomographic measurements were performed at the Ringhals 4 nuclear power plant in Sweden. The measurements were carried out on a PWR fuel assembly using portable equipment. Analysis described in this re-port has been performed with an alternative tomographic method. It was originally developed in an investigation of the applicability of tomogra-phy for verification of the integrity of nuclear fuel, performed by Uppsala University for the Swedish Nuclear Power Inspectorate (SKI).

The method has since then been further developed for tomographic measurements of the relative pin power with high accuracy (1–2 %, 1 S.D.).For this purpose, a high-precision device has been constructed. Having a weight of 27 tons, the device is not intended for inspection purposes although it is still transportable.

Some differences are discussed below between the conditions for a portable device, with which the data analyzed in this report has been collected, and the type of device for which the algorithm has been developed. Also implications on the analysis are accounted for.

[12] International Nuclear Verification Series No. 1. 2003. *Safeguards Techniques and Equipment*. 2003 Edition, International Atomic Energy Agency (IAEA), Vienna, Austria.

Abstract: The 1990s saw significant non-proliferation-related developments in the world, resulting in a new period of safeguards development. Over several years an assessment was made of how to strengthen the effectiveness and improve the efficiency of IAEA safeguards. In May 1997 this culminated in the adoption by the IAEA Board of Governors of a Protocol Additional to Safeguards Agreements which significantly broadens the role of IAEA safeguards. As a consequence, the IAEA safeguards system entered a new era. Together with the introduction of the strengthened safeguards systems, in 1997 the IAEA began to publish a new series of booklets on safeguards, called the International Nuclear Verification Series (NVS). The objective of these booklets was to help in explaining IAEA safeguards, especially the new developments in safeguards, particularly for facility operators and government officers involved with these topics. The current booklet, which is a revision and update of IAEA/NVS/1, is intended to give a full and balanced description of the techniques and equipment used for both nuclear material accountancy and containment and surveillance measures, and for the new safeguards measure of environmental sampling. A completely new section on data security has been added to describe the specific features that are included in installed equipment systems in order to ensure the authenticity and confidentiality of information. As new verification measures continue to be developed the material in this booklet will be periodically reviewed and updated versions issued.

[13] Ehinger MH. 1990. *Computerization of the Safeguards Analysis Decision Process*. CONF-900607-3, Proceedings of the Topical Meeting on Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond, Nashville, Tennessee.

Abstract: Nuclear materials safeguards regulations are evolving to meet new demands for timeliness and sensitivity in detecting the loss or unauthorized use of sensitive nuclear materials. The opportunities to meet new rules, particularly in bulk processing plants, involve developing techniques which use modern, computerized process control and information systems. Using these computerized systems in the safeguards analysis involves all the challenges of the man-machine interface experienced in the typical process control application and adds new dimensions to accuracy requirements, data analysis, and alarm resolution in the regulatory environment.

[14] Burr T. 2008. "Statistical Methods in Nuclear Nonproliferation Activities at Declared Facilities." *Nuclear Safeguards, Security, and Nonproliferation*. JE Doyle, Editor, Amsterdam: Elsevier Inc.

Abstract: Nuclear nonproliferation is a multi-layered effort that begins with steps to prevent nuclear material that could be used as a weapon from leaving the peaceful energy cycle. In nuclear safeguards at known facilities with declared operations that main purpose of nuclear material accounting (NMA) measurements is to confirm the flows and inventory of special nuclear material (SNM) to within relatively small control limits. In addition, containment and surveillance (C/S) is used to try to confirm there has been no diversion of SNM. NMA, C/S, and related nonproliferation topics that involve statistical methods are described. A key function of periodic NMA measurements is to confirm the presence of SNM in accountability vessels to within relatively small measurement error.

[15] International Atomic Energy Agency (IAEA). 1999. *IAEA Safeguards: Cost/Benefit Analysis of Commercial Satellite Imagery*. SKI Report 99:14, C Anderson, Author. SSC Satellitbild Aktiebolag, Kiruna, Sweden. Accessed March 31, 2009, at http://inisdb.iaea.org/fulltext/p/30/044/30044714.pdf.

Abstract: This document–IAEA Safeguards: cost/benefit Analysis of Commercial Satellite Imagery constitutes a first report from SSC Satellitbild, giving the Agency tentative and initial estimates of the potential cost- and time-savings possible with the new proposed technology.

[16] Kuno Y, D Donohue, M Hedburg, and S Balsley. 2005. *Increase in the Role of Destructive Analysis for Safeguards Verification–A Strong Measure Against World Concerns on Proliferation*. Proceedings of the Global–Nuclear Energy Systems for Future Operations and Global Sustainability, Paper No. 169, the Atomic Energy Society of Japan, October 9-13, Tsukuba, Japan.

Among the tools that the IAEA presently uses for Safeguards assurance, nuclear Destructive Analysis (DA), as a state-of-the-art determination technique providing highest possible measurement accuracy, is extremely important for drawing quantitative Safeguards conclusions. In particular, DA is the best approach for detecting "bias defects," which arise when small amounts of nuclear material are diverted over a protracted length of time. DA for environmental sampling for Safeguards (ESS) has also been internationally recognised as a very strong tool for drawing safeguards conclusions. The number of DA samples for ESS has constantly increased over the last 10 years, whereas the analytical needs for the measurement of environmental samples as well as special samples such as Complementary Access (CA) have also remarkably increased in the last few years. Analytical requirements for CA samples tend to be complex, e.g., elemental and isotopic determinations in a variety of matrices, determinations of chemical form in organic and inorganic compounds. An update of the capabilities of IAEA-DA for both nuclear materials and environmental samples as well as future directions based on recent trends in DA is presented in this paper.

[17] Laughter MD. 2008. *Safeguard Applications Options for the Laser-Based Item Monitoring System (LBIMS)*. ORNL/TM-2008/086, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Abstract: Researchers at Oak Ridge National Laboratory (ORNL) are developing a Laser-Based Item Monitoring System (LBIMS) for advanced safeguards at nuclear facilities. LBIMS uses a low-power laser transceiver to monitor the presence and position of items with retroreflective tags. The primary advantages of LBIMS are its scalability to continuously monitor a wide range of items, its ability to operate unattended, its low cost of implementation, and its inherent information security due to its line-of-sight and non-broadcasting operation.

The primary proposed safeguards application of LBIMS is described in its name: item monitoring. LBIMS could be implemented in a storage area to continuously monitor containers of nuclear material and the area in which they are stored. The system could be configured to provide off-site notification if any of the containers are moved or removed or if the area is accessed. Individual tags would be used to monitor storage containers, and additional tags could be used to record information regarding secondary storage units and room access. The capability to register small changes in tag position opens up the possibility of several other uses. These include continuously monitoring piping arrangements for design information verification or recording equipment positions for other safeguards systems, such as tracking the opening and closing of autoclaves as part of a cylinder tracking system or opening and closing valves on a sample or product take-off line. Combined with attribute tags, which transmit information from any kind of sensor by modulating the laser signal, LBIMS provides the capability to wirelessly and securely collect safeguards data, even in areas where radio-frequency or other wireless communication methods are not practicable. Four application types are described in this report: static item monitoring, in-process item monitoring with trigger tags, multi-layered integration with trigger tags, and line-of-sight data transfer with attribute tags. Field trials for each of these applications are described.

3.4 Proliferation by Non-State Actors Literature

There is some debate about the role of non-State actors in proliferation. Some of this debate is exacerbated by the use of the word: "proliferation." In the broadest sense it can be used to mean spread of weapons-applicable nuclear technology. For the purpose of this research we use a narrower definition

(Section 2.0): "*Attempts by non-State-sponsored actors to acquire, process, and weaponize nuclear material with the intention to develop at least one nuclear weapon that may involve collaboration with other groups or State.*" In any case it is clear that the role of non-State actors in proliferation needs further consideration.

An article [1] in CQ Press, a division of *Congressional Quarterly*, makes the point that the fact a black market in nuclear weapons exists lends credence to the concern that so-called rogue nations and terrorist organizations like Osama bin Laden's Al Qaeda network might acquire nuclear weapons [1]. A. Q. Khan's, the father of Pakistan's nuclear bomb, confession of peddling nuclear technology to Libya and other rogue States fuels this concern in a major way. A. Q. Khan operated a black-market trade in centrifuges, blueprints for nuclear-weapons equipment, missiles capable of delivering nuclear weapons, and other technology. His network included manufacturers in Malaysia, middlemen in the United Arab Emirates, and the governments of Libya, North Korea, and Iran. There were indications that he attempted to market proliferation technology in Syria [1]. To have built up this network "under the radar" through institutional barriers is disconcerting. His success leads many to believe that, unchecked, terrorists or terror States will use the same kinds to networks to achieve nuclear weapons. Even IAEA General Director El Baradei is quoted as saying that: "*Eventually, inevitably, terrorists will gain access to such materials and technology, if not an actual weapon. If the world does not change course we risk self destruction.*" [1]

In his article titled: "*Peering into the Abyss – Non-State Actors and the 2016 Proliferation Environment*" [2] Russell makes a projection about what the nuclear proliferation environment will look like in 2016. Russell warns that up until now there has been a tendency to think about and address the threat of proliferation by non-State actors by focusing on the so-called "demand side" of proliferation and leaving unaddressed the role that a growing variety of non-State actors may play in shaping the "supply side" of an emerging proliferation substructure. Russell claims that the proliferation network established by Pakistani A. Q. Khan provides a precursor to a proliferation environment that may include or even be dominated by transnational corporations, quasi-governmental entities, and individuals operating on the fringes of government control in weak or failed States.

Russell shows that there are an accelerating number of organizations structures that operate across State borders [2]. He shows that there is also a growing increase in the number of nongovernmental organizations, and transnational corporations with their corresponding foreign affiliates around the world. Russell defines a non-State proliferation market substructure to include four characteristics: 1) legitimate trade in dual-use items that can be used and diverted for nonconventional use in weapons programs by State or non-State actors, 2) front companies and subsidiaries of quasi-governmental organizations, 3) illicit smuggling networks, administered by States, transnational criminal organizations and/or terrorist groups, and 4) servicing demand by these illicit networks and violent non-State actors. Table 3.3 illustrates how non-State actors interact in the Weapons of Mass Destruction (WMD) supply and demand sides of the proliferation environment.

Table 3.3. Non-State Actors and WMD Proliferation Supply and Demand (from Russell [2]

Non-State Typology	**Supply Side**	**Demand-Side**
Industrial Entities	Provide transnational-based networks to service demand from State- and non-State and quasi-State groups. In the pre-2000 environment, the overwhelming demand was for turnkey operations. The 2016 environment may feature a more ‘‘subcontracted’’ approach to supply like that in the A. Q. Khan supply and distribution network.	None, except to satisfy legitimate trade in dual-use materials.
Quasi-Governmental Organizations	Organizational structures like Pakistan’s Atomic Energy Commission and Korean Workers’ Party Bureau in the Democratic People’s Republic of Korea, Iran Revolutionary Guard Corps in Iran, and the China North Industries Corporation can operate outside formal governmental control.	Can also serve as marketing agents to actively ‘‘create’’ demand for products or can seek to acquire capabilities for themselves.
Non-Governmental Organizations	Potential unwitting role as masking agent for quasi-governmental or State-run proliferation activities.	None
Warlords and Militias	Potential role in serving as subcontractors and transit facilitators for larger networks.	Seek unconventional capabilities as part of competitive process with rival warlords or States.
Transnational Criminal Organizations	Service illicit markets in nuclear and other WMD materials due to perceived value of the assets.	Perception that WMD have intrinsic value stimulates demand for illicit trade.
Transnational or Nationally Based Terrorist Groups	While the Japanese terrorist group Aum Shinrikyo built an extensive biological and chemical production infrastructure, the calculation on the supply side for terrorist groups remains: Why build it if you can buy it? That said, a variety of terrorist attacks reportedly involving chemical weapons have been disrupted in the 2001-2006 time period.	Seek unconventional attack options as part of enhancement of group capabilities, either for negotiating leverage or for a simple desire to inflict mass casualties. For example, Al Qaeda is widely reported to have attempted to buy nuclear warheads in Central Asia.

Gaffney proposes in his article [3], *Globalization and Nuclear Proliferation*, that globalization and proliferation may be intimately linked. He describes globalization as: “*…the interconnected of the world, especially through trade, but in new and intricate ways that constitute a qualitative change and on a scale that far outstrips previous episodes of globalization.*” [3] He proposes that the process of globalization, as it makes technology, education, and other aspects of modern life more available to more countries and individuals, could be stimulating proliferation. Gaffney traces the current era of globalization and nuclear proliferation and makes the connection that outside the Cold War context, most countries that have pursued nuclear weapons were on the margins of globalization. He makes the analogous claim that the aspiration of terrorists for nuclear weapons stems from their inability to cope with globalization. Globalization threatens elite control, liberates women, is relentlessly secular, and is economically disruptive–bringing uncertainties with the opportunities. He concludes that as globalization spreads and opens up economic possibilities for populations that the terrorists and rogues we are concerned about eschew those opportunities and could find proliferation as a way to opt out, or not to join globalization.

The authors of "*Can Terrorists Build a Nuclear Weapon*?" [4] include nuclear physicists, specialists in chemical and metallurgical processing of plutonium and uranium, and specialists in explosives. Two options for nuclear devices to be built by terrorists are considered: the so-called crude design and a more sophisticated design. The crude design is one in which either of the methods successfully demonstrated in 1945–the gun type and the implosion type. The authors also consider a more sophisticated design but note that even though a smaller amount of fissile material could be used to the same effect as the early design, it would require a heavier and more powerful assembly mechanism. This may have a "cancelling" effect for a terrorist, so the differentiation may not be deciding factor; besides, the sophisticated design was reported by the authors to be very difficult to reproduce, even for a nuclear weapons laboratory. The authors of this report do not discount the credibility of terrorists building a nuclear weapon. Among the conclusions that the authors offered, based on crude weapon design principles, are the following [4]:

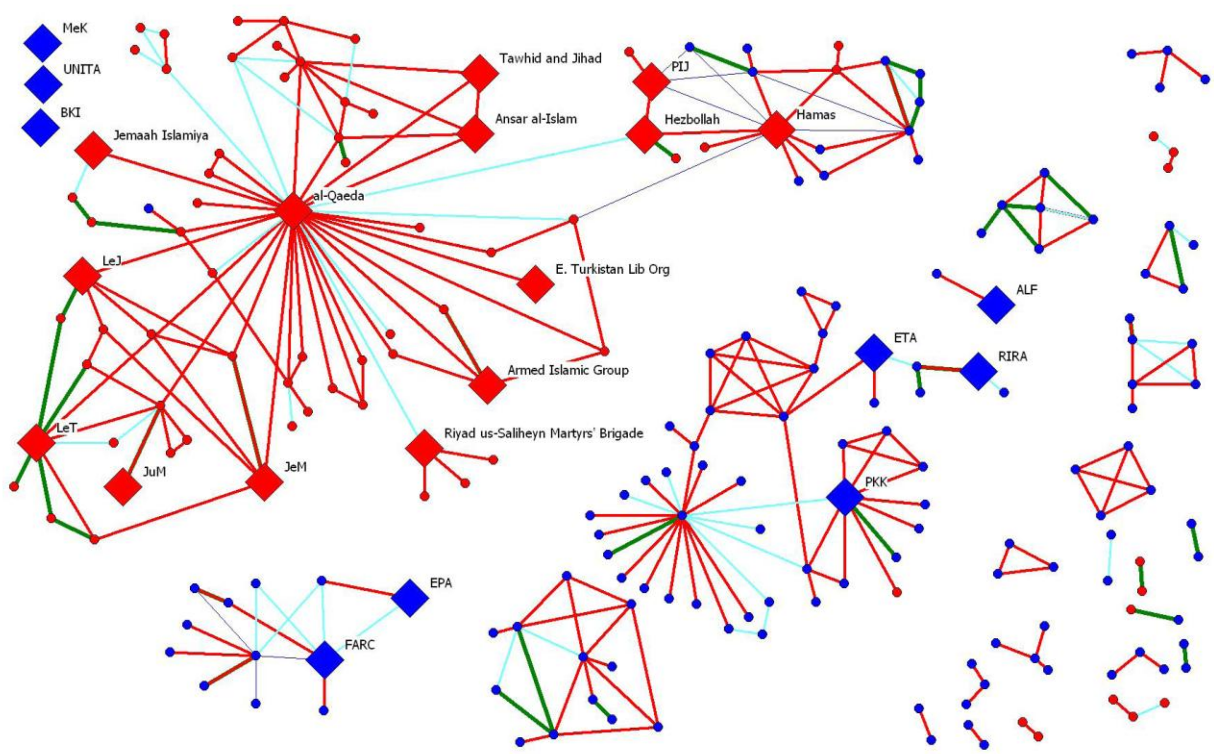
- Such a device could be constructed by a group not previously engaged in designing or building nuclear weapons, providing a number of requirements were adequately met.
- To achieve rapid turnaround (that is, the device would be ready within a day or so after obtaining the material), careful preparations extending over a considerable period would have to have been carried out, and the materials acquired would have to be in the form prepared for.
- The amounts of fissile material necessary would tend to be large– certainly several (and possibly ten) times the so-called formula quantities.
- The weight of the complete device would also be large–not as large as the first atomic weapons (~10,000 pounds), since these required aerodynamic cases to enable them to be handled as bombs–but probably more than a ton.
- Within the confines of the crude design category–that of a device guaranteed to work without the need for extensive theoretical or experimental demonstration–an implosion device could be constructed with reactor-grade plutonium or highly enriched uranium in metal.

Cirincione, a member of the Weapons of Mass Destruction Commission, initiated by the Swedish government on a proposal by the United Nations, makes a global assessment of nuclear threats and the primary point that the world lacks a shared international assessment of the proliferation threats [5]. Without shared threat assessments it is difficult to focus political, diplomatic, and even military power to do what needs to be done. Cirincione also makes the point that nuclear terrorism is the most serious threat. He states: "*While States can be deterred from using nuclear weapons by fear of retaliation, terrorists who have neither land, people, nor national futures to protect, may not be 'deterrable.' Terrorist acquisition of nuclear weapons poses the greatest single threat to the United States*." [5]

The author also discusses two other frightening possibilities: 1) regional conflicts that threaten nuclear use and 2) breakdown of the nonproliferation regime, but also provides a few possibilities under a category he refers to as "nuclear terrorism and transfers." He notes that diversion of nuclear weapons or material from a national arsenal might be performed by a group other than terrorists and that nuclear black market and cooperative proliferation may involve collaborating groups or States.

Clunan takes a different tact in a conference report [6] titled "*Ungoverned Spaces, Non-State Actors, and WMD Proliferation.*" She discusses so-called ungoverned spaces as they relate to non-State actors and WMD proliferation. She offers the concept of softened sovereignty as a paradigm to help us focus on proliferation pathways. Clunan discusses "dangerous spaces" and governance gaps in those States. Governance gaps can generate no-go zones in cities, rural insurgencies, and radicalized immigrant pockets of refugees. Weak States with capacity gaps or functional holes may turn to surrogates (such as organized crime in the Former Soviet Union [FSU] States) or may be in only marginal control of tribal or border regions such as those that exist in Afghanistan/Pakistan, Yemen/Saudi Arabia, and Central Asia. Dangerous spaces host dangerous transactions (e.g., dirty money, digital flows, and illicit economic activities) and can be the hub of different kinds of illegal flows. Proliferation pathways might be spawned in such spaces, although not all such spaces would be prone to nuclear proliferation; certain areas within the FSU would be candidates as well [6]. Chechen groups executed numerous thefts of radioactive material and allegedly serve as a transshipment point for radioactive material.

Asal and Rethmeyer write about the possibility of violent non-State actors utilizing what they call chemical, biological, radiological, or nuclear (CBRN) weapons [7]. The authors leverage data from the Monterey WMD dataset and the Memorial Institute for the Prevention of Terrorism (MIPT) and try to identify characteristics of organizations most likely to pursue CBRN weapons. While this work is not exclusive to nuclear proliferation, it does show the use of a kind of social network model (shown in Figure 3.3) to reveal and assess the alliance and connections between violent organizations–illustrating that it is possible to take a view of non-State actors that is too compartmentalized.



Diamonds = pursued CBRN terrorism; Circles = have not pursued CBRN terrorism; Red nodes = Islamists; Blue nodes = non-Islamist; Red lines = alliances; Green lines = familial alliances; Light blue lines = suspected alliances; Dark blue lines = rivals and allies.

Figure 3.3. Network Connections, Terrorist Organization 1998-2005 (from Asal [7])

Steinhausler worries about legal instruments to prevent non-State-actor proliferation in: "Legal Instruments to Prevent Nuclear WMD Use by Non-State Actors." [8] However, he limits his view of non-State-actor proliferation by saying, "*Non-State actors have three possibilities to actually carry out such a threat: (a) theft or purchase of a functioning nuclear device (e.g., from a military source); (b) provision of a nuclear device from a rogue state in possession of nuclear weapons technology; or (c) access to an adequate amount of weapons-grade HEU in order to build a crude nuclear device*." This view, which the author is not alone in, does not quite extend to the possibility of a non-State actor acquiring, processing, and weaponizing material to produce a nuclear weapon. We note that to develop the appropriate legal instruments the world community must agree on what non-State-actor proliferation is.

These references are considered to be representative of this part of problem space; however, we acknowledge the controversy surrounding the realistic possibility of non-State-actor proliferation but suggest that non-State actors have a role that needs to be more thoroughly understood.

References[1]

[1] Thomas C, Editor. 2004. "Nuclear Proliferation and Terrorism–Can 'Rogue' States and Terrorists Acquire Nuclear Weapons?" *The CQ Researcher* 14(13):297-320. Accessed April 15, 2009, at www.thecqresearcher.com.

Abstract: The recent discovery of a global black market in nuclear weapons and related technology has intensified concerns that so-called rogue nations and terrorist organizations like Osama bin Laden's al Qaeda network might acquire nuclear bombs. The network, run by the "father" of Pakistan's atomic bomb, A.Q. Khan, sold nuclear-weapons materials to Iran and North Korea, which have refused to sign the Nuclear Nonproliferation Treaty (NPT). Virtually all the other nations of the world are signatories. President Bush responded to the revelations about Khan's network with a plan to strengthen international anti-proliferation efforts, including calling on the U.N. Security Council, to require all States to criminalize proliferation of components that could be used to make weapons of mass destruction. While arms experts commended the president for focusing on proliferation, some said his proposals did not go far enough.

[2] Russell James. 2006. "Peering into the Abyss: Non-State Actors and the 2016 Proliferation Environment." *Nonproliferation Review* 13(3).

Abstract: The George W. Bush administration has successfully reoriented national policy and convinced the international community of the absolute necessity of denying weapons of mass destruction to terrorist groups. In addition to utilizing the tools of existing export-control regimes, Washington promulgated the Proliferation Security Initiative and helped push through United Nations Security Council Resolution 1540 to expand the toolkit available to States to prevent the spread of dangerous technologies and weapons to terrorist groups. While these efforts are long overdue, they address only one aspect of the proliferation threat posed by non-State actors. Current efforts focus on the ''demand'' side of proliferation from terrorists but inexplicably leave unaddressed the role that a growing variety of non-State actors may play in shaping the supply side of an emerging 2016 proliferation market substructure. The proliferation supply network, established by Pakistani scientist A. Q. Khan, provides a precursor to a dangerous new proliferation environment dominated by transnational corporations, quasi-governmental entities, and individuals operating on the fringes of government control in weak or failing States that lack the will and the resources to implement effective export-control regimes. All States need to develop a more comprehensive and holistic view of the future role that a burgeoning plethora of non-State actors will play in nuclear proliferation by 2016.

[3] Gaffney HH. 2006. "Globalization and Nuclear Proliferation." *Strategic Insights*. V(6). Accessed April 15, 2009 at http://www.ccc.nps.navy.mil/si/2006/Jul/gaffneyJul06.asp.

Abstract: Globalization as we know it now emerged after World War II. Proliferation as we know it now also emerged after World War II─not only with the advent of nuclear weapons, but with the advent of long-range ballistic missiles, starting with the

[1] The abstracts included here were taken primarily from corresponding published abstracts, forewords, or paper or report introductions and other summary materials. However, this material was typically edited to produce abstracts of similar length and tone.

German V-2. Are globalization and proliferation in some kind of symbiotic relationship, growing with, and as a result of, each other? Is the process of globalization, as it makes technology, education, and other aspects of modern life, available to more and more countries─and even individuals or private organizations─stimulating proliferation?

[4] Carson M, T Taylor, E Eyster, W Maraman, and J Wechsler. 1987. *Can Terrorists Build Nuclear Weapons?* Paper prepared for the International Task Force on the Prevention of Nuclear Terrorism, Nuclear Control Institute, Washington, D.C. Accessed April 15, 2009, at http://nci.org/k-m/makeab.htm.

Abstract: Two options for nuclear devices to be built by terrorists are considered here: that of using the earliest design principles in a so-called crude design and that of using more advanced principles in a so-called sophisticated design. A crude design is one in which either of the methods successfully demonstrated in 1945─the gun type and the implosion type─is applied. In the gun type, a subcritical piece of fissile material (the projectile) is fired rapidly into another subcritical piece (the target) such that the final assembly is supercritical without a change in the density of the material. In the implosion type, a near-critical piece of fissile material is compressed by a converging shock wave resulting from the detonation of a surrounding layer of high explosive and becomes supercritical because of its increase in density. A small, sophisticated design is one with a diameter of about 1 or 2 feet and a weight of one hundred to a few hundred pounds, so that it is readily transportable (for example, in the trunk of a standard car). Its size and weight may be compared with that of a crude design, which would be on the order of a ton or more and require a larger vehicle. It would also be possible, in about the same size and weight as a crude model but using a more sophisticated design, to build a device requiring a smaller amount of fissile material to achieve similar effects.

[5] Cirincione J. 2004. "A Global Assessment of Nuclear Proliferation Threats," Weapons of Mass Destruction Commission, Stockholm Sweden.

Abstract: There are new proliferation dangers but no agreed assessment. Despite decades of disarmament efforts, global nuclear arsenals remain dangerously high and two new nations are now pursuing nuclear weapons programs. The danger is not just that the nuclear club could grow from the current eight to nine or ten nations, but that a new breach in the nuclear dam could unleash a flood of new entrants, collapsing global restraints and making every regional crisis a potential nuclear crisis. New nuclear weapon States may be less restrained in their nuclear use doctrines. Further, if North Korea, Iran, or other nations in volatile regions develop nuclear weapons production capabilities, they might, willingly or unwillingly, share, sell, or otherwise transfer weapons, materials, or skills to terrorist groups. Thus far, we lack a shared international assessment of what the proliferation threats are and the priority that should be assigned to each threat.

[6] Clunan A. 2009. "Ungoverned Spaces, Non-State Actors, and WMD Proliferation." Presented at *Tomorrow's Proliferation Pathways: Weak States, Rogues, and Non-State Actors* Conference Report on July 17-18, 2008 conference in Belfast, Maine. Accessed April 15, 2009, at http://www.ccc.nps.navy.mil/events/recent/2008ProlifPathways_rpt.asp.

A diverse grouping of experts, including government officials, military officers, academics, and analysts gathered together on July 17th and 18th in Belfast, Maine at the University of Maine's Hutchinson Center to convene *Tomorrow's Proliferation Pathways: Weak States, Rogues, and Non-State Actors.* Co-hosted by the School of Policy and International Affairs of the University of Maine and U.S. Naval Postgraduate School's Center for Contemporary Conflict, the conference was sponsored by the Defense Threat Reduction Agency's Advanced Systems and Concepts Office (DTRA-ASCO).

This conference sought to help map proliferation pathways and improve our understanding of the forces that create, shape, and exploit these pathways. Examining the roles weak States, non-States, and rogues play in the formation of proliferation networks is part of this exploration. These networks are born, grow and either evolve or die in the process of generating and exploiting proliferation pathways. Understanding how proliferation networks succeed or fail in accomplishing their functions and how they evolve and adapt to countermeasures is of paramount interest.

[7] Asal V, G Ackerman, and R Rethemeyer. 2007. *Connections Can Be Toxic: Terrorist Organization Factors and the Pursuit and Use of CBRN Terrorism*. John F. Kenney School of Government at Harvard University. Accessed May 13, 2009, at http://www.hks.harvard.edu/netgov/files/NIPS/Rethemeyer_ConnectionCanBeToxic_IDs.pdf.

Abstract: The prospects of politically violent non-State actors utilizing chemical, biological, radiological, or nuclear (CBRN) weapons has captured the imaginations of not only public officials and the news media, but also a sizeable group of scholars who have sought to better define and characterize this apparent threat. Yet little of this work is quantitative in nature and global in scope. This study presents an analysis of CBRN pursuit and use that leverages data from the Monterey Weapons of Mass Destruction dataset and the Memorial Institute for the Prevention of Terrorism (MIPT). Our findings suggest that organizations embedded in alliance structures and based in authoritarian countries with relatively strong connections to a globalized world are more likely to use or seek to develop CBRN weapons. Contrary to previous studies, we failed to find a significant relationship between CBRN pursuit or use and either religious ideology or two measures of organizational capabilities.

[8] Steinhausler F. 2009. "Legal Instruments to Prevent Nuclear WMD Use by Non-State Actors." *Strategic Insights*. VIII(1). Accessed April 15, 2009, at http://www.ccc.nps.navy.mil/si/.

Abstract: Data collected since 1991 indicate that some groups involved in terrorist activities have been interested in acquiring fissile material to terrorize society with nuclear weapons of mass destruction (WMD). Non-State actors have three possibilities to actually carry out such a threat: (a) theft or purchase of a functioning nuclear device (e.g., from a military source); (b) provision of a nuclear device from a rogue State in possession of nuclear weapons technology; or (c) access to an adequate amount of weapons-grade HEU in order to build a crude nuclear device.

The world community faces the challenge whether the legal instruments are adequate to prevent proliferation of nuclear materials and technologies leading ultimately to the deployment of nuclear weapons and WMD use by non-State actors. International law and decision-making mechanisms are—besides covert intelligence or military operations—one of the possibilities to address this global challenge. The current international nuclear WMD non-proliferation regime originated about forty years ago.

Over the past four decades it encompassed a multitude of treaties, conventions, and recommendations. These rules cover a wide range, such as the Treaty on the Non-Proliferation of Nuclear Weapons, the Missile Technology Control Regime, and U.N.-induced initiatives, such as declarations of nuclear-free zones in different regions. The major components of these international legal efforts will be discussed below with regard to their ability to prevent nuclear proliferation by non-State actors.

3.5 Social Modeling Literature

Modeling in the social sciences has been an integral part and natural evolution of social science research. Like the physical sciences, social science has as its purpose understanding, explaining, and predicting phenomena. These explanations, in the early stages, started out as qualitative descriptions. For example, anthropologists might describe the social behavior of pacific islanders using data gathered by living among them and observing their customs [1]. The use of mathematical models in social science evolved from the desire to be more precise in describing phenomena, predicting behavior, and testing theories. Observation led to theories which, when described precisely, became models that had their basis in mathematics as an unambiguous language for communicating. For example, Clark Hull developed mathematical equations that described the degree of learning and motivation as functions of precisely defined independent variables. His methodology was much like Euclid's, consisting of a set of postulates used to derive theorems, which were carefully checked through experimentation [2]. So mathematical models emerged as an extension of qualitative descriptions of social science by using the language of mathematics that is more precise than ordinary discourse and which allows one to make quantitative predictions.

The breadth of social science topics that have been subject to mathematical modeling is almost as diverse as social science itself. Figure 3.3 shows the topics covered in an introductory textbook on mathematical models in social and life science [3]. The models are categorized as being deterministic, axiomatic, probabilistic, or simulations. The breadth of topics ranges from the arms race to epidemics, and includes individual and social choice among others. Just about any subject within the social science realm has been subject to mathematical modeling. The *Journal of Mathematical Social Science* http://www.elsevier.com/wps/find/journaldescription.cws_home/505565/description#description) emphasizes the unity of mathematical modeling in economics, psychology, political sciences, sociology, and other social sciences. There are also specific journals of Mathematical Psychology (http://www.elsevier.com/wps/find/journaldescription.cws_home/622887/description#description) and Mathematical Sociology (http://www.tandf.co.uk/journals/titles/0022250x.asp) to name just two more. The aim and scope of *The Journal of Mathematical Sociology*, for example, is *"...oriented toward a mathematical understanding of emergent complex social structures rather than to an analysis of individual behavior. These structures include, for example, informal groups, social networks, organizations, and global systems."*

It is often the case that when mathematics and social science are mentioned together, the listener will think of statistics. Statistics are an important part of the scientific method for determining whether experimental results represent real effects or were due to chance. Statistics are also useful in describing or modeling phenomena or discovering relationships among variables; however, mathematical social science models encompass much more than statistical reasoning, as can be seen in Figure 3.3.

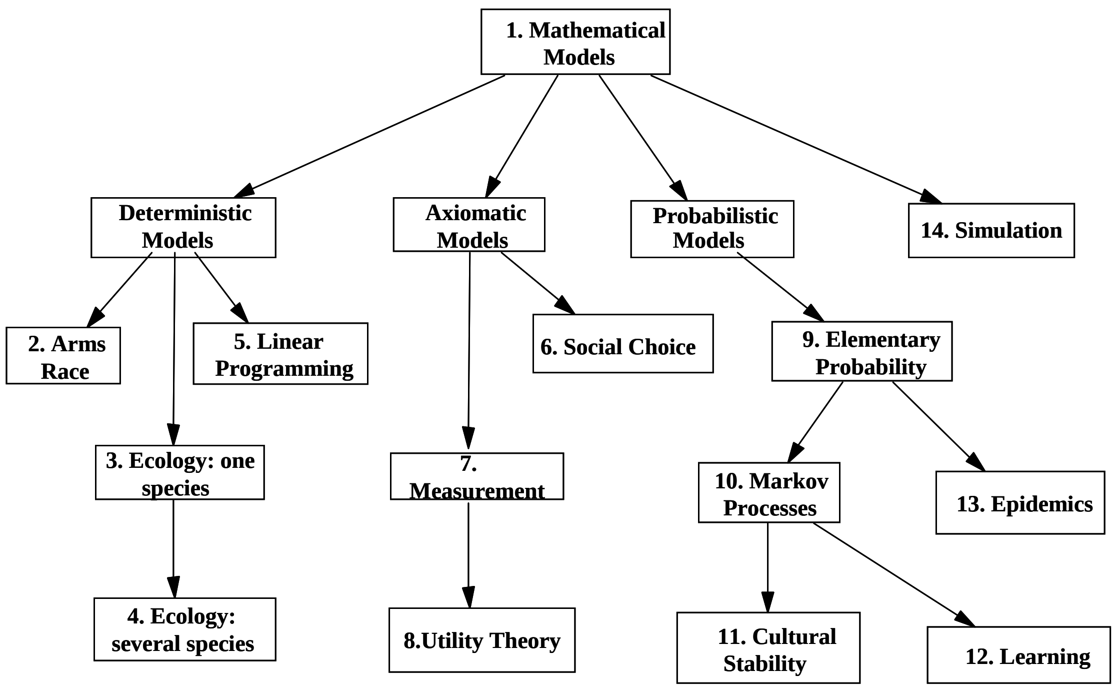


Figure 3.4. Topics from Introductory Text on Social Science Models

The process of social science modeling is analogous to the scientific method used to advance all of science. The scientific method consists of observing the world and forming hypotheses. Hypotheses are statements about how the world works. They form the basis for predictions that can be tested through additional observation or experiment (see Figure 3.4).

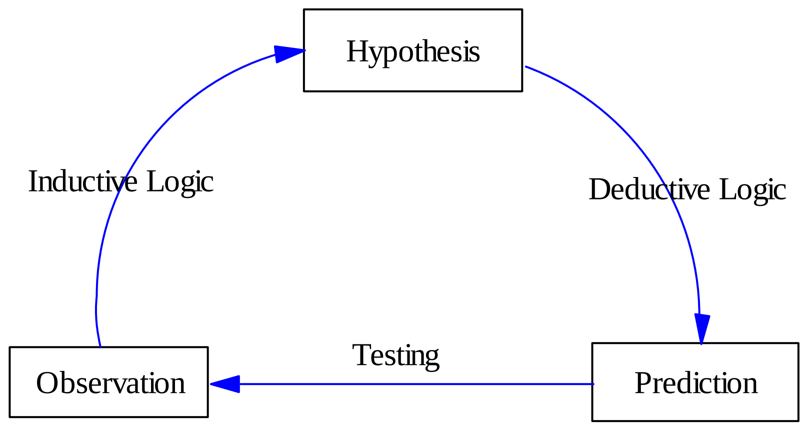


Figure 3.5. The Scientific Method

As a hypothesis or, possibly, a collection of hypotheses become supported through observation and experiment they may be elevated to the class of a scientific theory. Scientific theories are ways of organizing vast amounts of data. Their purpose is to provide an explanation for a broad class of phenomena within a specific scientific discipline. Building and testing social science models is much like testing hypotheses. "*A model is a simplified picture of a part of the real world. It has some of the characteristics of the real world, but not all of them. It is a set of interrelated guesses about the world. Like all pictures, a model is simpler than the phenomena it is supposed to represent or explain*." [4] Figure 3.5 shows a process for developing mathematical models [5]. Models are abstractions of the observed world. They represent the essential elements of some phenomena of interest. The model is always simpler than the world. This simplicity clarifies the relationships among variables of interest. This abstraction makes use of inductive logic; the model can be thought of as type of hypothesis about how some phenomena in the world work. The model allows us to make predictions that are derived using deductive logic. The predictions are compared to data obtained from observations, possibly experimentation, but other types of observational data as well. It is not the case that all science lends itself to experimentation; there are other paradigms for advancing scientific understanding. Finally, modeling is an interactive process in which the model is modified as predictions are compared to data. However, as we discuss further in the section on validation, the importance of fitting a model to data will depend on the purpose for constructing the model. We may be interested in how changes in policy would affect behavior in situations for which there is no data.

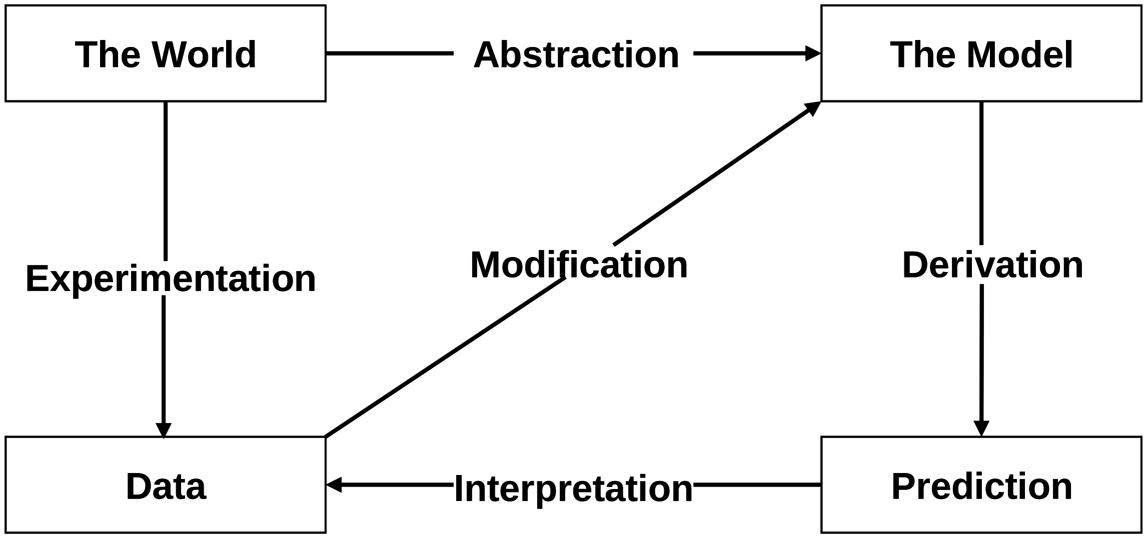


Figure 3.6. Process of Model Development within Science [5]

One class of social science models that have relevance to proliferation are decision models. These models have been studied by psychologists working in the area of human judgment and decision-making; economists, who assume rational actors in their economic theories; managers interested in organizational decision theory as well as consumer choice; and philosophers, who see decision-making as a type of logical thinking to be analyzed for standards of rationality. Decision models fall into the categories of normative, descriptive, and prescriptive. Normative models set the standards of rationality. Like logical reasoning, it purports to set the standard of how decisions should be made by perfectly rational actors having the resources to obtain all the information relevant to the decision. Descriptive decision-making has as its purpose descriptions about how individuals actually make decisions. This has been studied extensively by psychologists, economists, and others [6][7]. Normative decision-making purports to describe how decisions should be made given the practical limitations in time and other resources [8]. Applied decision analysis tends to fall into two categories: one in which uncertainty is the predominant feature [9], and one in which value tradeoffs predominate [10]. Herbert Simon [11] originally brought up the issue that rational human beings have limited resources for decision-making, and that rationality was bounded and that decision-makers made decisions that were good enough given their importance and the tradeoff in effort applied to the decision, which he called "Satisficing" [12]. More recently, Gigerenzer [13] and others have been exploring situations in which simple heuristics can lead to decisions that are as optimal as more elaborate normative methods. Another area of research in decision-making is naturalistic decision-making, also called "recognition-primed" decision-making [14][15]. This area of decision analysis takes its inspiration from firefighters who must make decisions in real time. The decisions are based on past experience and recognizing similar situations and their experience with the outcomes associated with actions taken. This is in contrast to the paradigm in which decisions are made based upon some algorithm that maximizes utility.

The National Research Council reviewed social modeling efforts for the U.S. Air Force by looking at what they refer to as individual, organizational, and societal (IOS) modeling research programs in the various research communities of interest. They evaluated the strengths and weaknesses of the programs and their methodologies to determine which have the greatest potential for military use. According to the National Research Council, the mission of the U.S. military today has shifted from force-on-force warfare towards combating insurgents and terrorists networks and therefore: "*Models of human behavior in social* *units–teams, organizations, cultural and ethnic groups, and societies−are needed to understand, predict, and influence the behavior of these social units.*" [16]

The National Research Council describes the state of the art of human behavioral modeling as: 1) verbal conceptual models, 2) cultural modeling, 3) behavior of humans in groups and organizations (i.e., macro-level-formed models), behavior of individuals (i.e., micro-level-formed models), and 4) behavior of an individual within groups (i.e., meso-level-formed models). Verbal conceptual models characterize entities, variables, or events/processes/mechanisms and relations among them in words–not equations or mathematical or operational formulations. Cultural modeling is of two types; one type is concerned with modeling growth and distribution of cultural phenomena, while the the other is concerned with describing a group's culture. Modeling behavior of humans in groups includes system dynamics and organizational theory modeling. It also includes expert systems that simulate decision-making and problem-solving. Modeling individual behavior includes cognitive architectures, which are simulation-based cognitive-affective models, which add in modeling of human emotion. Meso-level modeling typically models interactions and influences among individuals in groups.

The National Research Council specifically evaluated IOS models (nearly all of which are sponsored by an agency or branch of the U.S. Department of Defense (DoD). The conclusions of their report [3] include identification of problems or pitfalls in five major categories:

1. Modeling strategy–matching the problem to the real world
2. Verification, validation, and accreditation
3. Modeling tactics–unwarranted assumptions about the social, organizational, cultural, and individual behavior domains–and matching the scope of the model to the scope of the phenomena modeled
4. Differences between modeling physical phenomena and human behavior–dealing with uncertainty and adaptation
5. Combining components models−problems from linkages that occur within and across levels of analysis.

There is a large body of social science literature that isn't concerned with building mathematical models per se. In fact this is characteristic of the vast majority of social science research. Much of the proliferation literature also falls into this category. Recent research being carried out in the DOE laboratories has been putting a different twist on social science modeling. It has been reviewing social science literature and building mathematical models derived from this literature after the fact. Social science, regardless of whether an explicit model is constructed, consists of variables and hypothesized relationships amongst those variables. This work identifies those relationships and develops mathematical models in the form of a Bayesian net to be used for assessing the threat of violence amongst potential terrorist groups and individuals. This approach to developing mathematical models that incorporate social science after the fact represents a departure in the history of social science modeling. It is within this sprit that we propose to develop social science models for assessing nuclear proliferation. As noted earlier in Section 2.1 theories of proliferation can be classified as falling into one of four groups:

1. Technical capability
2. National and international security
3. Domestic politics

4. National identity and psychology.

In the past, theories of proliferation have focused on one of these to the exclusion of the others. We believe that as the political and economic realities of the world evolved explanations of proliferation have changed to emphasize one of these four perspectives. However, each perspective has a legitimate contribution to make in predicting proliferation. As we discuss later in the paper, our models will integrate and appropriately weight elements from all four groups. The weights would reflect current political realities as well as the latest scientific knowledge and data into a mathematical model for proliferation assessment.

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Abstract: The National Research Council was asked by the U.S. Air Force to review relevant IOS modeling research programs in the various research communities, evaluate the strengths and weaknesses of the programs and their methodologies, determine which have the greatest potential for military use, and provide guidance for the design of a research program to effectively foster the development of IOS models useful to the military. The formal Statement of Task for the study includes the following specific items: 1) review the state of the art of the subset of the social sciences perceived as having the greatest payoff in terms of informing future computational model developments, 2) review the state of the art in societal modeling applications serving the U.S. Department of, Defense (DoD) and related agencies, with special emphasis given to computational modeling and simulation-based approaches, 3) review the state of the art in the three computational modeling communities outside DoD (cognitive science and individual behavioral modeling, network analysis and multi-agent organizational modeling, and multi-resolution modeling and simulation) and identify strengths and shortcomings in each, 4) identify how gaps in societal behavioral modeling applications serving DoD and related agencies might be filled by conceptual models in the social sciences; computational modeling approaches now under way in the social science community; and closer linkages between the cognitive science community, the network/organizational modeling community, and the multi-resolution modeling and simulation community, and 5) develop a research and development roadmap to fill current application gaps for the near-, mid-, and farther term.

4.0 Proliferation-Relevant Modeling Methodologies

4.1 Modeling Opportunities

A number of models and modeling approaches were identified during the literature search in the areas of theories of State-sponsored proliferation, proliferation resistance assessment, safeguards analysis, and non-State-actor proliferation. Approaches included multi-attribute utility analysis, event-tree/fault-tree models,[1] Markov models,[2] statistical models, such as regression analysis, risk-based modeling approaches, and simulation approaches. PNNL has specific experience in developing two other modeling approaches for use in techno-social analytics: Dempster-Shafer[3] models and Bayesian network[4] (BN) models.

This research team proposes to use techno-social modeling approaches to address analysis of proliferation assessment. Three of the most fundamental proliferation-related questions that might be asked are:

- Question A – What is the likelihood that entity X–either a country or non-State actor–will decide to develop a nuclear weapons program?
- Question B – What is the proliferation resistance of a nuclear energy system Y?
- Question C – What is the proliferation resistance of nuclear energy system Y when it is operating in the environment of entity X?

Pertaining to Question A: There are a number of theories and little consensus about what factors explain why a country decides to develop nuclear weapons. Case studies have often been performed to support particular theories. In some cases statistical analysis based on what is known about past attempts by different countries to develop nuclear weapons has been used to support proposed proliferation factors. (Theories about the propensity of a State to develop nuclear weapons are discussed in Section 3.1, while the possibility of non-State proliferation is discussed in Section 3.4). The possibility of non-State proliferation has received little attention and has not been included in the analysis of State-sponsored proliferation. Consideration of State and non-State proliferation together may lend to novel approaches to proliferation modeling and additional insights.

This research will investigate modeling proliferation using inference models−evidence mathematics. Proliferation theories might be used to support BN models like the simplified example model shown in Figures 4.1. Shown in the figure are the results for a State that is not a recognized proliferation threat.

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[1] Event tree and fault tree models are graphical models that are used to visualize and/or quantify the relationship between events.
[2] Markov models are used to characterize a process or chain of events that have the Markov property. The Markov property means that, given the present State, future States are independent of the past States and will be reached through a probabilistic process instead of a deterministic one.
[3] The Dempster-Shafer theory is a mathematical theory of evidence based on “belief functions” and “plausibility reasoning,” which is used to combine separate pieces of information (evidence) to calculate the probability of an event. The theory was developed by Arthur P. Demspter and Glenn Shafer.
[4] Bayesian Network models are graphical probability models that represent a set of variables and their probabilistic independencies. Formally, Bayesian networks are directed acyclic graphs whose nodes represent variables, and whose missing edges encode conditional independencies between the variables. The word “Bayesian” comes from use of Bayes theorem and is derived from the work of Reverend Thomas Bayes.

This model attempts to capture some salient factors relevant to a state's decision to proliferate; such as, technical capability and the regional political situation. Figure 4.2 is the same model, but shows different results for a State that is a recognized proliferation threat. In these examples, preliminary probabilities were elicited using a structured elicitation process with a subject matter expert and we do not show the underlying probability distributions used to quantify the model. None-the-less, preliminary results in using these models comparing a state that is not a recognized proliferation threat and a state that is seem promising. A similar modeling approach could potentially be used to examine State- and non-State proliferation together.

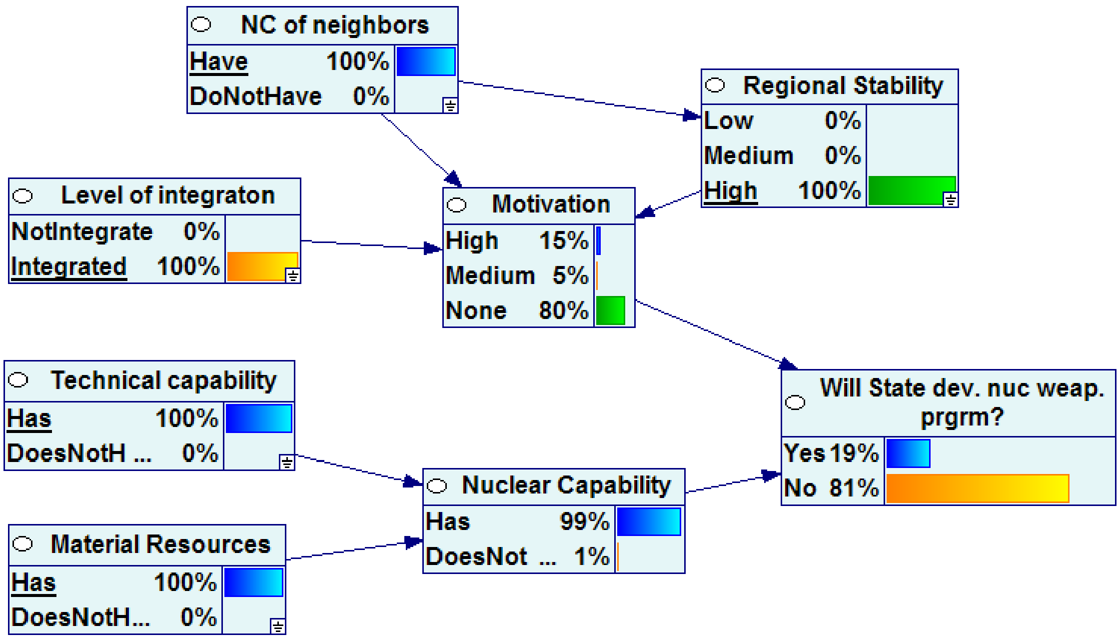

Figure 4.1. Example BN Model of a Low-Risk Proliferation County

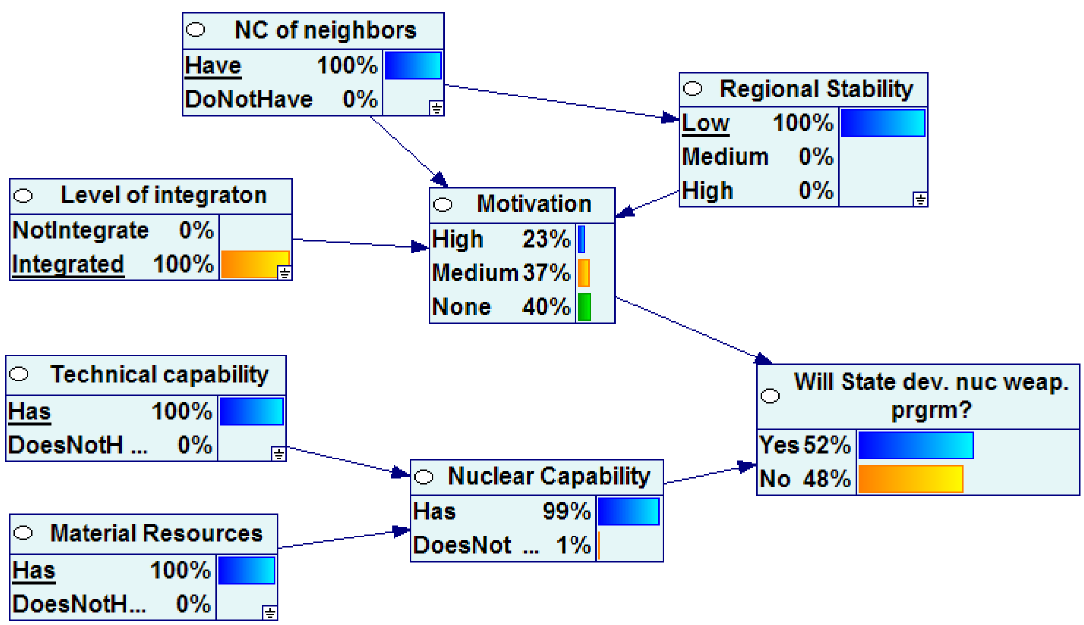

Figure 4.2. Example BN Model of a High-Risk Proliferation County

Pertaining to Question B: Various approaches and methodologies have been proposed to assess the proliferation resistance of nuclear energy system facilities (proliferation resistance literature is discussed in Section 3.2). An international approach being developed and supported by the GIF PP&PR working group incorporates a structured expert elicitation. The proliferation resistance risk assessment measures developed by the PR&PP [1] are shown in Figure 4.3.

Measures and Metrics	Metric Scales Bins (Median)	Proliferation Resistance
Proliferation Technical Difficulty (TD) Example metric: Probability of pathway failure from inherent technical difficulty considering threat capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Proliferation Cost (PC) Example metric: Fraction of national resources for military capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-100% (90%)	High
	>100% (>100%)	Very High
Proliferation Time (PT) Example metric: Total time to complete pathway	0-3 mon (2 mon)	Very Low
	3 mon-1 yr (8 mon)	Low
	1-10 yr (5 yr)	Medium
	10 yr-30 yr (20 yr)	High
	>30 yr (>30 yr)	Very High
Fissile Material Type (MT) Example metric: Dimensionless ranked categories (HEU, WG-Pu, RGPu, DB-Pu, LEU); interpolation based on material attributes	HEU	Very Low
	WG-Pu	Low
	RG-Pu	Medium
	DB-Pu	High
	LEU	Very High
Detection Probability (DP) Example metric: Cumulative detection probability	A	Very Low
	B	Low
	C	Medium
	D	High
	E	Very High
Detection Resource Efficiency (DE) Example metric: GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)	<0.01 (0.005 GWyr/PDI)	Very Low
	0.01-0.04 (0.02 GWyr/PDI)	Low
	0.04-0.1 (0.07 GWyr/PDI)	Medium
	0.1-0.3 (0.2 GWyr/PDI)	High
	>0.3 (1.0 GWyr/PDI)	Very High

Material Type Description

HEU = high-enriched uranium, nominally 95% 235U;
WG-Pu = weapons-grade plutonium, nominally 94% fissile Pu isotopes;
RG-Pu = reactor-grade plutonium, nominally 70% fissile Pu isotopes;
DB-Pu = deep burn plutonium, nominally 43% fissile Pu isotopes;
LEU = low-enriched plutonium, nominally 5% 235U.

Detection Probability

A - Significantly lower cumulative detection probability than the IAEA detection probability and timeliness goal for depleted, natural, and LEU uranium.
B - 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of depleted, natural, and LEU uranium).
C - 20% in 3 months, 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of spent fuel/irradiated material).
D - 50% in 1 month, 90% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity HEU/separated Pu).
E - Significantly greater cumulative detection probability than the IAEA detection probability and timeliness goal for HEU/separated Pu.

Figure 4.3. GIF PR&PP Working Group Proliferation Resistance Measures

Figure 4.4 illustrates conceptually how the measures defined in the GIF methodology might be informed by social modeling. Proliferation theories can be used to identify behavioral, social, and cultural factors that explain the motivation of a country or organization to develop nuclear weapons. GIF proliferation resistance assessments evaluate the intrinsic and extrinsic characteristics of nuclear energy systems to understand proliferation risk by applying six proliferation resistance measures to potential proliferation pathways. Consideration of the behavioral, social, and cultural factors can be integrated into consideration of the proliferation measures against proliferation pathways. In this way behavioral, social, and cultural factors could be used to inform nuclear energy system design (i.e., intrinsic characteristics) and safeguards (i.e., extrinsic characteristics) improvement. Bayesian networks and other analytical methods could be used to integrate social and technical models.

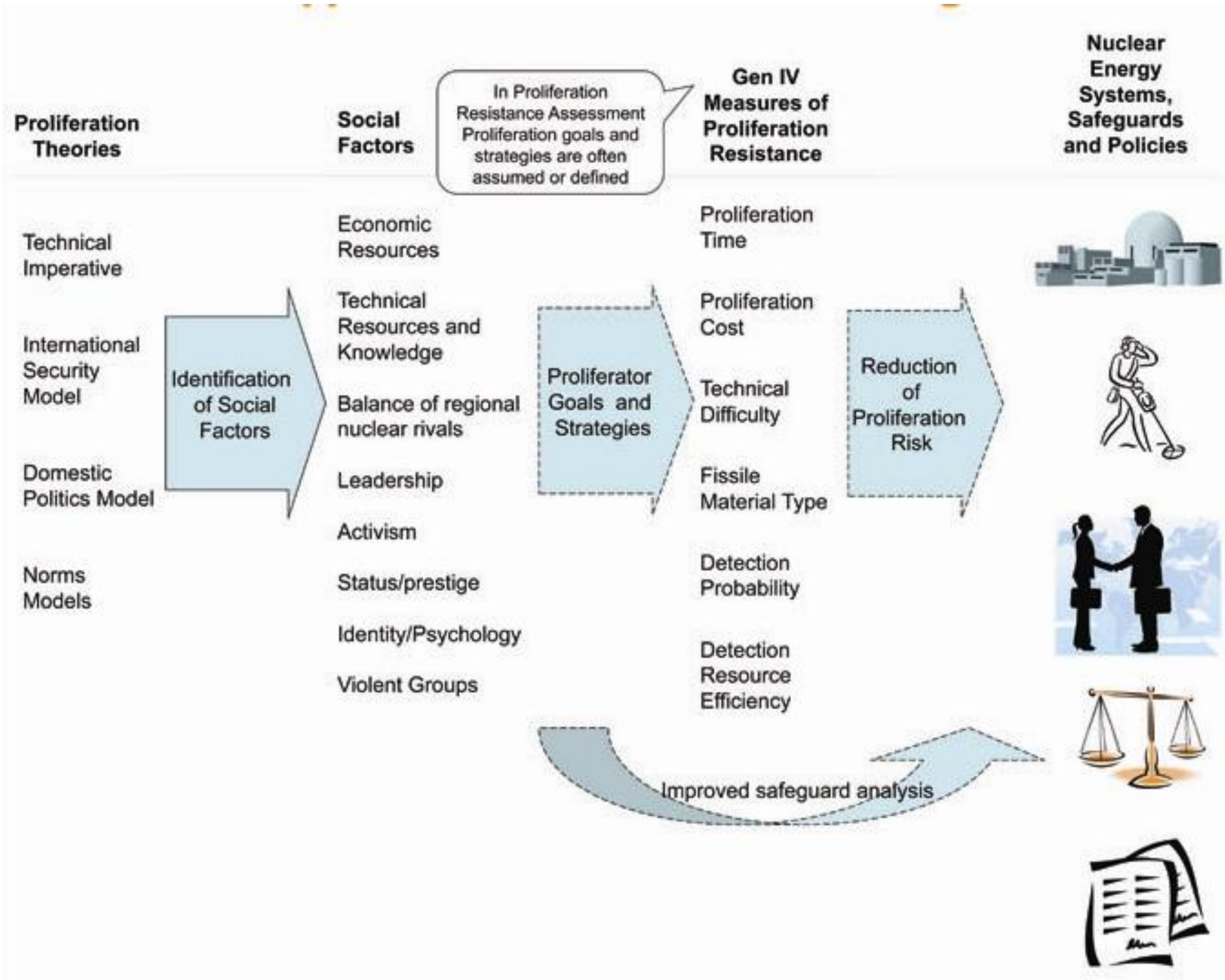

Figure 4.4. Integration of Social Factors into Use of Proliferation Resistance Measure

Pertaining to Question C: Assessing the question of: "What is the proliferation resistance of nuclear energy system Y operating within the environment of entity X?" has not been explicitly addressed in open-source literature. Although proliferation resistance assessment approaches often are purported to consider the "threat," typically the threat is assumed to be of some particular nature. Figure 4.5 below illustrates the importance of being able to evaluate not just the proliferation resistance of a technology and the propensity of an entity to proliferate, but to analyze the two together to determine the actual proliferation threat to a specific piece of technology operating within a specific environment. As shown in the figure, the proliferation resistance of a technology is not independent of the environment in which t is deployed.

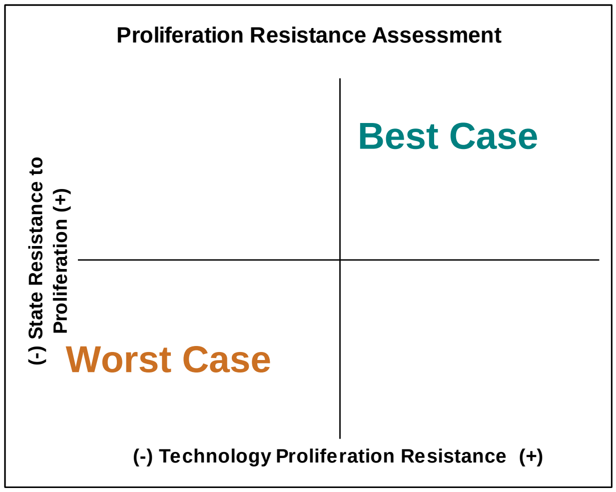

Figure 4.5. Social Versus Technical Resistance to Proliferation

Henry Kissinger said in recent Newsweek article: [2] *"A critical issue in nonproliferation strategy will be whether the international community can place the fuel cycle for peaceful uses of nuclear energy under international control. Is the IAEA capable of designing a system that places the enrichment and processing of uranium and plutonium* ***under international control and in the locations*** (our emphasis) *that do not threaten nuclear proliferation?"*

Social modeling can inform various aspects of the proliferation resistance assessment process. As seen above, social factors could be explicitly considered when evaluating a facility or system's technology proliferation resistance using defined proliferation resistance measures. Social modeling might be used even further by helping to predict which proliferation strategy an entity might use based on the predisposition of different actors. General proliferation strategies a state might take include:

1. Concealed production of nuclear material and concealed processing or enrichment. (no declared reactors, processing facilities, or enrichment plants)
2. Surreptitious diversion of material from declared reactor or other facility (which may involve misuse) and concealed processing or enrichment
3. Surreptitious diversion of material from declared reactor or other facility (which may involve misuse) and misuse of a declared processing or enrichment facility
4. Concealed production of nuclear material and/or concealed processing or enrichment
5. Declared facilities to produce or process nuclear material and then "breakout" from the NPT.

Non-State strategies for proliferation are not as well defined, but might include these strategies along with other new strategies, such as blackmail, theft, and networking.

An entity's strategy will likely be determined, at least in part, by the entity's time constraints, technical capability, economic and material resources, and willingness to be detected by the IAEA and international community. In some situations, it could also be determined by a willingness to incur significant harm (either bodily harm at the individual level, or harm to international prestige and security on the State level), as well as potential for cooperation from other actors. The planned modeling approach for this project is to leverage other PNNL research by using Bayesian nets to combine and inform a model that can answer questions like Questions A, B, and C.

Additionally, for research areas that have been traditional to NA-22 SAM program there are, no doubt, further opportunities for social modeling in the area of Integrated Modeling that would inform or complement modeling that exists in the area of Advanced Spectroscopy, Facility Modeling, and Geospatial Modeling.

The potential utility of using social information or modeling to complement Geospatial Modeling can be illustrated by a case of diversion of nuclear materials described in a 2004 report, *Nuclear Security Culture: The Case of Russia*, where a large number of facility staff worked together with government regulators to steal and sell isotopes [3]. The scheme was so well-managed that the fact of diversion became known only by a fluke. The conspirators did not bother to hide their expensive cars and houses, which were incongruous in a very small town where the main industry, Elektrokhimpribor, paid small salaries. This incongruity attracted the attention of law-enforcement officers who drew a parallel between the financial well-being of several employees at the facility and the situation on the very small world market in isotopes, where prices had dropped dramatically and it had become surprisingly hard to sell. The lesson is that consideration of social information can help define patterns or signatures of potential proliferation activity that are worth trying to detect.

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4.2 Summary of Key Data

All models require data, both as input to the model and as a means of testing its validity. Data for social science models can be difficult to obtain—especially numerical data. Much of the data for social science models will be the mental models of experts in the field and may not be available in writing. Among the written sources of data are the specific stories of countries that attempted or succeeded in developing nuclear weapons along with the supporting facts and circumstances of those stories [1][2][3][4][5][6][7][8][][9][10][11][12]. Also of clear interest is data already used by analysts to defend particular proliferation theories and factors defined as contributing to those theories, especially quantitative data such as is used by Meyer, Singh, and Jo in their analyses [13][14][15] (see Section 3.1).

However, by proposing the use of inference modeling, data could be any information that provides evidence used in the proliferation model, so in this sense the data are vast. This data could include cultural, economic, political, technical, and scientific information; it could include information about facility or system designs, safeguards measures, safeguards agreements, transfer of knowledge, transfer of technologies; it could include information on social dynamics, group dynamics, leadership dynamics, and international dynamics; it could include specific details about particular nuclear energy system facilities and the humans that work in, on, or near those facilities; it could include specific improvements in nuclear material detection, measurement, or monitoring; it could include a wide variety of information, ranging from general to very specific. The challenge will be to identify those data sources having the greatest relevance for modeling the questions for which we propose to find answers.

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5.0 Identification of Key Challenges

5.1 Model Validation

This section provides a discussion on how to validate models, philosophical perspectives on validation, preliminary remarks on a comprehensive approach to model validation, and a comprehensive approach to model validation

5.1.1 How to Validate the Models

There are distinct philosophical perspectives on model validation. Key issues are the purpose for building models, what it means for a model to be valid, and the validation process. The greatest amount of common ground concerns why we build models. Models are typically constructed to improve decision-making by providing better information and understanding as a basis for evaluating alternatives. While models are sometimes built simply to understand phenomena, there is usually the hope that they will ultimately have utility. Even pure science is funded with the expectation that it will eventually be profitable. What does it mean for a model to be valid? This question has generated a lot of literature with diverse points of view. One popular perspective is that the validity of models is determined by whether they can reproduce historical data. While it is important to fit models to data when it is available, it is our perspective that this is only one aspect of validation. Confidence in the validity of models, many of which often lack hard data, will depend as much, if not more, on the process by which they are constructed and their documentation than on testing them after the fact for goodness of fit. As a case in point, two models can fit historical data equally well and yet have dramatically divergent predictions. The choice of which is the better model will come down to the cogency of the causal mechanisms that are built into the model and the confidence it inspires by being open and transparent.

An important aspect of validation is the documentation, which provides the rationale for the logic underlying the design of the model and how it works. The fact is that at some level, all models are wrong [1]. They are an abstract representation of one aspect of reality. No model can perfectly reflect the reality they are designed to represent. Even if one could build such a model, itwould be too complex to be useful. Providing more detail than needed creates unnecessary complication. Models should be detailed enough to provide a realistic assessment of the problem they were designed to help solve, but be as simple as possible while still providing the insights needed for solving the problem for which they were constructed. Models should be judged relative to the extent they meet performance expectations and objectives. The purpose of validation is to develop confidence in using them to inform decision- making. The process for developing this confidence is not a single procedure. Instead, model validation consists of a number of activities which, when taken together, create confidence in the usefulness of the model and helps to establish boundaries or parameters within which the model performs well. This section briefly describes some philosophical perspectives on validation and some of the ways in which one can create confidence in the model and its usefulness for decision-making.

5.1.2 Philosophical Perspectives on Validation.

To put validation into perspective it is useful to briefly review some of the divergent philosophical positions. Kleindorfer and Ganeshan [2] claim that validation theories fall into one of three categories:

Justificationism versus Antijustificationism, and an attempt to find a middle ground. According to them: "*A justificationist believes that there is a unique ultimate basis either in experience or in rational thought into which a model or a theory must be resolvable if one is to validate it. Depending on whether one is an empiricist or a rationalist, this basis is either to be found in direct experience, or in clear, certain, self-evident ideas found in one's own mind.*" [2]

They point out the difficulty, if not the impossibility, of validation from a Justificationist perspective. Of particular interest to validation is the problem of induction. They characterize this as the difficulty of drawing general conclusions given limited experience of the model from which to generalize. It will help to clarify subsequent discussion of verification and validation (V&V) to explore the problem of induction in a little more detail. While it is often the case that inductive arguments are used to argue from specific premises to general conclusions that is not the defining characteristic of an inductive argument [3]. An argument consists of a list of Statements, called premises, and a final Statement, called the conclusion. As Skyrms [3] points out, deductive *valid* arguments are ones in which the conclusion must be true if the premises are true, and inductively *strong* arguments are ones in which there is a high probability that the conclusion is true if the premises are true. Mathematical systems, like Euclidean geometry, are examples of deductively valid arguments. Theorems in geometry are a logical consequence of the axioms. Theorems in these systems are true because they are actually a restatement of the axioms in ways that were not necessarily obvious until one lays out the premises in a logical fashion. On the other hand, science is, by its very nature, inductive. The purpose of science is to explain phenomena and make predictions based on empirical observations using a rational methodology. Scientific theories are never proven to be true. As Popper [4] points out, we can never prove a theory true; we can only disconfirm theories. As evidence accumulates that is consistent with a theory we develop more and more confidence in it. However, there is always the possibility of a "paradigm" shift [5] in which the data gets reinterpreted and a different theory is seen as a better explanation, just as the Copernican heliocentric theory of the universe provided a better explanation for the motion of the planets than Ptolemy's earth-centered theory.

The relevance of this to V&V will become more apparent in the light of concise definitions. A number of different definitions for both V&V are provided in the literature and the Sandia Report provides a number of examples. Because V&V are often used together there can be some confusion of their distinct purposes. Most definitions are very similar, but the one the Sandia Report settles on makes the distinction between the two most clear. We adopt the Sandia Report definitions:

- ***Verification*** refers to methods that help determine the internal logical correctness, consistency, sufficiency, and accuracy of a computational model.
- ***Validation*** refers to methods intended to gather evidence of the external logical correctness, consistency, sufficiency, and accuracy of a computational model.

Verification is about internal consistency. It is like a deductive argument. Validation concerns the validity of the models' predictions or conclusions. It is like an inductive argument. Consequently, we can never be 100% certain of the validity of a model. It is like a scientific theory; the more we work with it the greater confidence we can have in it and the better we are able to recognize the limits of its applicability. The best we can hope for is a strong inductive argument. Like the case for a scientific theory, the validity of a model will have its basis in both empirical observations and rational assertions, which we claim to be valid simply because they appeal to our sense of what is reasonable.

According to Kleindorfer and Ganeshan, [2]no one can provide a non-circular logical argument for either an empirical or rational basis for validation. They conclude that "Justificationism is no longer in vogue." They go on to discuss various types of Antijustificationism, including Falsificationism, Kuhnianism, and Instrumentalism, among others. Falsificationism is generally attributed to K. Popper [4]. Instrumentalism, for example, has a conventionalistic element, which holds that a model or theory may have elements that are put in for aesthetic reasons or convenience more than anything else. Ultimately, Kleindorfer and Ganeshan conclude that an approach that has elements of both Justificationism and Antijustificationism may prove to be the most fruitful?. We are also proposing a middle ground, as discussed earlier.

5.1.3 Preliminary Remarks on a Comprehensive Approach to Model Validation

Validation occurs on three levels. Models that make use of social science need to be validated on three levels [6] (and cited in Sandia Report [8]). These are shown in Figure 5.1. First is the validity of the discipline: "Is it recognized as a legitimate form of inquiry, with methods, theories, and datasets that lead to generalizable, reliable knowledge about reality?" To use the example from the Sandia Report, it would not be valid to use astrology as basis for explaining behavior to psychologists. Second is the validity of the approach: "Within the discipline, is the proposed approach, with associated concepts, directions, data, and methods, recognized as an appropriate framework for the problem proposed?" Third is the validity of the constructs and concepts: to what extent do disciplinary practitioners agree on the definition, implementation, applicability, measures, approaches, assumptions, contextual boundaries, and implications of the concepts?

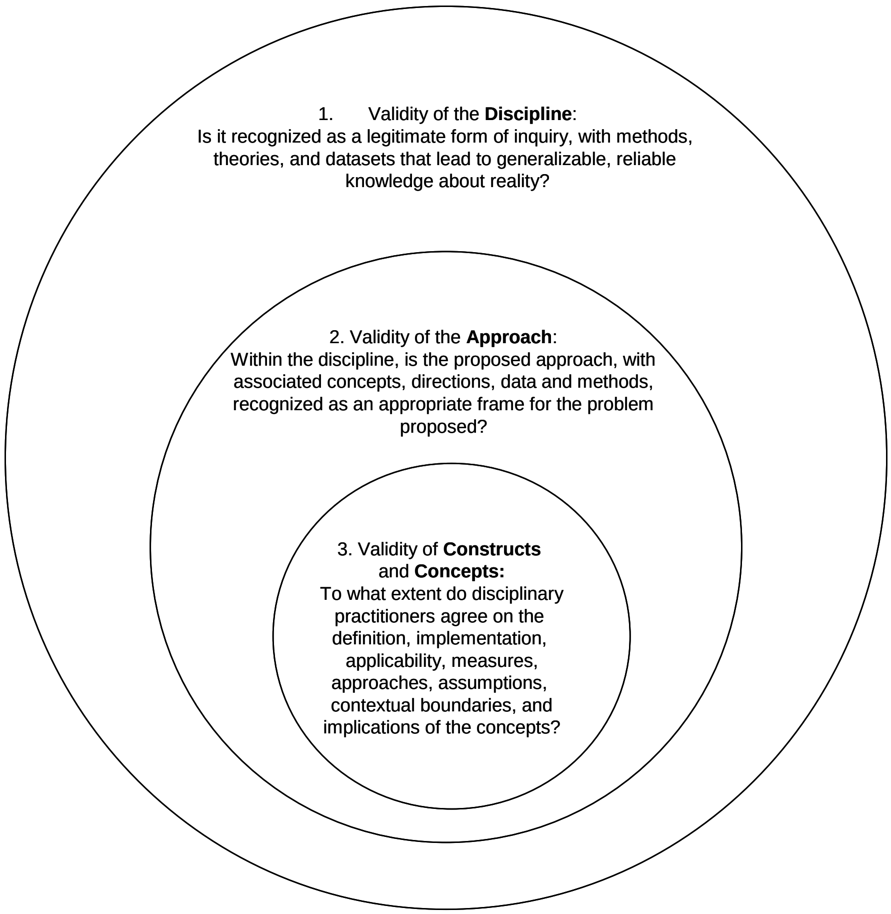

Figure 5.1. Hopkins Hierarchy of Validity (from Wise [6] and cited in Sandia Report [8].)

Validation Effort. Because validation is never complete, one needs to consider the marginal value of additional validation relative to the cost. Sargent [7] provides an illustration of this concept reproduced in Figure 5.2.

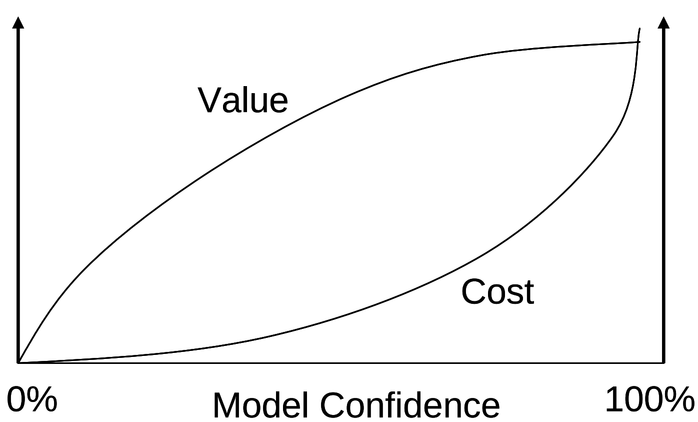

Figure 5.2. The Value of Model Confidence Versus Cost (from Sargent [7])

As can be seen in Figure 5.2, the marginal benefit-to-cost ratio is initially high and becomes less at higher levels of confidence.

5.1.4 A Comprehensive Approach to Model Validation

The approach we describe has elements from several sources, including Sterman [1], Sargent [7] and a Sandia National Laboratories report [8]. Validation is in part due to the process of constructing a model and in part comparing it to available data. It is elements of Justificationism and Antijustificationism. It is both rationalist and empiricist and tentatively at times steps beyond the rationalist empiricist dichotomy to social constructionist. It also recognizes that all models have limited applications and advocates falsification as a means of determining limitations and the domain of applicability. Because of the wide diversity of models in both content and methodology, it is not possible to recommend a specific procedure applicable to all models; the following elements of validations should be addressed in varying degrees, depending on the situation.

1. Clarity of Purpose. It is important from the outset to have a clear understanding of why the model is being built and what specific decision or problem is being addressed. The purpose will determine the domain of interest, what variables need to be included, and the accuracy of the data. Is the purpose to make a specific numerical prediction or to develop a general understanding of relationships? If the latter, a qualitative model may be sufficient to develop clarity about the mental model underlying the behavior of interest and will be enough to provide the additional insight needed, or it could be that rough approximations of numerical estimates will be sufficient to observe the behavior of interest without obtaining precise estimates. Models are valid to the extent they fulfill their intended function. A statement of the models intended use should guide all subsequent validations activities.

2. Documentation. Detailed documentation is important for creating a transparent model that inspires confidence in the results and awareness of its limitations. As a builder, it is also important to capture the rationale while it is clear during the process of construction. It can be very frustrating when one has a clear reason for defining a relationship a certain way, but can't remember later what the basis for it was. Some software applications have provisions for documenting; make good use of it during the construction process. Comprehensive documentation greatly facilitates subsequent validation activities, especially conceptual validation.

3. Conceptual Validation. A model is conceptually valid to the extent that the relationships among the variables are theoretically or empirically compelling. One source of these relationships is the relevant science. Within science, these relationships may have their basis in a body of scientific knowledge relevant to the modeling domain, such as well-known scientific principles or laws, or there may be scientific empirical data that support the relationships. In the absence of a clear basis within the body of relevant science there should be rational or logical basis that is clear and self-evident or intuitively compelling. Conceptual validation includes activities that would fall under the concept of construct validity from Hopkin's Hierarchy of Validity. Construct validity asks whether those knowledgeable of the discipline agree with the definitions, implementation, measures, and assumptions [6]. A model is conceptually valid to the extent all the relationships can be justified either empirically within a body of science or rationally based on logic and rhetoric.

4. Behavioral Validation. A model is behaviorally valid to the extent the behavior of the model is reasonable. This activity consists of exercising the model to determine if it works as anticipated. Are the input-output relationships consistent with expectations? Test the model's behavior for extreme conditions. Run the model under a variety of assumptions to see if the output changes with input in ways

that are reasonable or consistent with expectations. Behavioral validation includes aspects of what Sargent [7] calls face validity; i.e., the input-output relationships are reasonable.

5. Data consistency. There are three types of data: numerical, written, and mental. According to Sterman [1] mental data is by far the greatest source of information for social science models. Interviewing someone to learn their mental models may not only be the only source of information, but the best source from which to build social science models. Written data can serve as a surrogate for direct interviews. Actual numerical data is difficult to obtain for social science models. Determining the model's consistency with mental models is one aspect of conceptual validation. When models are built based on published literature the ideal check is to verify with an expert to ensure that the literature has been interpreted correctly. When actual numerical data is available, goodness-of-fit tests can be carried out to determine consistency.

6. Utility. While not strictly an aspect of validation and verification, an important consideration in model evaluation is utility. This will be fulfilled to the extent the model meets the requirements for which it was designed, but more importantly, will the client make use of the information generated by the model to make decisions? Models get used to the extent that they are transparent, that there is confidence in its validity, and it is easy to use and understand. If a model is not used the process of constructing it may have been an intellectually rewarding experience for the builders, but the client received nothing of value for their investment. A useful model that is actually used by the client is more likely to result if there is excellent communication between the modelers and the client throughout the construction process—especially in the early stages of model development, when the purpose is being defined and the design specified.

7. Other validation Tests. Each model represents a unique situation and we can only provide general guidelines for model verification and validation. There will always be other validation tests that should be performed, depending on the model and the context. Some of these are specific to the modeling methodology. For example, validating a simulation model will involve different procedures than validating a Bayesian net.

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Abstract: More than 25 years ago, Naylor and Finger suggested that the problem of validation in simulation was analogous to the problem of validating scientific theories in general. They went on to prescribe an eclectic approach to validation in simulation that they put together from what they viewed at the time as an exhaustive description of the possible philosophical alternatives. A considerable development has taken place in the philosophy of science since Naylor and Finger wrote their paper, most notably the justificationist positions in the philosophy of science they appealed to that have been largely discredited. We attempt here to provide a new examination of the various relevant positions. And we also attempt to show, in one way or another, how these positions provide additional perspectives on overcoming some of the conceptual difficulties involved in simulation validation.

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Abstract: This paper discusses verification and validation of simulation models. The different approaches to deciding model validity are presented; how model verification and validation relate to the model development process are discussed; various validation techniques are defined; conceptual model validity, model verification, operational validity, and data validity are described; ways to document results are given; and a recommended procedure is presented.

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Abstract: Sandia National Laboratories is investing in projects that aim to develop computational modeling and simulation applications that explore human cognitive and social phenomena. While some of these modeling and simulation projects are explicitly research oriented, others are intended to support or provide insight for people involved in high consequence decision-making. This raises the issue of how to evaluate computational modeling and simulation applications in both research and applied settings where human behavior is the focus of the model: when is a simulation "good enough" for the goals its designers want to achieve?

In this report, we discuss two years' worth of review and assessment of the ASC program's approach to computational model verification and validation, uncertainty quantification, and decision making. We present a framework that extends the principles of the ASC approach into the area of computational social and cognitive modeling and simulation. In doing so, we argue that the potential for evaluation is a function of how the modeling and simulation software will be used in a particular setting. In making this argument, we move from strict, engineering and physics oriented approaches to V&V to a broader project of *model evaluation*, which asserts that the systematic, rigorous, and transparent accumulation of evidence about a model's performance under conditions of uncertainty is a reasonable and necessary goal for model evaluation, regardless of discipline. How to achieve the accumulation of evidence in areas outside physics and engineering is a significant research challenge, but one that requires addressing as modeling and simulation tools move out of research laboratories and into the hands of decision makers. This report provides an assessment of our thinking on ASC Verification and Validation, and argues for further extending V&V research in the physical and engineering sciences toward a broader program of model evaluation in situations of high consequence decision-making.

5.2 Political Sensitivity to Integrating Cultural Information

Evaluating the proliferation propensity of a state or non-State actor can result in politically sensitive outcomes. Defining a proliferation likelihood score, especially a quantitative score in which countries, social groups, or other organizations can be ranked or compared can be especially sensitive because of potentially perceived discrimination by those States that have low proliferation resistance indicators. As such, to evaluate political, social, and cultural information in a manner that differentiates but does not discriminate between States or non-State entities, it is important to employ objective, unbiased, well-defined, and founded measures in a systematic approach.

6.0 Conclusion

Based on the literature search it is concluded that there are opportunities to use social models to improve understanding and assessment of proliferation-related problems. In fact, for decades analysts have theorized about the factors that dictate whether a State pursues the development of nuclear weapons–these factors are primarily social factors or are factors that are intimately related to social factors (e.g., national identity, leadership, politics, domestic security, economic capability). Social modeling offers a way to formalize or leverage this body of analysis and theory.

Opportunities for social modeling specifically identified in this report are related to overarching kinds of assessment (e.g., the proliferation resistance assessment of a nuclear energy system, or the assessment of a set of safeguards). However, a seemingly untapped potential exists to augment, support, inform, or complement specific focused kinds of assessments, modeling, or research (e.g., social modeling to support specific use of satellite imagery to identify proliferation activity, specific technology for detection of clandestine facilities, or computerization of a safeguards analysis decision process.) In the area of geospatial modeling more explicit use of social modeling might be used to help identify activities or social patterns that correlate to proliferation activity.

Yet another opportunity for social modeling is the area of non-State proliferation, particularly as it relates to what some analysts call the "supply-side." The supply-side substructure of nuclear proliferation might be considered to include manufactures, scientists, middlemen, transporters, opportunists, and violent groups who contribute to proliferation by supplying technology, knowledge, and material to the world. The interconnection of these groups is of interest because globalization has produced a large number of organizations that operate across State borders. Analysis of social networks that show the connections, characteristics, and goals of the groups in this substructure may yield interesting clues about proliferation and the role of non-State actors.

Opportunities exist for social modeling in proliferation assessment. The challenge of this research is to identify opportunities where social modeling can have a significant impact and demonstrate its utility. Our approach will be to select a social modeling opportunity related to an overarching type of assessment that has promise to be used in other or in more specific kinds of applications. We intend to leverage research at PNNL by using Bayesian networks to model applicable social science or theory. Validation of these models will be an important step to demonstrating utility and will be built in parallel, based on the modeling application developed.

Appendix A

Definitions

Appendix A

Definitions

Bayesian Network - A graphical probability model that represent a set of variables and their probabilistic independencies. Formally, Bayesian networks are directed acyclic graphs whose nodes represent variables, and whose missing edges encode conditional independencies between the variables. The word "Bayesian" comes from use of Bayes theorem and is derived from the work of Reverend Thomas Bayes. [1]

Dempster-Shafer theory - A mathematical theory of evidence [2] based on "belief functions" and "plausibility reasoning," which is used to combine separate pieces of information (evidence) to calculate the probability of an event. The theory was developed by Arthur P. Demspter and Glenn Shafer.

Non-State actors – Sub-national or multi-national groups including terrorist organizations.

Non-State proliferation – Attempts by non-State actors to acquire, process, and weaponize nuclear material with the intention to develop at least one nuclear weapon that may involve collaboration with other groups or States.

State-sponsored nuclear proliferation - State sponsorship of material acquisition, processing, and weaponization activities with the intention to develop at least one nuclear weapon.

Proliferation resistance – That characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by States to acquire nuclear weapons or other nuclear explosive devices.

Safeguards – As used in regulation of domestic nuclear facilities and materials, the use of material control and accounting programs verify that all special nuclear material is properly controlled and accounted for, and the physical protection (also referred to as physical security) equipment and security forces.

As used by the International Atomic Energy Agency (IAEA), verifying that the "peaceful use" commitments made in binding non-proliferation agreements, both bilateral and multilateral, are honored. [3]

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