

A Systems Approach to Assessing Nonproliferation Strategies

Arian L. Pregoner, Robert J. Glass, Arlo Ames, Walter E. Beyeler,
Sharon DeLand, and Adam David Williams
Sandia National Laboratories*
P.O. Box 5800, Albuquerque, NM 87185

Abstract

Nuclear nonproliferation efforts traditionally have focused on controlling the supply of proliferation-relevant technology, material, and expertise. As barriers to diffusion of all three have been lowered, there is increased acknowledgement of the need to reduce demand for such weapons, and, in cases where efforts to prevent proliferation have failed, the need to develop effective international responses. However, with few exceptions, approaches to nonproliferation have remained qualitatively the same over the last sixty years. In addition, many states whose active support is essential, view nonproliferation as primarily a U.S. issue and in some cases see U.S. military superiority as a more serious threat to their security than nuclear proliferation. Such states are often unresponsive to requests to strengthen their nonproliferation efforts. In this paper we develop a basic systems dynamics model of the process of proliferation against which nonproliferation strategies can be assessed. This basic model includes both processes of acquisition of nuclear weapons and processes that motivate states to seek nuclear weapons. Next we develop simple models of nonproliferation strategies and demonstrate how they impact the process of proliferation. We then offer observations about the relative impact of different strategies, given hypothetical initial and boundary conditions. Finally, we recommend additional work to improve the model and make it accessible to the nonproliferation community both for discussion and for testing hypotheses.

Introduction

Nuclear nonproliferation efforts have evolved over time in response to a changing international environment. International Atomic Energy Agency (IAEA) safeguards coupled with diplomacy were the prevailing nonproliferation strategies until the Indian nuclear test in 1974, which triggered much more intensive efforts on international export control and the formation of the Nuclear Suppliers Group. The end of the Soviet Union in 1991 and fears of unsecured nuclear weapons and material resulted in creation of a broad range of cooperative threat reduction efforts to improve nuclear security; in the same time frame, the failure of the IAEA to detect the Iraqi nuclear program led to the IAEA Additional Protocol. Since 9/11 many new approaches have been tried, ranging from capacity building to help developing countries implement nonproliferation obligations, to the Proliferation Security Initiative aimed at interdicting illicit shipments. There have also been calls for internationalization of portions of the nuclear fuel cycle and for reducing the salience (and numbers) of nuclear weapons.

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These efforts to limit the spread of nuclear weapons take place within a global system of states, each of which has its own domestic concerns and reasons for participation in the nonproliferation regime. This large “system of systems” is both complex and adaptive. It is complex (not simply complicated) because it is composed of many, many similar parts that interact to create emergent behavior (e.g., economic bubbles, wars) and structure (e.g., supply networks, treaties and influence networks). It is adaptive because it contains humans and human institutions that learn and modify their interactions over time. Thus, to be effective, nonproliferation strategies must be able to influence a complex adaptive system of systems to limit the spread of nuclear weapons.

Because of this complexity, it is difficult to predict (or even understand) the ultimate impact of nonproliferation strategies. However, analysis tools and methodologies have been developed to understand the behavior of complex adaptive systems in other disciplines and could be applied to nonproliferation. The purpose of this paper is to take the first step in establishing a formal systems analysis framework and methodology to evaluate and design nonproliferation strategies.

This first step consists of a graphical conceptual model of the process of proliferation and strategies that are intended to influence it. The proliferation model includes a description of why states seek nuclear weapons (NW) as well how they acquire them. We also enumerate nonproliferation strategies and show how they may impact the process of proliferation. Our goal at this stage is to achieve a clear representation of the process of proliferation and the intended (and unintended) impacts of nonproliferation strategies. Future steps to mathematically implement the conceptual model will allow evaluation of the trade-offs between costs and benefits of various strategies.

Conceptual Model of Proliferation

The graphical conceptual model is based on system dynamics modeling methodology. In this methodology, models consist of four types of elements:

- Stocks are nouns that represent accumulations of things (states with nuclear weapons, states with nuclear technology, available nuclear technology) or states of being (insecurity, inequity, isolation). The stocks are represented by rectangles in the model.
- Flows represent actions or activities that influence the level of stocks. Flows can be physical processes such as acquisition of nuclear weapons or nuclear technology, or non-physical, such as threatening a state’s security or denouncing a states’ behavior. Flows are represented by pipes with arrows in the direction of flow.
- Connectors join components of a model: they transmit actions and information required to generate flows. When a connector links a stock back to its flow, a feedback loop is created. Feedbacks (either positive or negative) introduce nonlinearity to the structure of the system. Connectors are represented by arrows.
- Convertors modify flows and provide information about how quickly or slowly an action happens. They are represented by circles.

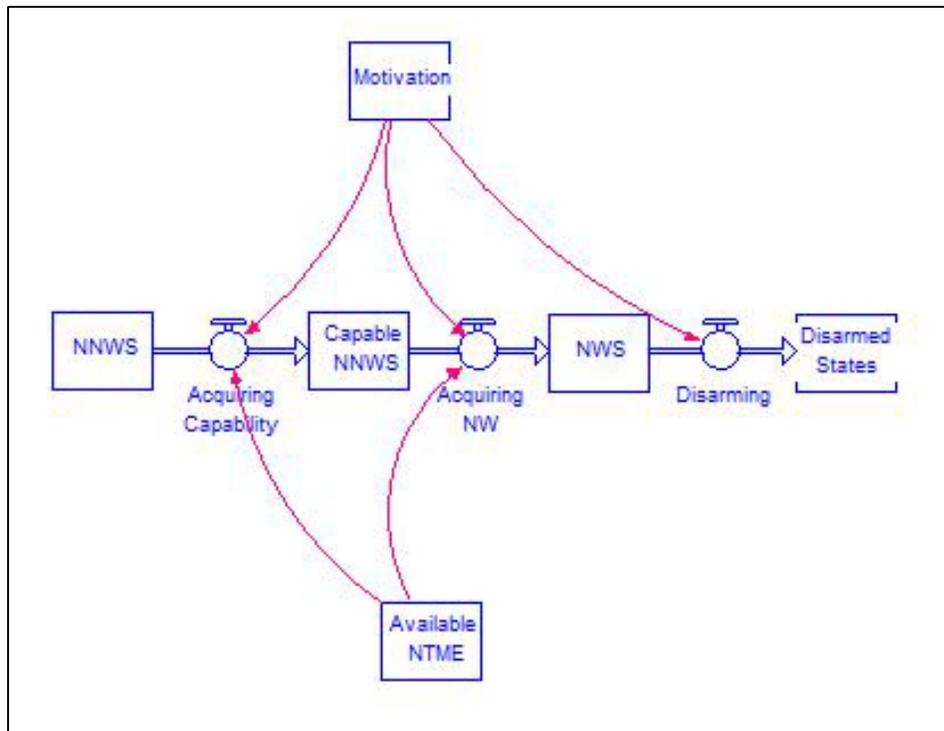
Using this graphical language, we begin with a very simple view of proliferation. At its core are four basic stocks: states without nuclear weapons (NNWS), states without nuclear weapons but with the capability to make nuclear weapons (Capable NNWS), states possessing nuclear weapons (NWS), and states that have disarmed (Disarmed States) (see Figure 1). These stocks are connected by three processes: acquiring the capability to make nuclear weapons, acquiring

nuclear weapons, and disarming. Although states that have disarmed could technically be considered Capable NNWS, we treat them as a separate category, primarily because reconstitution of a nuclear weapons capability (should they choose to re-arm) would be very different from the process of acquiring nuclear weapons in the first place.

Two critical factors influence the direction and rate of flows embodied by the acquiring and disarming processes: 1) motivation to pursue and acquire nuclear weapons, and 2) technological capability, which we describe as consisting of nuclear material, technology and expertise (NTME). These elements are depicted in Figure 1 with arrows denoting influence: without motivation a state will neither acquire nor give up nuclear weapons. Similarly, the availability of nuclear material, technology and expertise is essential for successful acquisition.

In this simple model the paths denoted by flows between the different stocks are depicted as flowing only in one direction. In practice, they could change direction, but the process would be hysteric, i.e., different from simple reversal. This is because the state of the system is path dependent, a multi-valued function of motivation and capability that depends on history. For example, reversing the acquisition path may require more (or less) motivation once certain steps along the path have been accomplished.

Figure 1. Basic model of the process created using STELLA™ software.ⁱ



Adding Structure to Motivation and Capability

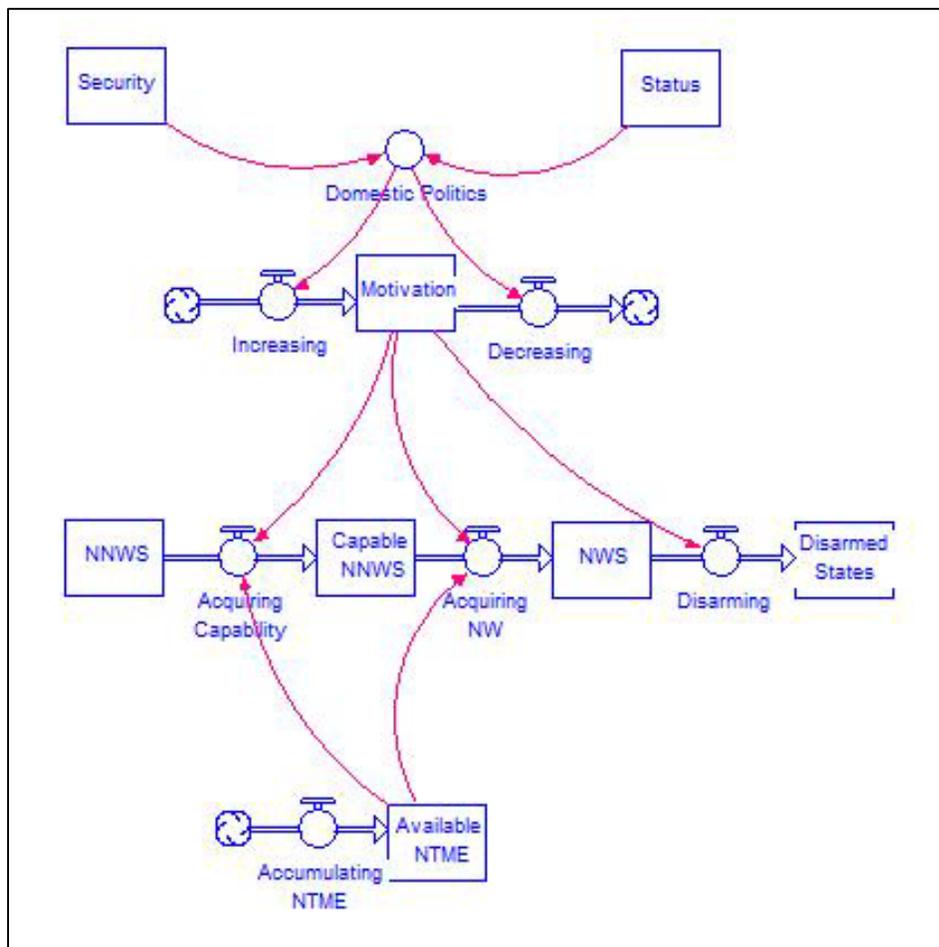
Motivation to pursue a nuclear weapons program is generally thought to stem from a combination of causes: national security concerns, prestige (or status) associated with nuclear weapons, and domestic politics.ⁱⁱ In the model, we represent this by showing that motivation increases or decreases as a function of a state's security or status, with the degree determined (at

least in part) by domestic politics. We treat “domestic politics” differently from “security” or “status:” whereas security and status are stocks that can increase or decrease, domestic politics is a factor in determining, for a given degree of security or status, how motivated a state will be to pursue a nuclear weapons program. These same conceptual elements influence the motivation to disarm, although the functional relationships will be different.

Capability to develop nuclear weapons depends on access to nuclear material, technology and expertise (NTME). States may acquire this capability from a variety of sources, which we represent in the model by “available NTME.” Available NTME accumulates through a variety of processes, e.g., natural diffusion of technical capability, clandestine activities, or black market networks. However the exact mechanisms are not important for the purposes of this basic model.

This simple representation of capability and motivation, coupled with the processes of acquiring nuclear weapons and disarming is shown in Figure 2. More detail could be added, but this is sufficient for the next step: thinking about how and where strategies impact the system. For the sake of brevity, we will focus in the remainder of our paper on nonproliferation strategies and defer analysis of disarmament strategies to the future.

Figure 2. Adding structure to motivation and capability.



Nonproliferation Strategies

Nonproliferation strategies have evolved over time in response to changes in the proliferation landscape. They can be thought of both in terms of their intended impact and their possible unintended consequences, as shown in Table 1.

Table 1. Nonproliferation strategies. Yellow indicates that the strategy is intended to influence capability, blue that it is intended to influence motivation, and green indicates both.

Strategy	Intended Impact	Possible Unintended Consequences
Classification of Information	Restrict availability of NW-relevant information.	
Security Alliances	Increase security of states in alliance.	Could decrease security of states outside.
IAEA Safeguards	Restrict availability of nuclear material (implemented in NNWS)	Asymmetry between NWS and NNWS may reinforce sense that NWS have higher status.
Diplomatic Pressure	Change the “motivation” calculus.	If public, could fuel domestic political arguments for NW.
Sanctions	Punish states for illicit nuclear programs to change the “motivation” calculus.	Could be perceived as unjust and reinforce sense that NW brings status.
Export Control	Limit availability and prevent acquisition of NTME.	Could be perceived as unjust and reinforce sense that NW brings status. Short supply could increase demand for NTME.
Military Action	Slow or disrupt the process of acquiring nuclear weapons or NTME. Reduce motivation of other countries to attempt to acquire NTME or NW. Could also be used to forcefully disarm a NWS.	Could decrease security in states that fear they could be a future target. Could be perceived as unjust and reinforce sense that NW brings both security and status.
Cooperative Threat Reduction	Limit availability and prevent acquisition of nuclear weapons and NTME.	
Missile Defense	Protect states from attack by nuclear missiles, and thereby increase their security. Deny military value of nuclear weapons to proliferators, thereby reducing their motivation to acquire NW to improve security.	Could decrease security of states outside protective shield.
IAEA Additional Protocol (AP)	Disrupt the process of acquiring NTME / NW by early detection of clandestine activities.	Could be perceived as unjust by NNWS, and reinforce sense that NW brings status.
Proliferation Security Initiative (PSI)	Disrupt the process of acquiring NTME / NW by detecting and interdicting illicit shipments of nuclear material and technology	Could be perceived as against international law, and reduce commitment to NPT.
Capacity Building	Restrict availability of NTME by improving international capabilities to prevent theft or unauthorized transfer.	
Nuclear Arms Reductions	Enhance commitment to NPT by NNWS.	Could increase security concerns by states under so-called “nuclear umbrellas.

Figure 3 provides a mapping of the intended impacts of nonproliferation strategies onto the basic model.ⁱⁱⁱ Most strategies are aimed at limiting capability by preventing states from becoming “NW-capable” or limiting the widespread availability of nuclear material, technology, and expertise (each of these processes is the target of 6 strategies). Of the strategies that aim to impact motivation, only two are intended to enhance security and those focus on only a subset of states. None are intended to increase the status of states without nuclear weapons. At this stage we have not attempted to quantify the effectiveness of nonproliferation strategies.

Figure 3. Intended impacts of nonproliferation strategies.

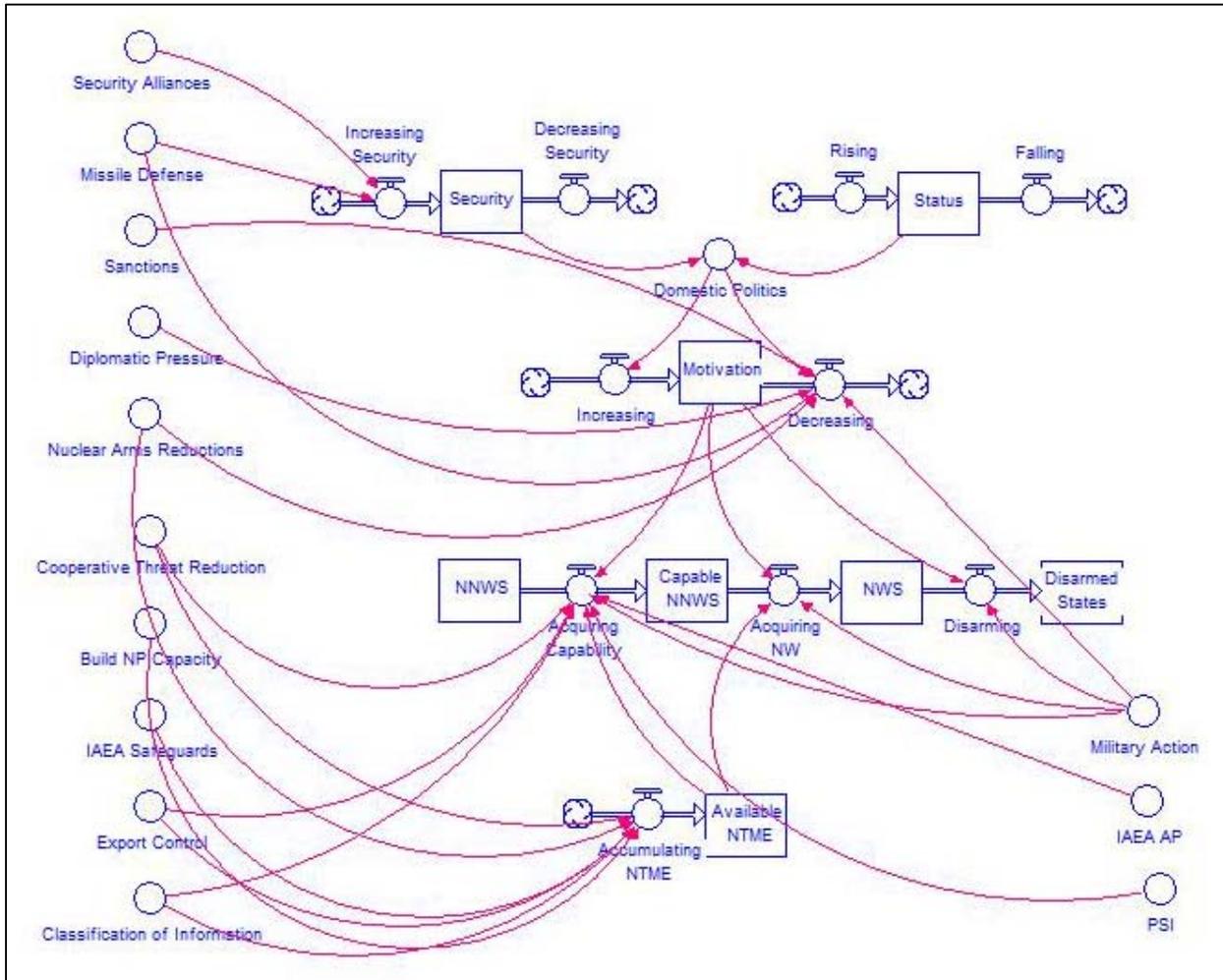
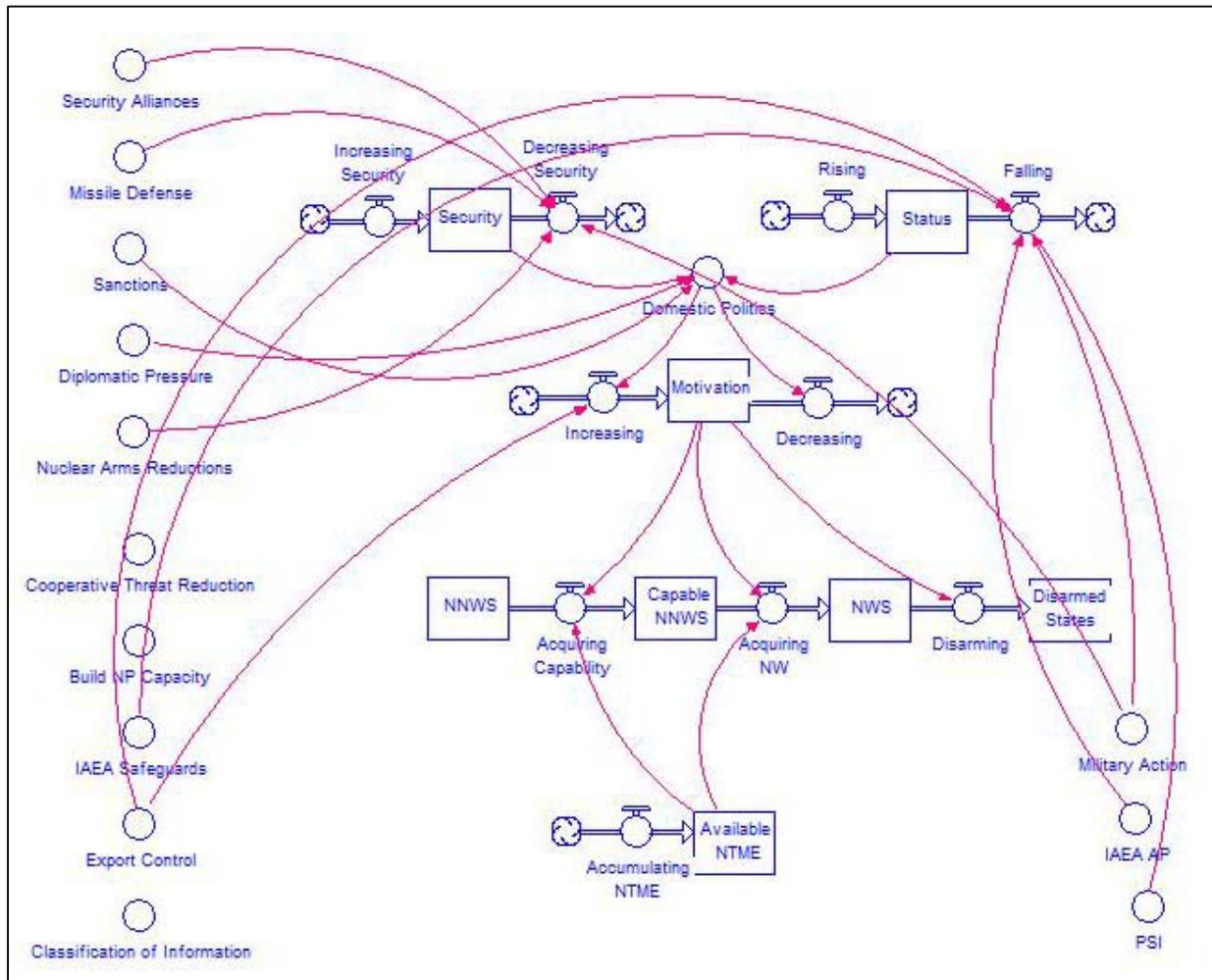


Figure 4 shows a mapping of the possible unintended consequences of nonproliferation strategies onto the basic model. Interestingly, the unintended consequences of four of the nonproliferation strategies decrease security of some states and four also act to decrease the status of states (either in its own eyes or possibly in the eyes of others). We have made no attempt to quantify the strength of the unintended consequences relative to intended impacts (which will depend on specific circumstances), but the mapping demonstrates that some strategies might actually have the opposite of the intended impact.

Figure 4. Possible unintended consequences of nonproliferation strategies.



We thought of no unintended consequences for three of the strategies: cooperative threat reduction, building nonproliferation capacity, and classifying information. However, with regard to the last, we note that when information is widely available, the strategy of classifying information can lead to a false sense of security. The same is the case for export control measures.

We highlight two examples of the differences between intended impacts and unintended consequences of nonproliferation strategies (without commenting on their relative strengths).

The first is the proposal by George W. Bush in February 2004 to prohibit the export of uranium enrichment and spent fuel reprocessing technologies except to those states that already possessed them. The intent was to limit the availability of technology required to make nuclear weapons material, especially given the expected growth in nuclear energy world-wide. However, the unintended consequence was opposition by several states, including nonproliferation stalwarts (and uranium producers) Canada and Australia who did not wish to permanently give up the option to enrich uranium, (which would allow them to extract additional economic benefit). Both countries announced their intention of exploring acquisition of enrichment capabilities within a few months. Unable to convince the Nuclear Suppliers Group to adopt the new export control policy, it eventually died.

A second example is the Obama administration's embrace of the eventual elimination of nuclear weapons and announcement of measures to reduce the salience and size of the U.S. nuclear arsenal. The intent was to demonstrate U.S. commitment to eventual nuclear disarmament (NPT Article VI) and thereby to increase the motivation of NNWS to implement their nonproliferation obligations vigorously, and it has received approval by many NNWS. However, some states under the so-called nuclear umbrella of the United States feared that the new policy could signal reduced U.S. commitment to their security.

While we do not suggest that the mappings shown in Figures 3 and 4 are completely accurate, we find that the process of graphical representation of the impacts of nonproliferation strategies can lead to productive discussion and provides the basis for more rigorous future analysis.

Discussion and Conclusions

While any analysis of a complex issue presumes a mental model of the system being analyzed, graphical modeling using a systems-dynamic methodology forces clarity, can lay assumptions bare and yield insights that otherwise may not be apparent. Creation of a mathematical model forces an additional round of clarification as mathematical functions must be formulated and supported with data or heuristics.

This relatively simple graphical model of nonproliferation highlights that both motivation and capability play an important role in determining whether a state is ultimately successful in acquiring nuclear weapons. The relative paucity of nonproliferation strategies aimed at shifting the motivational calculus, especially in a non-coercive manner, suggests that further attention to developing cooperative approaches that reduce motivation is needed. Furthermore, recognizing that security and status are ultimately indicators of standing in a much broader global regime, it is important to explore how measures outside of the nonproliferation regime itself (e.g., cooperation on trade, economics, environmental issues, etc.) could enhance the regime. We believe that identifying additional measures that can improve security and enhance status of non-nuclear weapon states, and mapping their intended impacts and potential unintended consequences are some of the important next steps for this work.^{iv}

Much more historical data would be required to ascertain whether the unintended consequences hypothesized in Table 1 actually have materialized and to assess the relative impacts of strategies and their unintended consequences. As changes are proposed, such data will be useful in predicting the likely effectiveness of proposed measures, as well as determining allocation of time and resources among many competing strategies. It will be difficult to distinguish between the possible outcomes of alternative strategies without a quantitative model that supports both

uncertainty analysis and cost/benefit analysis. Thus taking the next step toward developing a mathematical representation will be important in enhancing the utility of this model.

We are considering what mathematical formulations to use in this next step. We note that the simplicity of the system dynamics approach and its emphasis on feedbacks can be useful in identifying domains of behavior. However, as we examine the list of possible unintended consequences for current measures, it becomes clear that the impact of a strategy will be different depending on which state (or group of states) is implementing it and which state (or states) is the target. Therefore, while we can represent the intended impacts of strategies in a simple lumped or aggregated model, their actual impact will be more complex and will require representation that recognizes the internal structure or connections between individual states within the global system.

For instance, an aggregate mathematical model of the conceptual model presented in this paper would contain an equation that describes the rate at which states seek or acquire nuclear weapons as a function of their motivation and capability. Realistically, such an equation will depend on the specifics of individual states. This suggests that using an agent-based approach in which each individual nation is represented, could be beneficial. The same conceptualizations for proliferation processes would apply to each individual state but would be augmented with international interactions and perceptions of other nation's intentions.

In summary, the authors have presented a graphical model of the nonproliferation regime including an assessment of both the intended and unintended impacts of many nonproliferation measures. The model highlights the disparity between measures aimed at reducing the motivation to acquire nuclear weapons and the measures aimed at controlling nuclear technology, materials, and expertise. This model can be further enhanced in at least three different ways. One next step is to identify new strategies to strengthen the sense of security and status for members of the nonproliferation regime without needing to acquire nuclear weapons. These strategies could be mapped out to identify both intended and unintended consequences. Second, developing mathematical formulations for the processes represented in the model, including the mechanisms by which nonproliferation strategies impact their rates, will force additional clarity and help assess the benefits of going on to a full mathematical model. Third, the enhanced model could serve as the context for developing an agent-based approach that allowed exploration interactions and impacts at the individual nation level.

ⁱ STELLA is a registered trademark of isee systems, inc.

<http://www.iseesystems.com/software/Educatin/StellaSoftware.aspx>

ⁱⁱ Scott D. Sagan, "Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb," *International Security* 21 (3) Winter 1996/1997), pp. 54 – 86.

ⁱⁱⁱ We understand that "commitment to the NPT" has a number of operational effects, including a commitment to implement export control, border security, material security, etc. Therefore, in the conceptual model we represent it as influencing the process "accumulating NTME." High commitment to NPT would decrease the rate of accumulation, whereas low commitment might increase it. In addition, increasing commitment to the NPT would likely correspond to reducing motivation to seek nuclear weapons.

^{iv} The suggestion to include one or more non-nuclear weapon states in good standing with the NPT as permanent members of the U.N. Security Council is an example.