DYNAMIC AGENT BASED MODELING USING BAYESIAN FRAMEWORK FOR ADDRESSING INTELLIGENCE ADAPTIVE NUCLEAR NONPROLIFERATION ANALYSIS

A Dissertation

by

ROYAL ALBERT ELMORE

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Chair of Committee,	William S. Charlton
Committee Members,	David Boyle
	Craig Marianno
	Justin Yates
Head of Department,	Yassin A. Hassan

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ABSTRACT

Realistically, no two nuclear proliferating or defensive entities are exactly identical; Agent Based Modeling (ABM) is a computational methodology addressing the uniqueness of those facilitating or preventing nuclear proliferation. The modular Bayesian ABM Nonproliferation Enterprise (BANE) tool has been developed at Texas A&M University for nuclear nonproliferation analysis. Entities engaged in nuclear proliferation cover a range of activities and fall within proliferating, defensive, and neutral agent classes.

In BANE proliferating agents pursue nuclear weapons, or at least a latent nuclear weapons capability. Defensive nonproliferation agents seek to uncover, hinder, reverse, or dismantle any proliferation networks they discover. The vast majority of agents are neutral agents, of which only a small subset can significantly enable proliferation. BANE facilitates intelligent agent actions by employing entropy and mutual information for proliferation pathway determinations. Factors including technical success, resource expenditures, and detection probabilities are assessed by agents seeking optimal proliferation postures.

Coupling ABM with Bayesian analysis is powerful from an omniscience limitation perspective. Bayesian analysis supports linking crucial knowledge and technology requirements into relationship networks for each proliferation category. With a Bayesian network, gaining information on proliferator actions in one category informs

defensive agents where to expend limited counter-proliferation impeding capabilities. Correlating incomplete evidence for pattern recognition in BANE using Bayesian inference draws upon technical supply side proliferation linkages grounded in physics. Potential or current proliferator security, economic trajectory, or other factors modify demand drivers for undertaking proliferation. Using Bayesian inference the coupled demand and supply proliferation drivers are connected to create feedback interactions.

Verification and some validation for BANE is performed using scenarios and historical case studies. Restrictive export controls, swings in global soft power affinity, and past proliferation program assessments for entities ranging from the Soviet Union to Iraq demonstrates BANE's flexibility and applicability. As a newly developed tool, BANE has room for future contributions from computer science, engineering, and social scientists. Through BANE the framework exists for detailed nonproliferation expansion into broader weapons of mass effect analysis; since, nuclear proliferation is but one option for addressing international security concerns.

DEDICATION

For my grandparents and parents who sacrificed so much in two generations to bring me to this point.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. William Charlton, and my committee members, Dr. Boyle, Dr. Marianno, and Dr. Yates, for their guidance and support throughout the course of this research. Specifically to Dr. Charlton I will always remember the NUEN 656 discussions on stochastic process and marble based discussions on cultural sensitivities.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the National Science Foundation and Nuclear Nonproliferation International Safeguards Fellowship for financial support.

Finally, thanks to my mother and father for their encouragement and to my wife for her patience and love.

NOMENCLATURE

ABM	Agent Based Modeling
API	Application Programmer Interface
BANE	Bayesian Agent Based Modeling [ABM] Nonproliferation Enterprise
CAS	Complex Adaptive Systems
CMA	Civil Military Affairs
CWMD	Counter Weapons of Mass Destruction
DoD	Department of Defense
DOE	Department of Energy
GUI	Graphical User Interface
IC	Intelligence Community
MAS	Multi-Agent System
NNSA	National Nuclear Security Administration
SQL	Structured Query Language
WMD	Weapons of Mass Destruction
WME	Weapons of Mass Effect
UF_6	Uranium Hexafluoride

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CHAPTER I

INTRODUCTION

Living with nuclear and dual use technology advancements is a reality, and will remain so for the foreseeable future. Evolving global networks of suppliers and increasing global technical competence offer new technologies with nuclear proliferation applications. Monitoring all legal and illicit trade is overwhelming government resources, as well as intergovernmental and non-government organizations (NGOs). Justifications for obtaining nuclear weapons remain largely unchanged since 1945, and focus primarily on security, economics, and prestige.

Policy and technical analysts respectively monitor important elements causing and enabling nuclear proliferation. However, future intelligence and government decision-making cycles will require deep and simultaneous integration of policy and technical analysis to keep up with modern proliferation efforts. Developing new proliferation assessment techniques to leverage modeling and simulation advancements is crucial for directing limited counter proliferation resources and political capital. Decision-makers with constrained resources should understand a broad range of contingencies stemming from their choices. Covering an emerging innovation for nuclear proliferation could be rendered infeasible on national sovereignty grounds by major international states. Recognizing the interplay of networked technical and policy relationships is important for future proliferation assessment tools.

To help inform policy decisions, a dynamic counter proliferation tool with the follow requirements was developed:

1. Create a dynamic and iterative computational nuclear proliferation methodology using agent based modeling and Bayesian analysis that is usable by analysts from a range of technical and policy backgrounds.
2. Implement information theory and optimization based agent decision making to emulate real world proliferation and counter proliferation challenges.
3. Indicate the interconnected relationship between the social science and technical fields for proliferation outcomes.
4. Consider information entropy and uncertainty impacts for proliferation network evolution.

Contextual awareness of potential proliferation expansions is vital for strengthening global nonproliferation. Understanding how social and professional networking, along with physics based opportunities and limitations, will aid in determining emerging nonproliferation challenges. The United States must be positioned to justify its assertions of threats to international partners in a manner at least understandable to other states.

I.A. History of Nuclear Proliferation Assessment Methodologies

The focus of nuclear nonproliferation tools over the last few decades has been on Proliferation Resistance (PR) assessments. PR is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States intent on acquiring nuclear weapons or other nuclear explosive devices.[1] The quantification of PR for different pathways is important to judge the likelihood that an adversary could successfully surmount challenges particular to each pathway.

Current PR efforts tend to fall primarily within the categories of either “Barrier” or “Pathway” analysis systems. “Barrier” PR methodologies emphasize the material, technical, knowledge, and resource hurdles associated with overcoming a particular pathway, or set of pathways. “Pathway” analysis focuses on the PR associated with completing differently arranged proliferation pathways along routes that end with the acquisition of a nuclear weapon.

An overview of “Barrier” and “Pathway” PR methodologies clarifies the different assessment trajectories and their relative strengths and weaknesses. An interdependent framework could draw upon the strengths of each methodology to cover the weakness of the other. The resulting merger would yield a more robust analytical nonproliferation tool that can address the real world scenarios decision-makers face.

I.A.1. Trends in Proliferation Resistance Methodologies: Barrier Approaches

“Barrier” methods have several strengths that make them attractive PR tools. Compared to “Pathway” tools, “Barrier” systems are relatively simple to develop and implement due to their lower complexity. Ease of end user operation is another “Barrier” method advantage.

A major weakness of “Barrier” methods is a tendency towards being tuned to assess a particular set of pathways for PR analysis. The further a pathway is from the major facilities the “Barrier” method was designed to assess, the less reliable its PR values become. “Barrier” methods incorporate little intelligence on the part of the proliferator to overcome challenges. For instance, rather than domestically try to overcome a technical limitation a proliferator can seek advanced dual use technology components from another country. A proliferator can also simultaneously pursue multiple proliferation routes. The knowledge overlap thereby lowers the PR for two seemingly independent routes.

The genesis of most modern "Barrier" PR methods is the "Technological Opportunities to increase the Proliferation resistance of global civilian nuclear power Systems" (TOPS) program.[2] TOPS defined a framework consisting of a methodology and attributes used to compare the relative PR of full civilian nuclear fuel cycles. A further refinement to characterizing nonproliferation PR methodologies was the National Nuclear Security Administration's (NNSA) Nonproliferation Assessment Methodology (NPAM).[3] The NNSA NPAM provided guidelines for integrated PR attribute and scenario approaches which were roughly analogous to early defined "Barrier" and "Pathway" methods.

Later examples of existing "Barrier" methods include the Generation-IV International Forum Proliferation Resistance and Physical Protection (PRPP) and the AREVA-designed Simplified Approach for Proliferation Resistance Assessment (SAPRA).[4,5] The PRPP process can be flexibly employed for an in-depth characterization of the barriers associated with proliferating using a particular advanced nuclear energy system. SAPRA breaks down proliferation into the following four stages: (1) diversion of nuclear material, (2) nuclear material transportation to another site, (3) material transformation into weapon applicable form, and (4) material weaponization through physics package creation. The SAPRA form has additional modifiers, such as country technology profile to further inform the PR outcome.

Other "Barrier" methods are the North Carolina State University Fuzzy Logic Barrier (FLB) Method and Texas A&M University's (TAMU's) Proliferation Resistance Analysis and Evaluation Tool for Observer Risk (PRAETOR).[6,7] The FLB method uses Fuzzy Logic to assign quantitative weighting values to qualitatively ranked fuel cycle attributes. Direct ORIGEN-S coupling is used with the FLB to obtain isotopic data for each fuel cycle stage, which is then used in determining the fuel cycle's PR. PRAETOR is a proliferation resistance barrier assessment tool encompassing multi-attribute utility analysis (MAUA) that can employ weighting factors obtained by nuclear technology and non-proliferation expert solicitation. Like SAPRA, PRAETOR also breaks the nuclear proliferation barriers into the four categories of diversion, transportation, transformation, and weaponization. The separation of proliferation into these categories is an attempt to incorporate some "Pathways" information into a "Barrier" method.

I.A.2. Trends in Proliferation Resistance Methodologies: Pathway Approaches

PR "Pathway" analysis tools take into account the difficulty associated with the multiple pathways along a route that could end with nuclear weapons. With "Pathway" analysis, the adversary can receive credit for learning and adapting to successes and failures at different stages along the proliferation route. Proliferators can make tradeoffs in pursuing pathways to favor diversion or latent deterrent values of certain nuclear fuel cycle postures. From a predictive standpoint, "Pathway" tools are more realistic since proliferators are pursuing a set of objectives as best they see fit.

The scenario complexity for "Pathway" system models can prove troublesome to implement accurately without being overwhelmed by the details. The multitude of potential proliferator options for "Pathway" models also makes their PR results suspect unless they can be tested and benchmarked against real world scenarios or simulations. From a time and programming standpoint, building a credible "Pathway" tool can also be conceptually and resource intensive.

An example of an early "Pathway" tool, following soon after TOPS, was the Risk-Informed Probabilistic Analysis (RIPA) methodology.[8] RIPA was developed by Sandia National Laboratory and employs deductive reasoning in a manner comparable to fault tree analysis that predicts proliferator pathway activities in pursuit of a nuclear weapon. A major feature of RIPA was calculation of proliferator cost and time to accomplish different proliferation objectives.[9] Brookhaven National Lab (BNL) also developed a Markov model for the PRPP evaluation methodology that assesses pathways a proliferator might take during a specified scenario. The BNL Markov model includes transition, detection, and failure rates between possible pathways.

A more recent "Pathway" model involves a Bayesian network system initially researched and undertaken by Corey Freeman at TAMU and expanded upon by Michael Mella.[10,11] The TAMU Bayesian Pathway model provides an example for how an adversary could selectively improve aggregate success probability by intelligently sharing information between proliferation routes. However, this analysis requires significant pathway and adversary capability information. Without detailed knowledge of adversary proliferation pursuit strategy and progress, model fidelity can become an issue.

I.A.3. Proliferation Resistance Methodology Comparisons

Overall, “Pathway” methods have significant advantages compared to “Barrier” methods regarding real world PR scenario development. However, a series of more straight forward “Barrier” methods can play an important role in calibrating “Pathway” tools by benchmarking their results. This does not mean that “Barrier” tools will not have roles to play for strengthening and assisting with the incorporation of safeguards and security systems into nuclear fuel cycle facilities. In that regard, the “Barrier” tools hold a major advantage in that they are often well designed to assess individual “Pathway” component weaknesses.

I.A.4. Moving From Static to Dynamic Proliferation Analysis Tools

Not all nuclear proliferators are the same, and therefore they cannot be modeled the same if the expectation is to obtain useful information for policy and technical decision makers.[12] Agent Based Modeling (ABM) provides a computational structure in which individuals and organizations can be handled as agents each seeking to achieve a specific set of objectives.[13] An ABM framework allows the granular treatment of each unique agent to create a far more realistic encapsulation of how nuclear proliferation events occur. Hundreds to thousands or more agents in an ABM system can simultaneously interact, with each agent seeking to manipulate the evolving state of affairs to suit its goals.[14]

Prestige and relatively differential treatment associated with nuclear weapons possession has left some Non-Nuclear Weapons States (NNWS) to assert a national defense and sovereignty rationale for obtaining nuclear weapons. Furthermore, nuclear proliferation does not occur in a complete vacuum. Even the most sanctioned state has at least some low-level international connections. ABM provides a computational way to consider these, and many other, proliferation challenges.

Nuclear weapons development is governed by energy, mass, isotopic, and other physics defined requirements. Uncertainties exist regarding the exact status of nuclear proliferation by an entity. A proliferating entity must reach certain minimum technical proficiencies to acquire a nuclear arsenal. Bayesian analysis is suited to handle the active information seeking and denial situations surrounding nuclear proliferation efforts. The basis of Bayesian analysis is defining a theory, and then using updated information to increasingly prove or disprove its existence. A theory on the physics based constraints of nuclear proliferation can be modeled and then dictate proliferation scenario pathways.

Innovative tools are needed to combat global nuclear proliferation threats. In this research, a modular Bayesian ABM Nonproliferation Enterprise (BANE) tool was developed, implemented, and tested that uses Agent Based Modeling coupled with a Bayesian method for assessing proliferation pathway likelihoods. Agent Based Modeling offers capabilities for dynamically assessing intelligent and innovative nuclear proliferation adversaries and adaptive counter proliferation entities. With Agent Based Modeling, individual agent entities possess factors they seek to optimize when interacting with other entities. Agents are grouped in three broad categories: neutral, proliferating, and defensive agents. Objectives for considering agent proliferation pathways include technical limitations, relative economic cost, time, and difficulty of outside detection.

I.B. Justification of Bayes Theory and ABM from Nuclear Policy Perspective

Nuclear proliferation represents a nexus of strong policy and technical factors that are incredibly interconnected. Creating a framework for nuclear proliferation scenarios requires balancing between the proliferator's demands for nuclear weapons and the rate it can supply them, if possible. Demand-side nuclear proliferation drivers of rivalry, alliance, regime type, openness, and liberalization are perceived differently for each proliferating entity.[15,16] Supply-side nuclear proliferation drivers include sensitive nuclear assistance (SNA) along with domestic nuclear and associated knowledge, technology, resources, and industrial capacity.[17]

A state facing a potentially existential threat to its territory and citizens will maximally leverage its national resources, technology, and infrastructure to obtain a nuclear weapon. The Manhattan Project is a well-known and well-documented example of a multi-nation effort willing to expend significant economic resources to obtain a nuclear weapon. The United States was the largest Manhattan Project economic contributor and provided primary military oversight. Yet, the demand-driven Manhattan Project employed supply side international connections with the United Kingdom Tube Alloy nuclear weapon program.[18] Multi-national contributions to the Manhattan Project also came from the wide array of foreign born scientists who overcame critical supply-side technical hurdles.

Depending upon a state's leadership, substantial internal or external threats to its power could lead to a nuclear weapon posture marshalling similar national resource levels. The fanatically insular North Korean government struggled for a long time to try and match the technical achievements of the United States despite sixty years of global technological progress.[19] The North Korean Kim family dynasty, and its supporting oligarchy, perceives itself as under siege from outside efforts to subvert or overthrow it.[20] Falling back on its "juche" philosophy of self-reliance, the North Korean government was willing to subject its people to a harsh standard of living to cut off outside contact. However, the North Korean isolation was readily breached for supply side nuclear and missile program justifications. An example of North Korea escaping international isolation is its exchange of ballistic missile technology with Pakistan for gas centrifuge uranium enrichment.[21]

Beyond indigenous efforts a threatened state can rely on an alliance with an outside, nuclear armed state for balancing and deterrence. Whether the alliance alleviates some security concerns will impact future nuclear proliferation decisions. The United States' relationship with its European and Asian allies during the Cold War is an example of alliance supported deterrence. Through North Atlantic Treaty Organization (NATO) nuclear sharing the United States lessened Western European state motivations for nuclear weapons programs.[22]

The nuclear armed allied state is also positioned to influence its proliferating ally to cease independent proliferation activities as an alliance condition. The South Koreans and Taiwanese each attempted to proliferate in the 1960s through the 1980s.[23,24] Each time the United States pressed the South Korean and Taiwanese national governments to roll back their nuclear proliferation. In the end, the alliance and United States extended deterrence were more valuable to South Korea and Taiwan than uncertain nuclear weapon program progress.[25,26]

According to Matthew Kroenig, from a supply-side focus, SNA takes three forms: 1) providing information on nuclear weapon design and construction; 2) transferring substantial SNM; and, 3) helping with building and operating facilities to obtain highly enriched uranium (HEU) or separated plutonium.[27] Traditionally, SNA is considered a state to state transaction. SNA significantly decreases the resource cost, time, and probability of outside detection for a proliferating state. However, Muammar Gaddafi's Libya obtained SNA from the AQ Khan network without having the domestic capability to finish the attainment of nuclear weapons.[28] The provision of SNA therefore does not ensure a state will obtain nuclear weapons.[29] Furthermore, the Libya example demonstrates how counter proliferation activities can link beyond nuclear concerns to encompass broader international engagement objectives. Giving up its nuclear weapon program, whatever the subsequent repercussions for Gaddafi, was part of a Libyan effort to obtain normal international economic ties.

For a non-state proliferating entity acquiring transferred SNM or undertaking Special Nuclear material Theft (SNT) is critical. Outside obtaining an intact nuclear weapon, a non-state proliferating entity will be dependent on SNM received from another source. A non-state actor willing to sink a preponderant resource share into pursuing a nuclear weapon vis-à-vis other attack vectors lacks credibility.[30] The high hurdles for non-state entity nuclear weapon acquisition make such an investment strategy fraught with risks. From a terrorist perspective, attacks can take on a theater crucial for sustaining funding and recruitment.[31] Therefore, a terrorist organization almost singularly pursuing nuclear weapons would find itself insolvent in a short timeframe.

The United States DoD outlines the Counter Weapons of Mass Destruction (CWMD) threat from a counter proliferation standpoint.[32] The three DoD CWMD end objectives are: 1) no new WMD; 2) no WMD use; and 3) minimization of WMD effects. Enhanced intelligent and dynamic mapping of nuclear, and in the future other WMD, pathways by BANE covers the first DoD CWD desired end state. Exploring cooperative CWMD efforts internationally as defined by DoD is another area BANE is designed to address. Assessing CWMD contingencies through BANE proliferation and counter proliferation uncertainties handles the DoD goal of understanding possible proliferation outcomes. Additional DoD threat and vulnerability assessments can be initiated with the input of policy and technical experts to defeat and contain the effects of proliferation.

Scott Sagan correctly identifies the crucial interplay between nuclear proliferation demand and supply drivers.[33] With BANE, the pressures exerted on a state to proliferate influence the different national means to optimally reach the nuclear posture suiting the state's perceived objectives. BANE needed to consider the interplay between proliferating entity demand drivers and subsequent key nuclear supply chain access capabilities. Also, the continual counter proliferation action of defensive nonproliferation entities is needed for accurate modeling. Major perceived nuclear proliferation technical hurdles encountered can lead to a state seeking SNA, employing domestic austerity, pursuing outside balancing alliances, or temporarily curtailing the nuclear weapons program. A flexible nuclear proliferation assessment methodology handling these and other diverse challenges that cross between demand and supply proliferation drivers is possible with BANE.

CHAPTER II

BANE UNDERLYING THEORY

BANE fundamentally is an eco-system handling discrete agents with diverging and evolving proliferation goals and significant variations in the means to achieve them. The theory behind BANE has roots in Bayesian analysis, ABM, computational social sciences, nuclear engineering, and several other disciplines. BANE uses Bayesian analysis to estimate the technical success probability for the proliferator. ABM is employed by BANE to encompass the individual and organizational dynamics defining and sustaining proliferation. In this chapter, the basic theory of Bayesian analysis and ABM is presented.

II.A. Bayes' Theory Background

Bayesian theory has been around for centuries for considering conditional probability relationships. Within ABM, Bayesian analysis can aid agents in understanding the likelihood that seemingly casual occurrences can predict future events. The technical success probability for BANE depends upon Bayesian analysis undertaken with the commercial Bayesian software program Netica. Although Netica is modern computational software, Bayes' Theory has existed in publication since 1763.[34] Thomas Bayes' friend Richard Price published Bayes' seminal essay in the Royal Society Philosophical Transactions two years after Bayes died.[35]

An important insight recognized by Price was Bayes' mathematical treatise on discerning links between observed events and their likely initiating actions.[36] One way to describe Bayes' Theorem is to consider two statistically independent events, A and B. Defining the probability of A and B both occurring, P(A∩B), can be done using its constituents. This involves A's probability of occurring if B has happened, P(A|B); and, the probability of B's alone or mathematically:

$$P(A \cap B) = P(A|B)P(B) \tag{2-1}$$

The relationship between two events, P(A|B), occurring together may be known, along with the likelihood of one event, B, occurring independently. Equation 2-1 provides a means to consider events A and B happening together, absent information about event A happening independently. Similarly, rearranging Equation 2-1 yields an expression for P(A|B):

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \tag{2-2}$$

With mutually exclusive cases, Equation 2-1 works for A and B in reverse. If B's occurrence probability given A happening, P(B|A), and A's individual occurrence probability are known, then:

$$P(B \cap A) = P(B|A)P(A) \tag{2-3}$$

With a simple rearrangement we acquire:

$$P(B|A) = \frac{P(B \cap A)}{P(A)} \tag{2-4}$$

By substituting Equation 2-3 into Equation 2-2 the intersection probability is found to be:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)} \qquad 2\text{-}5$$

A's complement, Ac, consists of all events outside of A including the null set (i.e. nothing occurring). The probability of B occurring is equal to the sum of the probability of A and B occurring, the probability of just B occurring, and anything else happening including the null set. Thus, expanding the Equation 2-5 denominator, P(B), yields:

$$P(B) = P(B \cap A) + P(Ac \cap B) = P(B|A)P(A) + P(B|Ac)P(Ac) \qquad 2\text{-}6$$

Partitioning the independent variable A into independent variable constituents, A_i, produces:

$$P(B) = \sum_i P(B \cap A_i) = \sum_i P(B|A_i)P(A_i) \qquad 2\text{-}7$$

Substituting Equation 2-7 into Equation 2-5 yields the resulting Bayes' Theorem for a particular sub-state, A_i, in the multi-state event A:

$$P(A_i|B) = \frac{P(B|A_i)\,P(A_i)}{\sum_j P(B|A_j)\,P(A_j)} \qquad 2\text{-}8$$

Equation 2-8 is important from a Bayesian inference perspective. Bayesian inference uses an existing Bayesian relationship model and new evidence to determine updated outcome probabilities.[37] The biggest prerequisite for effective Bayesian inference is possessing some "prior" knowledge and belief surrounding a hypothesis before embarking on a statistical study. The "prior" knowledge allows for emerging evidence model adjustments to match real world or statistical events. After setting the initial Bayesian model, all consequent beliefs taking advantage of new information are "posterior" probabilities.

A major strength of Bayesian inference is incorporating data compilations from large databases. Disparate information across a wide array of topics can be collected for pattern assessments facilitating future information predictions and probabilities. Effective future Bayesian inference evidence updates benefit from a diverse set of applicable data sources. Many fields with big data implications including code decryption, military planning, economics, and neuroscience historically employ Bayesian inference.[38]

The physics requirements for nuclear proliferation can be captured in a network lending itself to Bayesian inference. However, uncertainty exists in the exact path options being kept open for nuclear proliferation. Computational tools, such as Netica, can leverage Bayes probability theory to support agents using machine learning (ML) capabilities to understand the circumstances surrounding their nuclear proliferation decision making.[39] A completely omniscient and omnipotent agent would not require ML skills since uncertainty and any resource or outside intervention limitations would be irrelevant. No entity within the scope of this thesis is completely omniscient and omnipotent, so ML is needed to model individual and human group nuclear proliferation choices.

II.B. Past Netica Graphical User Interface Basis for Nonproliferation Assessments

The Graphical User Interface (GUI) and Application Programmer Interface (API) are used for defining the BANE agent nuclear proliferation perspectives.[40,41] The Netica Application GUI is essential for BANE creation, updating, and visualization elements.

II.B.1. Netica Bayesian Network Overview

The Netica GUI is based upon “network” relationships between parent and children nodes. The background for initially creating the Netica GUI nonproliferation network comes from Corey Freeman’s thesis. Changes incorporating increased capabilities from the latest version of Netica are included. The theory behind the Netica GUI nonproliferation networks is important for understanding how BANE agents make technical success decisions.

For Bayesian models, the usage of nodes provides a model representation of a tangible product, process stage, or other event type. Node relationships are arranged from specific to general or general to specific. In specific to general models, more detailed information nodes govern probability distributions for more general nodes. The general to specific model layout is defined by less general nodes dictating the more specific node probability distributions.

Initial Texas A&M work preceding Corey Freeman on Bayesian nuclear nonproliferation analysis considered specific to general models. The Texas A&M models were built using the Netica GUI which started building a Netica institutional knowledge base. Figure 2-1 is a simple example of a Netica node network going from the specific to the general.

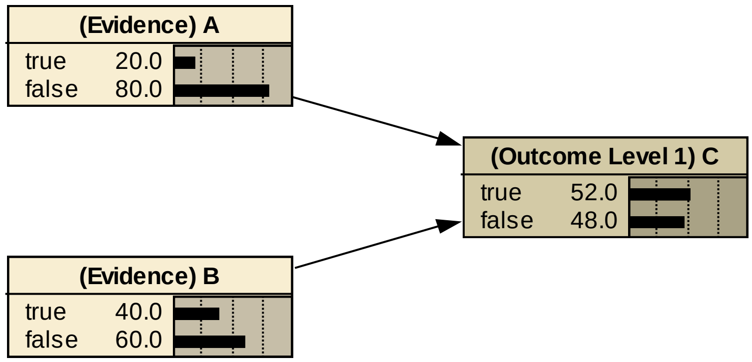
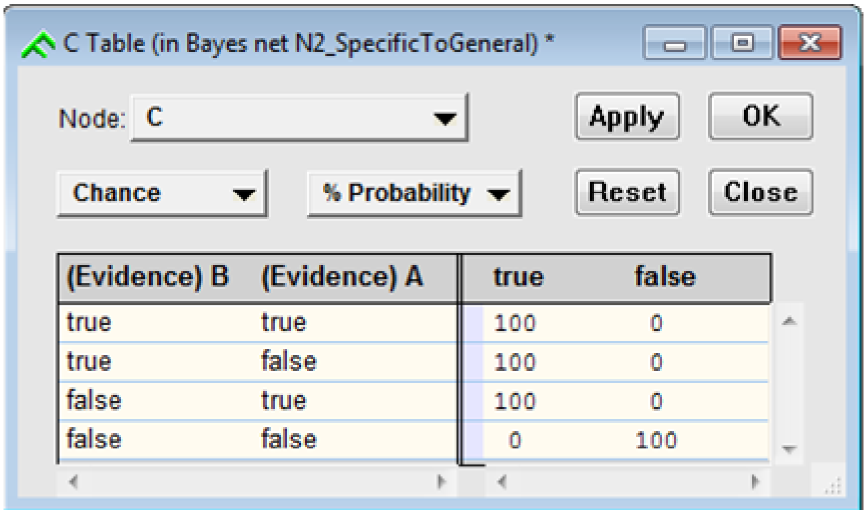


Figure 2-1. Simple Netica GUI parent child Bayesian network.

Probabilities for the parent nodes (A and B) being true or false directly affect the child node (C). In the Netica GUI, conditional probabilities and Bayes Theorem define the connected node causal linkages. A Netica GUI "truth table" is depicted in Figure 2-2 for the Figure 2-1 Netica network. Consequently, truth tables govern the resulting Netica GUI nodal selection probabilities.



(Evidence) B	(Evidence) A	true	false
true	true	100	0
true	false	100	0
false	true	100	0
false	false	0	100

Figure 2-2. Truth table with prior probabilities for Figure 2-1 simple Netica GUI simple to general Bayesian network.

The truth table in Figure 2-2 provides a means to understand the conditional probability governing node C shown in Figure 2-1. The equation defining the node C true probability using state subscript T for true and subscript F for false is:

$$\begin{aligned} P(C_T) &= P(C_T \mid A_T, B_T)P(A_T)P(B_T) + P(C_T \mid A_T, B_F)P(A_T)P(B_F) \\ &+ P(C_T \mid A_F, B_T)P(A_F)P(B_T) + P(C_T \mid A_F, B_F)P(A_F)P(B_F) \end{aligned} \tag{2-9}$$

Using the numbers for node A and B true and false states to find C_T:

$$\begin{aligned} P(C_T) &= 1.0*0.2*0.4 + 1.0*0.2*0.6 + 1.0*0.8*0.4 + 0*0.8*0.6 \\ &= 0.08 + 0.12 + 0.32 = 0.52 \end{aligned} \tag{2-10}$$

From a Bayesian perspective using Equation 2-8 the C_T is calculated:

$$P\left(C_T \middle| A,B\right)=\frac{\sum_i P\left(C_i \middle| A_i,B_i\right) P\left(A_i\right)P\left(B_i\right)}{\sum_j P\left(C_j \middle| A_j,B_j\right) P\left(A_j\right)P\left(B_j\right)} \qquad \text{2-11}$$

In the Equation 2-11 numerator i represents the conditional probability relationship for the node of interest. In the Equation 2-11 denominator j represents true or false conditions for A and B. Employment of Equation 2-11 for the Bayesian relationship calculation results in:

$$\begin{aligned}P\left(C_T \middle| A,B\right)&=\frac{(1.0*0.2*0.4)+(1.0*0.2*0.6)+(1.0*0.4*0.8)+(0*0.8*0.6)}{\sum_j P\left(C_j \middle| A_j,B_j\right) P\left(A_j\right)P\left(B_j\right)}\\&=0.08+0.12+0.32+0=0.52\\ ,where \quad \sum_j P\left(C_j \middle| A_j,B_j\right) P\left(A_j\right)P\left(B_j\right)&=(1.0*0.2*0.4)+(0*0.2*0.4)+\\&\quad(1.0*0.2*0.6)+(0*0.2*0.6)+\\&\quad(1.0*0.4*0.8)+(0*0.4*0.8)+\\&\quad(0*0.8*0.6)+(1.0*0.8*0.6)=1.0\end{aligned} \qquad \text{2-12}$$

The conditional probability relationship in Equation 2-9, and especially Equations 2-8 and 2-11, scales easily with Bayesian analysis computer programs like Netica. The Bayesian probability for Equation 2-8 readily applies for nodes with more parent and child connections. Conditional probabilities linked with Bayesian analysis update quickly on Netica networks ranging from three nodes to thousands of nodes.

The Netica GUI provides a probabilistic equation short-hand alternative to writing the probabilities using Equation 2-9. The primary probabilistic equation stipulation is all node options must sum to 100 percent inside a truth table. An example of a basic Netica GUI truth table probabilistic equation is shown in Figure 2-3 for the Netica GUI network from Figure 2-1.

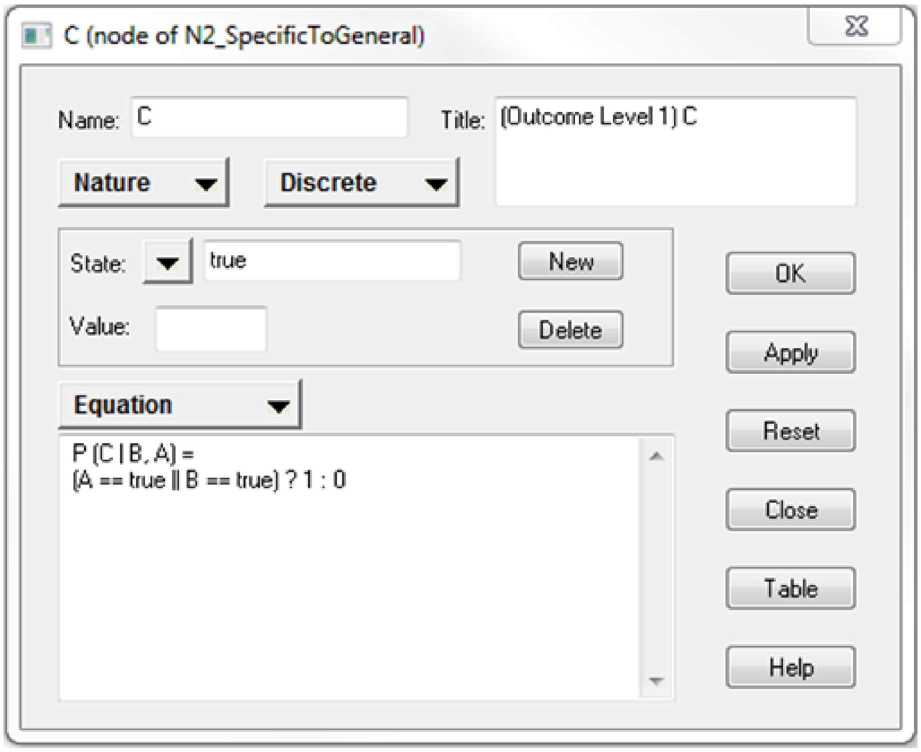


Figure 2-3. Using probabilistic equations to fill in simple Netica GUI Parent Child Bayesian network truth table.

The equation in Figure 2-3 shows a way to write the Bayesian Equation 2-8 within Netica. The probability of C being true is contingent upon either A or B being true. If A and B are false, then C is false.

Variable B in Equation 2-8 can be considered an observed event with a “prior” probability that allows for a coupled prediction of a “posterior” event probability. A more complicated Netica Bayesian situation involves Evidence A through D as parent nodes for the child node Pathway 1. A specific to general Netica GUI Bayesian network for the Evidence A through D relationship to Pathway 1 is defined in Figure 2-4. Pathway 1, along with Pathways 2 and 3, are in turn the parent nodes for their shared child node Likely Pathway.

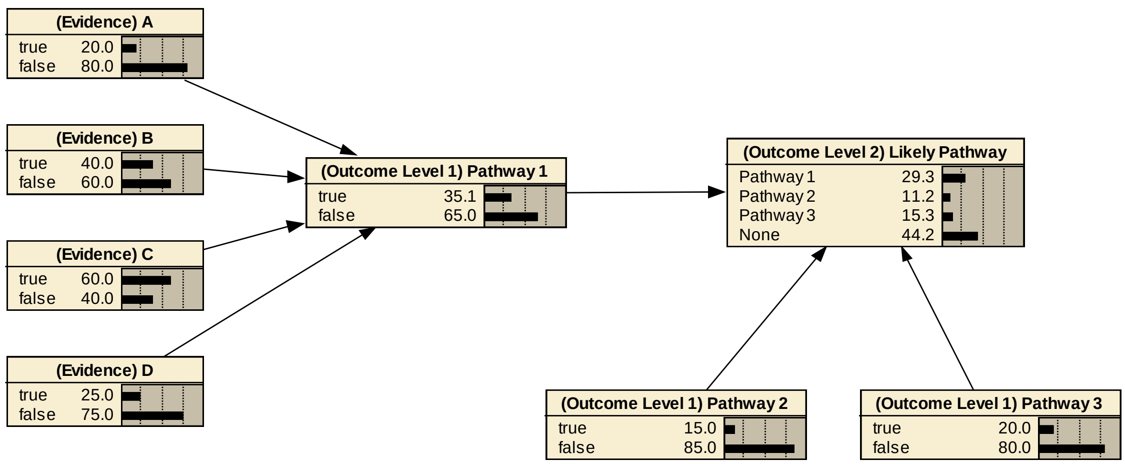
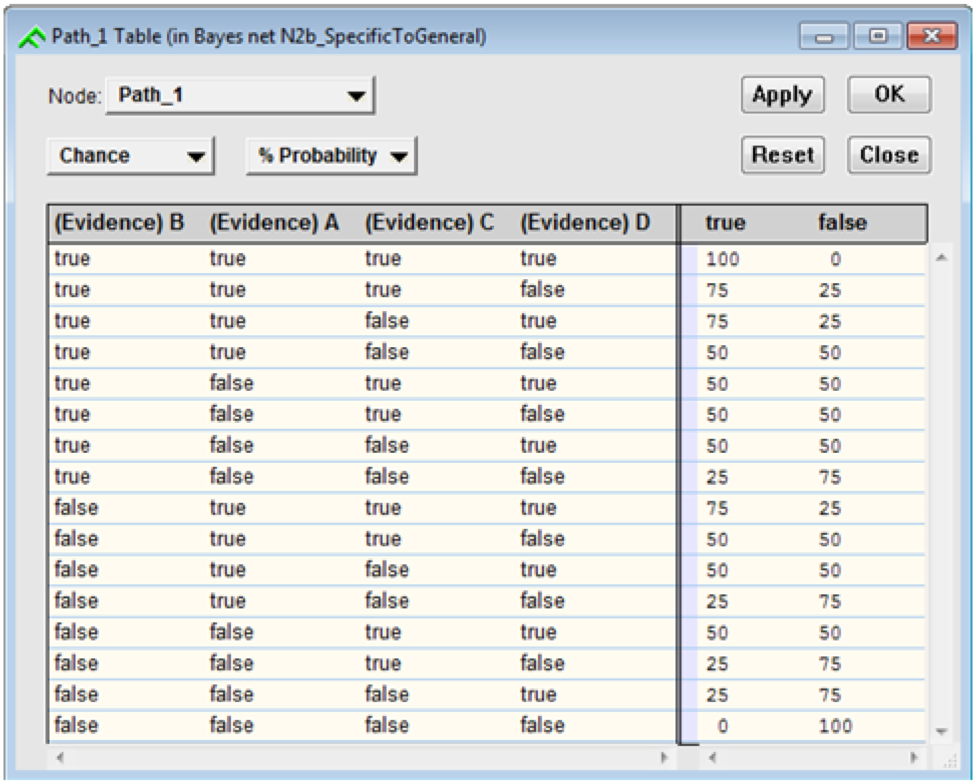


Figure 2-4. Netica GUI Bayesian specific to general network.

Only the "prior" probabilities are depicted in Figure 2-4, since no evidence has been assimilated. The initial probability values for Evidence A through D were selected to represent a range of evidence information. The methodology for Pathway 1 is based on the Bayesian analysis with conditional probabilities from Equations 2-8 and 2-11. The truth table prior probabilities for Pathway 1 are listed in the Figure 2-5 table graphic.



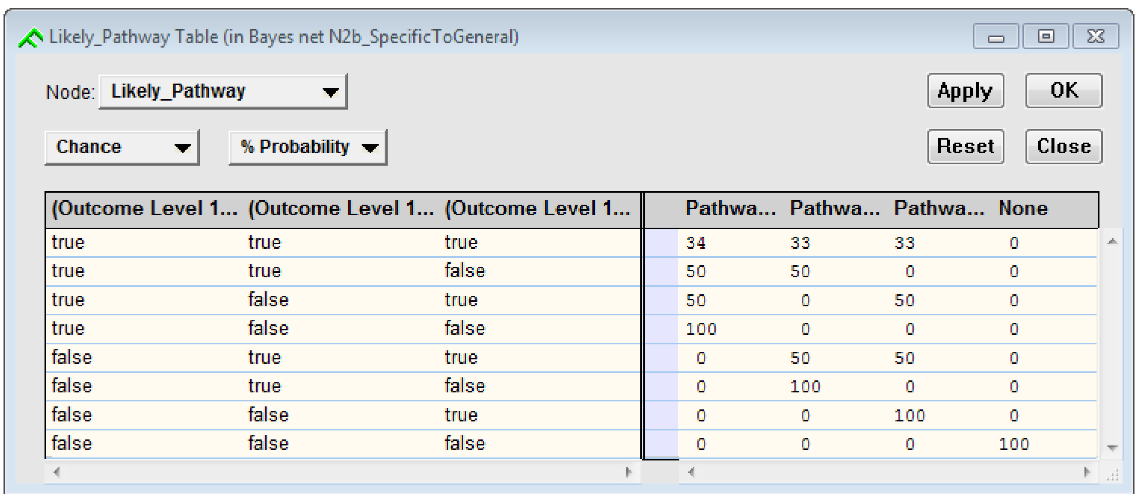
(Evidence) B	(Evidence) A	(Evidence) C	(Evidence) D	true	false
true	true	true	true	100	0
true	true	true	false	75	25
true	true	false	true	75	25
true	true	false	false	50	50
true	false	true	true	50	50
true	false	true	false	50	50
true	false	false	true	50	50
true	false	false	false	25	75
false	true	true	true	75	25
false	true	true	false	50	50
false	true	false	true	50	50
false	true	false	false	25	75
false	false	true	true	50	50
false	false	true	false	25	75
false	false	false	true	25	75
false	false	false	false	0	100

Figure 2-5. Pathway 1 truth table with prior probabilities for Figure 2-4 Netica GUI simple to general Bayesian network.

The Likely Pathway is a second level child of Evidence A through D and a first level child to Pathways 1 through 3. The probability values for Pathways 2 and 3 were selected for illustration purposes similar to Evidence A through D. The true probability for Pathway 1 using the Equation 2-8 methodology shown in Equation 2-12 with the Figure 2-5 truth table yields:

$$P\left(Pathway1_T \middle| A,B,C,D\right) = \frac{\sum_i P\left(Pathway1_i \middle| A_i,B_i,C_i,\mathrm{D}_i\right) P(A_i)P(B_i)P(C_i)P(D_i)}{\sum_j P\left(Pathway1_j \middle| A_j,B_j,C_j,\mathrm{D}_j\right) P(A_j)P(B_j)P(C_j)P(D_j)} = 35.1 \qquad 2\text{-}13$$

The truth table prior probabilities for the Likely Pathway are shown in Figure 2-6. Computing Likely Pathway true probability would use the Figure 2-6 truth table similar to the Pathway 1 calculation in Equation 2-15.



Likely_Pathway Table (in Bayes net N2b_SpecificToGeneral)

Node: Likely_Pathway | Apply | OK

Chance | % Probability | Reset | Close

(Outcome Level 1...	(Outcome Level 1...	(Outcome Level 1...	Pathwa...	Pathwa...	Pathwa...	None
true	true	true	34	33	33	0
true	true	false	50	50	0	0
true	false	true	50	0	50	0
true	false	false	100	0	0	0
false	true	true	0	50	50	0
false	true	false	0	100	0	0
false	false	true	0	0	100	0
false	false	false	0	0	0	100

Figure 2-6. Likely Pathway truth table with prior probabilities for Figure 2-4 Netica GUI simple to general Bayesian network.

If additional information later confirms that any of the Evidence nodes A through D are true or false, then they can be changed. In Figure 2-7, Evidence nodes A, C, and D are set to true. As can be seen, this increases the likelihood of Pathway being true.

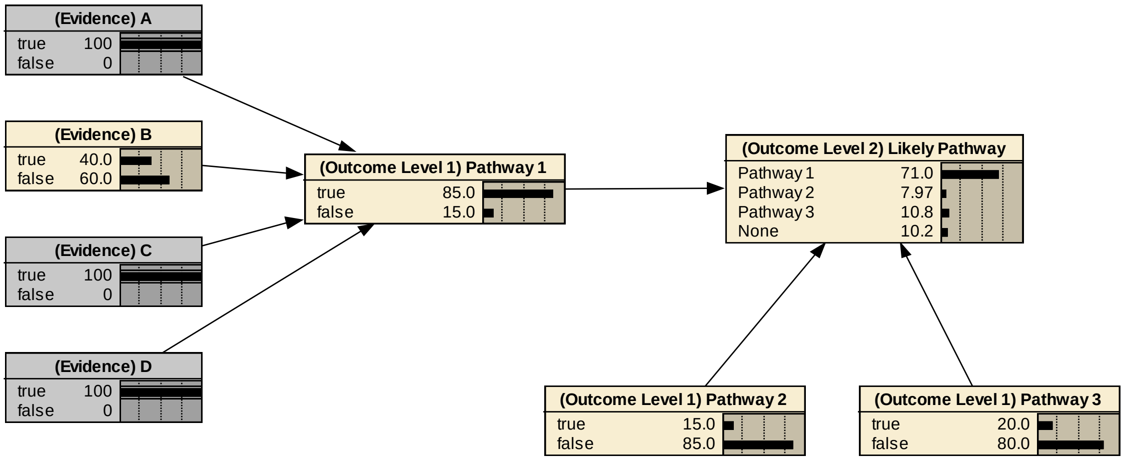


Figure 2-7. Netica GUI Bayesian specific to general network after evidence addition.

In the specific to general Netica model, parent node changes do not affect other parents. The individual pieces of evidence (A, B, C, and D) in Figure 2-4 are independent and the truth of one does not change the priors for the others. For complex and interconnected Bayesian networks, knowing one piece of evidence might increase awareness of other evidence. Therefore, the prior probabilities governing the Bayesian network could factor the information linkages not just between children but also other parents.

Networks organized from the general to the specific create a greater event dependence on evidence. This ensures that specific evidence causes changes along the network towards the more general outcomes as shown in Figure 2-8.

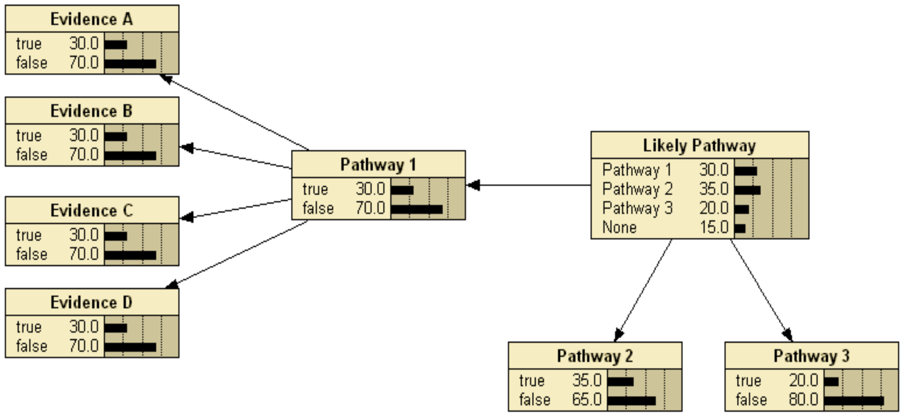


Figure 2-8. Netica GUI Bayesian general to specific network.

A major model flaw arises when one specific evidence node is considered as true. The true evidence node forces all the other evidence nodes to be true as well. Figure 2-9 shows a general to specific network with one piece of evidence having a controlling impact.

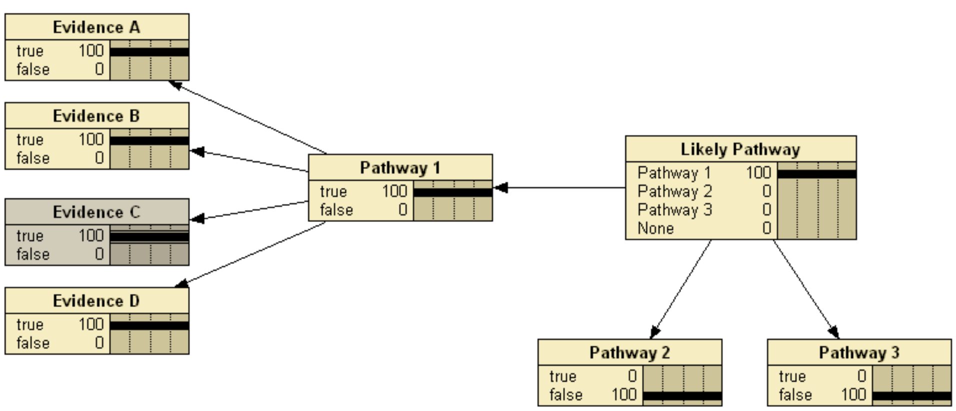


Figure 2-9. Netica GUI Bayesian general to specific network after evidence addition.

To prevent the specific evidence domination exhibited in Figure 2-9 for a general to specific network, an inverted node is inserted between the initial parent and children nodes. An "inverted" node has the original parent node probability distribution reversed. This arrangement forces a parent node to be true when the associated evidence probability distribution is zero. Inverted nodes are thereby superior for handling mutually exclusive evidence from priors.

The truth table must handle the reality that absolutely true or false evidence is unlikely in real world situations leading to node "softening" requirements. "Softening" means permitting some ambiguity in proliferation network nodes despite increasingly overwhelming certainty amongst related nodes. Accounting for non-absolute statements using "softening" better matches the knowledge confidence limitations associated with nonproliferation intelligence and evidence. There is a tendency to increase peripheral prior impacts due to cumulative Netica network "softening." The network in Figure 2-9 is shown in Figure 2-10 with an inverted node.

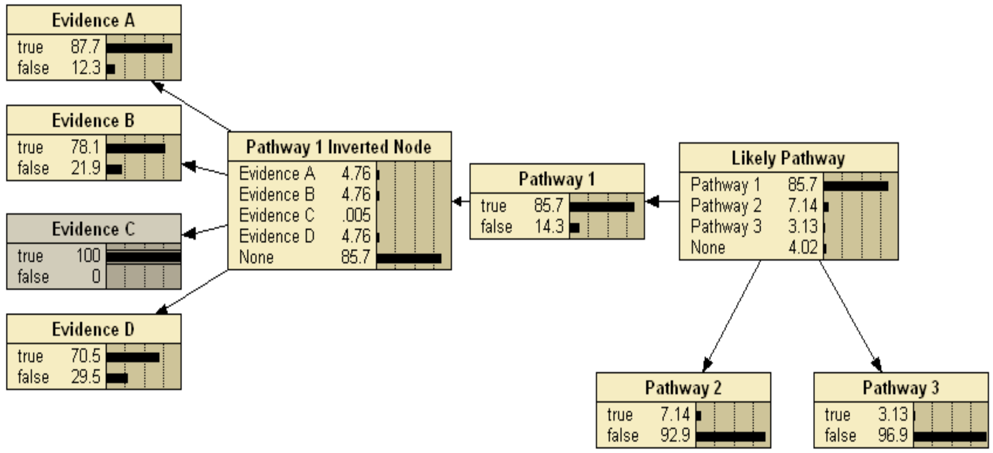


Figure 2-10. Netica GUI Bayesian general to specific inverted network after evidence addition.

Changing the inverted nodes into small circles adjacent to the parent nodes increased human readability. Thus, in the remainder of this document the inverted nodes appear as just small circles. Resources, technical knowledge, infrastructure, and desired nuclear arsenal arrangement are proliferator specific characteristics considered with inverted nodes attached to each top level general node. The proliferator specific inverted nodes inform the entire network regarding the proliferator likelihood of successfully obtaining the desired nuclear weapon position.

II.C. Agent Based Modeling Background and Theory

The genesis of ABM began before computers existed. In 1928, John von Neumann published the first paper on analog game theory covering zero-sum, two individual games.[42] Later von Neumann co-authored the 1944 book, "Theory of Games and Economic Behavior," which was the initial work on game theory with multidisciplinary implications.[43] Many branches of game theory have emerged including non-zero sum, simultaneous and sequential, and large population games.

Handling complex, real world analysis for an important and interconnected issue, such as nuclear proliferation, requires going beyond basic game theory. Advanced game theory simulations combining sequential (dynamic) and large population games equate to modern ABM. Contemporary ABM is a computational field enabling simulated agent interactions with other agents and their surroundings that has received significant notoriety in the last two decades.[44] From a computational emergence standpoint, ABM is a bottom up approach that can incorporate agents operating rationally to maximize perceived benefits while learning to improve adaptive behavior.[14]

The beginning of ABM can be considered Thomas Schelling's 1971 analog work on racial segregation using dozens of surrogates representing groups from different ethnic backgrounds in proximity.[45] In 1978, Schelling published "Micromotives and Macrobehavior," with more detailed topics derived from the segregation modeling.[46] The book was a foundation for digital ABM, which could take advantage of growing computer processing power for modeling. Schelling's work was ground breaking for mathematically modeling topics at the individual level such as race, relationships, and other social interactions that cause group behavioral preferences.

The wide spread availability of computer resources from personal devices to network clusters to cloud computing suit ABM. Each agent requires rules for triggering its own actions and mechanisms guiding interactions with other agents.[47] Advanced ABM systems allow for emergent behavior, whereby compounding single agent choices create group actions and patterns not initially programmed into the agents. Dissection of agent defined procedures can sometime uncover the causal relationships that subtly lead to emergence after different iteration or agent levels are reached.[48] Small activity clusters can propagate through ABM systems suggesting where key trigger thresholds are located. Where possible, unpacking the agent rules triggering emergent behavior can aid ABM program developers and users in ascertaining agent real world accuracy. The stipulated triggers matter because they can indicate opportunities for decision makers to interject policy, resources, technical solutions, or other means to alter individual or collective behavior. Often closely associated methods for ABM comprise Complex Adaptive System (CAS) and multi-agent systems (MAS).[49]

The range of fields for interdisciplinary ABM usage include economics, transportation preferences, military operations, and recently intelligence. The potential for ABM to inform economic policy was pointed out in a 2009 Nature article. [50] The variable granularity with ABM was noted in Nature. ABM allowed for economic modeling of single consumers, to institutions such as banks and Wall Street, to rule changing agents such as policy makers and regulators.[51] The nonlinear actions and resulting emergent phenomenon were proposed to better approximate real world financial behavior than more simplistic models.

The Transportation, Analysis, and SIMulation System (TRANSIMS) program was an ABM program initiated in the 1990s at Los Alamos National Laboratory (LANL).[52] TRANSIMS was initiated to meet US Department of Transportation (USDOT) and other federal agencies' missions to ensure dispersal of federal resources benefitted multiple communities. TRANSIMS has now spread to an open source, multi-core parallelized program that has been used internationally. Through a 2000 LANL and Sandia National Laboratories (SNL) partnership the National Infrastructure Simulation and Analysis Center (NISAC) was implemented.[53] NISAC models critical infrastructure management for the Department of Homeland Security (DHS) in areas such as physical or software interdependencies and biological agent dispersion pathways.

Militarily innovative computational modeling tools from fields such as ABM and Operations Research are growing in value.[54] Department of Defense (DoD) simulation development can be exacting and time consuming for major scenario planning. Human capital, technical, and financial resource limitations often combine to impede more than a few case studies being computationally performed.[55] The decade long United States counter insurgency effort as part of the War on Terror led to Civil Military Affairs (CMA) ABM and MAS.[56] At the strategic deterrence level, ABM has been employed for Ballistic Missile Defense (BMD) modeling.[57]

Beyond military applications, ABM is potentially gaining traction within the intelligence field. At George Mason University (GMU) a PhD student wrote a 2012 dissertation titled, “Agent Based Modeling in Intelligence Analysis.”[58] Using ABM for grasping how new technologies can alter military, political, or economic power structures is important for predicting shifting international alignments. Creating new methods for improving intelligence collection utilizing ABM is another frontier that might grow in the near future.

In the nuclear field, ABM research has been progressing on the University of Wisconsin-Madison initiated Cyclus tool and associated codes such as Cycamore.[59] The Cyclus code family is a module based and open source nuclear fuel cycle simulator. The physics based mechanics for Cyclus are well defined for high fidelity reactor physics based fuel analysis, isotopic generation and tracking, and other nuclear fuel cycle based calculations. A major goal of Cyclus has been to create and link modules with widely accepted scientific and technical nuclear data codes. Linkable modules can and will interface with codes such as ORIGEN and the Multiphysics Object-Oriented Simulation Environment (MOOSE).

Within Cyclus, agents are created with oversight for different fuel cycle facilities and the institutions that own the actual facilities. The nuclear facilities can take the form of fuel fabrication facilities, various nuclear reactor types, used fuel separation plants, geologic repositories, and more. Regions are Cyclus localities, and agents within regions have similarities like physical proximity or sharing the same government. Agents in Cyclus exchange commodities from mined raw uranium ore to finished enriched uranium or mixed oxide fuel (MOX) to spent fuel.

From a government support standpoint, Cyclus has been selected as the United States Department of Energy (DOE) next generation fuel cycle simulator. Cyclus can provide information to policy and decision makers across a wide spectrum. A high-level policy maker might focus on understanding the implications of an array of new and emerging nuclear fuel technologies and fuel cycles. The upper level government official might therefore be interested in the impact of current or proposed legislation and executive orders on nuclear industry growth. Stakeholders such as the United States Nuclear Regulatory Commission (NRC) might instead emphasize material accountancy.

ABM and similar systems for agent modeling have been steadily growing in users, breadth of research areas, and subsequent application. The ability to consider individual agent behavior or aggregate to group dynamics is crucial for more than cursory studies of complex interactions. Within the nuclear nonproliferation arena BANE is a tool that can combine security, economic, political, and other factors for assessing future proliferation pathway risks.

II.D. Agent Based Modeling Elaboration for Nuclear Nonproliferation

The 2003 Guidelines for Nonproliferation Assessment Methodologies (NPAM) report indicated ABM as a potential option for developing next generation proliferation assistance capabilities. ABM remains largely unexplored for nonproliferation applications. The 2003 NPAM report indicates the importance of this field as follows:

"The two-sided modeling approaches can potentially provide useful insights when proliferation analyses must consider cooperative or disruptive effects of interacting human actors. When a fundamental modeling uncertainty is the actions human beings might take, and when these actions are critical to the outcome of the scenario under investigation, then two-sided approaches (or more generally, n-sided approaches) help explore the space of possible outcomes. For ABM in particular, '… a simulation made up of agents, objects or entities that behave autonomously. These agents are aware of (and interact with) their local environment through simple internal rules for decision-making, movement, and action.'"[3]

A historical way to consider ABM is with its more simplistic game theory predecessor applied to the 1962 Cuban Missile Crisis (CMC). In the political science field, prospect theory is a game theory branch using agent perceptions as decision drivers. For an ABM social science system, prospect theory is integral since diverse individual and groups of humans reach different conclusions based on their backgrounds, expertise, resources, and situational perspectives.[60]

Using prospect theory for different agent utility theories and action can be tested for rationality. The ABM example using a CMC prospect and game theory approach draws heavily upon Mark Haas's article, "Prospect Theory and the Cuban Missile Crisis."[61] In the CMC, the Soviet Union was challenging the United States in a region where the United States had long been ascendant. Therefore, the Soviet Union was involved in challenging the existing order. The Soviet Union leadership under Premier Nikita Kruschev and the United States Presidential administration of John F. Kennedy were defining how such adjustment to the international system would occur. A prospect theory relationship indicates when maintaining the status quo is beneficial for a potential challenger:[62]

$$u_c(Q) > p\left[u_c(T)\right] + q\left[u_c(M)\right] + (1-p-q)\left[u_c(S)\right] \qquad \text{2-14}$$

where u_c is the challenger utility, Q represents the status quo from the challenger perspective, T stands for the defending entity deterrent assertions, p represents defender making threat, M indicates abrupt military actions, q represents the probability of immediate military actions, and S stands for the success of challenger altering the status quo.

From the defending entity standpoint, prospect theory can define when countering challengers is prudent. Cases where tolerating the status quo revision is better are governed by:

$$u_c(Q) > p\left[u_c(T)\right] + q\left[u_c(M)\right] + (1-p-q)\left[u_c(S)\right] \qquad 2\text{-}15$$

where u_d is the defender utility, A represents the defender acquiescing to the status quo challenge, C stands for the ongoing challenger actions despite defensive entity responses, B is challenger submitting to status quo power efforts, and r represents probability of continued revisionist activities.

Against a resolute and stronger than expected defensive entity, a challenging agent might elect to discontinue its threats to the status quo. Defining when some form of capitulation is the preferred challenger strategy comes from:

$$u_c(B) > s\left[u_c(H)\right] + (1-s)\left[u_c(S)\right] \qquad 2\text{-}16$$

where H indicates military conflict with the defending entity and s represents the "estimated" probability of conflict occurrence.

In a crisis such as the CMC, agents interacting are more prone to miscalculations and succumbing to uncertainty over time. The status quo agent perception for repeated challenger attempts readjusting the current system can alter decision selection. For a revisionist agent the perception of a temporary advantage or defensive agent distraction may lead to more aggressive posturing. Either challenging or defensive agents might find themselves with the perception that they are "pot committed" to maintaining their position. In those cases, altering course could result in the loss of unrecoverable resources or prestige.

Prospect theory handles agent divergence from expected utility theory behavior under different risk spectrum. The potential for a policy decision is based on its occurrence probability coupled with a weighting factor to define the value function. Thus, prospect theory provides a means to handle policy uncertainties beyond pure optimization functions. The compact prospect theory outcome is written:

$$V = \sum_{i} w(p_i) v(x_i) \qquad 2\text{-}17$$

where V is the expected outcome, p represents the perceived outcome probability for x, w(p) stands for the weighting function probability, and v(x) indicates the value function.

An important social science consideration in prospect theory is apparent regarding loss and gain risk acceptance amongst humans. There is a strong human willingness to tolerate risks when evading losses. When assessing gains there is a tendency to pursue smaller wins that seem more certain rather than attempt to secure larger wins with higher perceived attainment risks.[63] Equation 2-19 covers the prospect theory deviation for gains and losses. The utility function in Figure 2-11 captures the convex expectation in the loss regime, and the corresponding concavity for pursuing gains.[64]

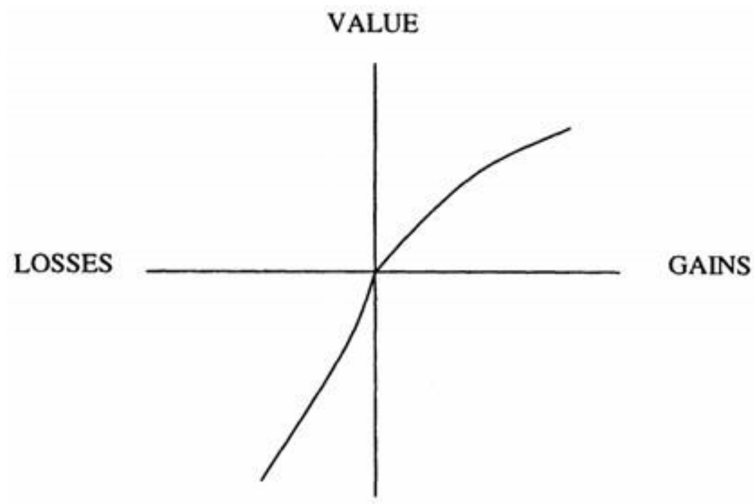


Figure 2-11. Generalized value function for risk acceptance.

For the convex loss avoidance in Figure 2-11, the entity is more risk seeking because the outcomes are perceived to be more beneficial and worth the trade-offs. Conversely, an entity in the Figure 2-11 concave gain expectation region would be more risk averse. The expected results at higher gain levels are less appealing relative to the predicted costs associated with the entity achieving them. Figure 2-11 handles the non-linearity associated with humans following optimal expected probability theory.[65] When people tend to believe an event is certain they can depart from expected prospect theory choices. Thus, over- or under-confident agents will make decisions at odds with reality because they are dismissing actual event probabilities.

Simplifying prospect theory for the intelligent agents involved in the CMC is possible by considering metastable situations. An example of meta-Game Theory is defined if the Soviet leadership assesses that is can anticipate the reaction of its United States counterparts.[66] In the metagame, the Soviet strategies of maintain (M) and withdraw (W) are augmented by American choices. The expected consideration of American confrontation (A) is weighed against the assessed American willingness to cooperate (B). The following CMC situations exist from the Soviet perspective using a simplified prospect theory:

1. W/W: choose W irrespective of US decisions (Withdraw unconditionally)
2. M/M: choose M irrespective of US decisions (Maintain unconditionally)
3. W/M: choose W if US cooperates, but M if US is confrontational (tit-for-tat)
4. W/M: choose M if US cooperates, but W if US is confrontational (tat-for-tit)

Table 2-2 shows the CMC meta-game options defined by the Soviet decision options. The options in the prior list for Table 2-2 are for a single situation / game selection point.

Table 2-I. Simplified prospect theory for single metagame state

		Soviet Union			
		W/W	M/M	W/M	M/W
		W Irrespective	M Irrespective	Tit-for-Tat	Tat-for-Tit
United States	B	(3,3)	(2,4)*	(3,3)	(2,4)
	A	(4,2)*	(1,1)	(1,1)	(4,2)*

In the single state CMC metagame the Soviets have the option for a withdrawal based on working with the United States. Running the metagame repeatedly in a dynamic fashion helps recreate the Soviet Union and United States CMC leadership decision evolution.[67] With the dynamic metagames, the decision table becomes far more complex with each decision opportunity iteration.

For the CMC case study, over time the gradual tit-for-tat nature of the compromise provides greater assurance to both parties of their intentions. The removal of uncertainty increases the stability of the third option. Dynamic games with regions of metastable cooperation or confrontation using prospect theory for social science proliferation decision making provide a sound BANE agent foundation.

II.E. Advantages of ABM using Bayesian Analysis

The intersection of ABM and Bayesian analysis has been explored in several fields. Simulation research in national and regional planning, economic and industrial choice selection, and military applications have included intertwined ABM and Bayesian analysis. ABM and Bayesian inference complement each other for improving emulation of real world intelligent decision making processes. Literature review of joint ABM and Bayesian research indicates ABM benefits for creating a range of diversely endowed and motivated actors. The Bayesian aspect brings the agent ability to assess their surroundings and relationships with each other to achieve their desired goals.

An ABM and Bayesian research nexus occurs for studying spatial planning regarding rural, village, and urban development. Three researchers from Wageningen University (WU) developed an ABM simulation for citizen, farmer, and nature conservationists.[68] The Netica GUI Bayesian program was used by the agents to decide and register their cooperation and satisfaction perceptions. The WU ABM scenarios demonstrate optimal levels of the agent self-selection aggregation. The impact of environmental variations and agent parameters along the lines of satisfaction alter the final outcome.

Stock markets represent the cumulative beliefs of millions of actors about the value of different service, industrial, aerospace, and other types of companies.[69] The Santa Fe Institute (SFI) put together an interdisciplinary team of economists and computer scientists to construct the Santa Fe Institute Artificial Stock Market (SFI-ASM). The SFI-ASM points out different levels of rational agent behavior can be augmented through learning methods such as Bayesian analysis. As an economics model, the SFI-ASM agent parameters can fluctuate to test different resource movement hypotheses.

A computational framework for the Chinese coal producers and power generation industry exists.[70] Contract negotiations between coal producers and power generators is modeled with variations in agent attributes. Employing Bayesian analysis reduced agent simulation decision time and improved negotiation efficiency. For one-on-one negotiations between agents, the ABM system can be approximated via Nash bargaining theory. The coal and power producer model thereby correctly shows that for small agent numbers simplified game theory models are accurate. However, for large agent numbers the more game theory models are overwhelmed vis-à-vis ABM.

Almost a decade ago an international workshop on, "Defence Applications of Multi-Agent Systems," was held in July 2005 in Utrecht, the Netherlands.[71] Ten papers on MAS were presented, and one in particular combined ABM and Bayesian belief networks (BBNs) for assessing information overload and mission success.[72] Specifically, the article employed BBNs to cover agent critical success factors (CSFs). Analysis of CSFs related to areas such as decision uncertainty related to achieving mission goals.

Other military applications of combined ABM and Bayesian include irregular warfare situations. The usage of ABM meshes well with simulating social science relationships including cultural preferences. Bayesian analysis is well suited for irregular scenarios where changes in dynamic situations can radically alter the threat environment. A United States Army modeling example using ABM and Bayesian analysis emphasizes the importance of the civilian populace in conflict zones.[73] BBNs are used for cognitive modules simulating civilian intelligent behavior.

Dynamic adversary interactions using ABM with Bayesian analysis have also been undertaken. The large defense contract BAE Systems created the Commander's Model Integration and Simulation Toolkit (CMIST) for dynamic ABM scenarios.[74] CMIST functions as an integrated development environment (IDE) for assessing political, military, social, economic, and information associated with different agents. The Bayesian modules are used for advanced intelligent adversarial responses. Agents using Bayesian modules can recognize preferential decisions based on evolving situational awareness.

The literature review indicates Bayesian analysis coupled with ABM shows promise for increasing simulation authenticity. In the multi-disciplinary nuclear nonproliferation field, social sciences including political science and psychology are intertwined with physics defined technology and industry. For instance, nuclear proliferation pathway selection has a strong connection basis tying directly into several social sciences. Key equipment transfers via espionage, economic considerations, or other means outside nuclear programs directly impact nuclear proliferation. External security threats may rapidly induce proliferation demand facilitating substantial new proliferator risk acceptance.

A few knowledgeable scientists reverse engineering or innovating a technology can suddenly shift proliferation preferences. Crucial expertise can overcome technical hurdles thought to raise a particular pathway's difficulty. Modeling nuclear proliferation supply-side and demand-side proliferation drivers requires handling many factor simultaneously. The employment of Bayesian analysis and ABM in other fields adds validity to its successful application for the complex nuclear nonproliferation arena.

CHAPTER III

BANE STRUCTURE AND ARRANGEMENT

An ABM tool using a Bayesian network analysis for estimating the probability of nuclear supply side technical success along with demand side proliferation drivers was constructed. The presence of defensive and neutral agents within the tool, named BANE, allows for simulation of covert nuclear proliferation agendas with and without attachment to civilian nuclear programs. The basis of BANE's structure is its modular, flexible arrangement for handling a wide variety of agents with a diverse set of objectives. BANE is designed for users with different background expertise and programming levels. A policy analyst using BANE will interface differently with it relative to a technical analyst or developer. As a computational proliferation assessment eco-system, BANE is built to be upgraded with new modules. Later incorporation of technology and policy challenges unknown during BANE development is imperative to prevent declining proliferation analysis utility.

III.A. Outline of BANE Agent Methodology

The rules governing agent actions are central to a nuclear nonproliferation ABM context. Agent operation guidelines should match the motivations and methods pursued by those engaged in, and countering, proliferation activities. Entities involved in nuclear proliferation cover a range of activities, but can be broken up into three main agent classes: (1) proliferating agents, (2) defensive agents, and (3) neutral supplier agents. Proliferating agents seek nuclear weapons, or at least a latent nuclear capability.

Defensive nonproliferation agents try to uncover, hinder, reverse, or dismantle any proliferation networks they discover. Neutral supplier agents represent the broadest class and comprise all other types of agents.

Some of the information on proliferating and defensive agent learning and interactions has been previously published in the 2013 Institute of Nuclear Materials Management (INMM) conference proceedings.[75] INMM has graciously granted permission to reuse this material in other publications, including this dissertation.

III.A.1. Proliferating Agents

Proliferating agents select pathways optimizing the likelihood of achieving their objective. The proliferating agent class types possess different attribute levels. Factors such as resource levels, indigenous technical capability, and nuclear weapon outlook affect proliferating agent pathway choices. As with reality, proliferating agents are free to make contact with each other and also neutral supplier agents. Through neutral suppliers, the proliferating agents can obtain access to dual use technology altering their proliferation pathways. Extended outlines for several proliferating agents are included in Table 3-I.

Table 3-I. BANE proliferating agents types. Reprinted with permission from 75.

Possible Proliferating Agent Posture	Objectives	Capabilities
State Seeking Latent Deterrence	- Obtain Nuclear Infrastucture and Capabilities Sufficient to Credibly Obtain Nuclear Weapons in Short Timeframe - Possess Plausible Justification for Nuclear Infrastructure	- Sizeable Economic, Technical, and Political Resources from the State - Military and Diplomatic Protection for National and International Entities Supporting Nuclear Infrastructure Development
State Seeking Nuclear Arsenal Exceeding 10 Weapons	- Covertly Develop Deliverable Nuclear Weapons Beyond Threshold of Inviting Preemptive Military Strike - Prioritize Concealment, Weapon and Delivery Reliability, and Program Sustainability Depending Upon Adversary Threat Profile	- Significant Economic, Technical, and Political Resources from the State - Shell Companies and Falsification of Economic Documentation for Dual Use, Technical, and Knowledge Growth
Non-State Actor Seeking Nuclear Arsenal	- Acquire Nuclear Material and Capability to Build at Least 1 Nuclear Weapon - Develop Means to Covertly Deliver Nuclear Weapon With Appreciable Nuclear Yield to Target	- Exploitation of Sympathetic or Potentially Persuadable Connections - Diffuse and Compartmented Network

Realistically, proliferators can establish relationships with other proliferators and sympathetic or oblivious neutral supplier agents. Proliferating agents therefore contact other proliferating agents and neutral supplier agents, as benefits their interest. Depending upon the neutral agent's affinity with the proliferator, its cooperation may require substantial coercive force, or other inducement measures. If the affinity relationships are high enough, then the neutral agent may enthusiastically assist the proliferator to the maximum extent possible. Proliferating and neutral supplier agents might offer SNA or important dual use technology opening up new proliferation pathways for exploitation.

III.A.2. Defensive Agents

Defensive agents analyze proliferating agent pathways for pursuing illicit nuclear weapons programs. The defensive agent class type capabilities vary significantly for detecting, hindering, and reversing proliferation. Preserving authenticity for defensive agents means ensuring they can create and break relationships with each other. Table 3-II provides a more detailed elaboration for a range of possible defensive agents.

Table 3-II. BANE defensive agents types. Reprinted with permission from 75.

Possible Defensive Agents	**Objectives**	**Capabilities**
International Atomic Energy Agency	- Prevent Misusage of Nuclear Infrastucture for Nuclear Weapons Production - Deterrence of Covert Nuclear Weapons Production	- Onsite Inspections of Declared Nuclear Facilities - Short Notification Inspections of Suspected Nuclear Facilities - Wide Area Environmental Sampling
Advanced National Intelligence Service	- Determine Pursuit of Nuclear Proliferation - Setback, Rollback, and Dismantle Nuclear Proliferation Networks	- Cyberwarfare on Critical Nuclear Proliferation Infrastructure - Imagery, Electronic, Human, and Special Intelligence Assets
National Government Defense Minisitry	- Ensure Military Disruption and Elimination of Critical Nuclear Proliferation Infrastructure - Removal of potential nuclear delivery systems	- Convetional Army, Navy, and Air Forces Platforms - Special Forces Units - Cyberwarfare
National Government Foreign Minisitry	- Non-military Resolution of Nuclear Proliferation Activities - Sustainable Nuclear Nonproliferation Verification Regime	- Provide Economic Incentives such as Trade, Financing, and Easing of Sanctions
Commerce Ministry and Customs Agencies	- Establishment of Export Control and Dual Use Equipment and Technology Regime	- Strengthened Export Controls

For counter proliferation, defensive agents can work individually or in concert to constrain neutral agent dual use technology availability. Defensive agents can also partner with other defensive or neutral supplier agents to hinder connection opportunities enabling rapid proliferation advancements. Defensive agents will have diverging goals for what constitutes a proliferation threat and what are the appropriate responses. These factors will combine to affect the limits of their cooperation.

The means for detecting and then disrupting proliferating agents will differ based on the defensive agents. Intelligence collection and interference resources are not uniformly distributed; thus, defensive agent strengths and weakness can deviate considerably. Variations in defensive agent nonproliferation capabilities cause substantial differences in their counter proliferation effectiveness depending upon the proliferating agents they confront.

III.A.3. Neutral Agents

The global economy consists of billions of individuals, millions of companies, thousands of conglomerates and affiliated organizations, and hundreds of national governments interacting daily. The majority of individuals and companies are far removed from proliferation activities. A fraction of the remaining individuals and companies have tangential connections to nuclear knowledge and technology of value to proliferators. At a lower level, only a small subset of individuals and companies add significant value for nuclear proliferation.

Neutral agents comprise the widest range of proliferators. Individuals, companies, and foreign governments fall within this class. Each neutral agent has objectives it seeks to satisfy by engaging in cooperative relationships with other agents. If diametrically opposed to a belief, a neutral agent can also undertake adversarial interactions to counter perceived threats. A set of generic neutral agents are presented in Table 3-III to indicate the broad span of the category.

Table 3-III. BANE neutral agents types. Reprinted with permission from 75.

Possible Neutral Agent Posture	Objectives	Capabilities
Foreign National Government	- Support Other Government With Positive Relations In Acquiring Nuclear Weapon Capabilities - Complicate the Strategic Calculus of Rival Nation	- Economic, Technical, and Political Resource Support as Determined in the National Interest of the State - Allow Routing of Dual Use Nuclear Equipment Through Justifiably Loose Export Controls
Corporation	- Economic Profits - National Patriotism - Support Proliferator With High Ideological Affinity	- International Supplier Network for Export Controlled Items - Access to Dual Use Resources - Plausible Deniability
Individual or Small Group of People	- National Patriotism - Religious, Ethnic, Political, Cultural, Economic Affinity	- Provide Insider at Critical International Corporations or Governments - Create Linkages for Proliferation Network Expansion

Despite the relatively small number of valuable neutral agents for nuclear proliferation, they are important enough for proliferating and defensive agents to warrant making and maintaining connections. A proliferating state agent possessing a multitude of legitimate neutral agent businesses will hold some sway over them. Through economic or political persuasion the neutral agents can be coerced into enabling nuclear proliferation. The more overt or desperate the proliferator gets, the more compliance they may elicit from the indigenous neutral agent. However, the proliferating agent risks increased scrutiny through any existing monitoring and connection establishment by the defensive agent of the co-opted neutral agent.

An outside neutral agent energetically supporting a nuclear proliferation program can provide dual use technologies or indirect economic and political support. Beyond just direct resource transfer, an active neutral supplier may aid in circumventing international export controls. Enabling plausible deniability creates a “sum is greater than the parts” situation, where the proliferator and outside neutral agent can work more closely with a decreased risk of direct incrimination. An outside neutral agent might prefer passively allowing knowledge and equipment transfers. If a major individual neutral agent in a company favors a proliferating agent they can induce the neutral agent company to not prevent technology transfers.

Relationships and influence with neutral agents will vary greatly depending on the defensive agent. For instance, the neutral agent individual or company could be located in the defensive agent country. In that scenario, the likelihood of affinity ties binding the neutral agent to the defensive agent counter proliferation effort is high. The neutral agent risk for shutdown, imprisonment, or heavy fines are all mechanisms to deter cooperation with proliferating agents.

When it comes to an outside neutral agent, defensive agents can approach other state level defensive agents with jurisdictional authority over the neutral agent. The jurisdictional defensive agent may then influence the neutral agent into opposing proliferation. The initiating defensive agent goal with that neutral agent is fulfilled in such a situation. However, if no defensive agents exist with oversight for the outside neutral agent then, the initiating defensive agent can elect to operate unilaterally or multilaterally with other willing defensive agents.

III.B. BANE Modular Configuration Overview

BANE is configured to uses modules called by the different agent classes when interacting dynamically. Several major module groupings are arranged by their BANE purpose and functionality:

- Netica GUI Interface and Visualization
- Netica API Parser
- Structured Query Language Database Storage
- Optimization Solver Methodologies
- Affinities and Influence
- Omniscience and Uncertainties

The first are the Netica GUI Interface and Visualization modules, which address the BANE developer and user requirements for setting up proliferation scenarios. The second module set revolves around the Netica API Parser operation. The API Parser modules interpret agent requests and then interact with specialized Netica .dne files.

Third, data storage within BANE is based on Structured Query Language (SQL) databases. SQL Server Access and Storage modules direct agent requests within other BANE modules to the appropriate SQL databases. Fourth, the Optimization Solver modules allow the agents to make decisions balancing technical success, resource expenditure, detection probability, and time considerations.

The fifth set of modules are for affinities and influence. In an ABM framework, interactions are determined based on affinities between agents across categories such as security concerns and economic opportunities. Influence relates to the change in affinities over time, and handles how agents grow closer or more distant. The Affinities and Influence modules are therefore interdependent and considered together.

The sixth module groups is for omniscience and uncertainties. Omniscience modules address evidence absences for agents trying to ascertain the actions and postures of other agents. Agents also face uncertainties in predicting their own technical progress, effective resource placement, detection thresholds, and action timeliness. The Omniscience and Uncertainties modules are linked within BANE for dealing with information limitations.

The modular BANE operational flow is determined by agent requirements for intelligent ABM decision making within a Bayesian framework. The required modules for internal and external engagement with other agents are accessed as needed. Figure 3-1 outlines at a high level how BANE operates during a simulation.

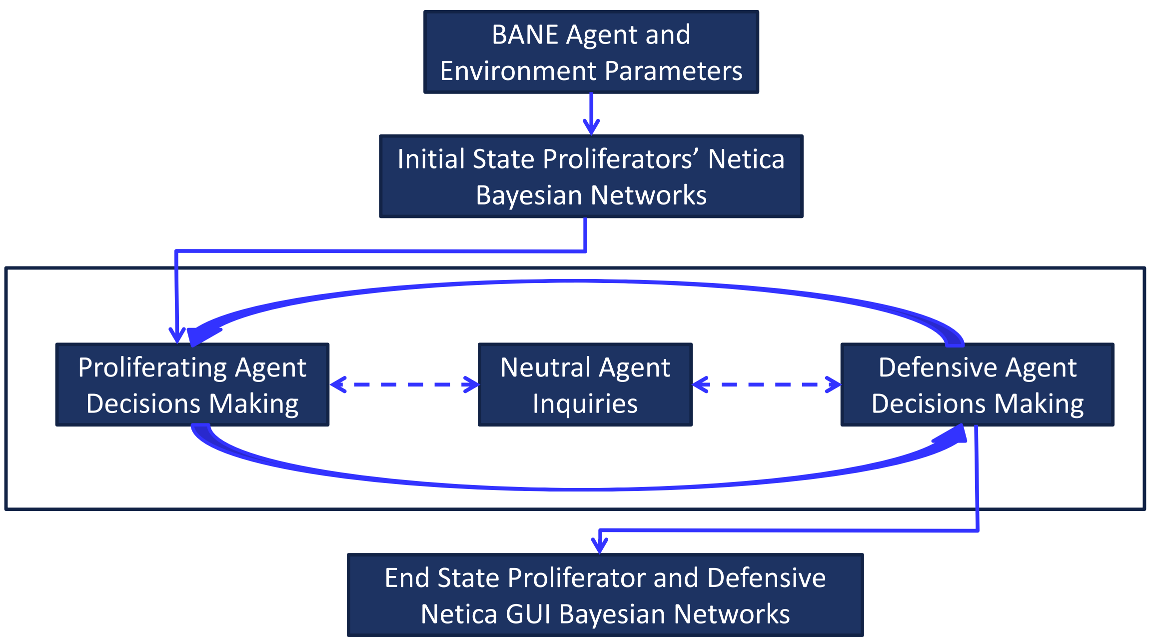


Figure 3-1. High level BANE operational flow

Prior to starting a BANE simulation, the agent and environment parameters are defined. Additional aspects of the Figure 3-1 operational flow will be explained in detail by the following figures and text. The Netica Bayesian network files for the proliferating agents are then modified according to the initial simulation conditions. The proliferating agents are the first class to run, and during the process they may reach out to the neutral supplying agents. Once the proliferating agent actions are complete the defensive agents begin running as shown in Figure 3-1. Like the proliferating agents the defensive agents also might interface with the neutral agents. BANE then functions iteratively with the proliferating and defensive agents interacting until at least one of the simulation end conditions is triggered.

The BANE functionality of the proliferating and defensive agents is more complex than shown in Figure 3-1. The path for each proliferating agent is indicated in Figure 3-2. For the defensive agents, Figure 3-3 designates how they use BANE modules for selecting choices.

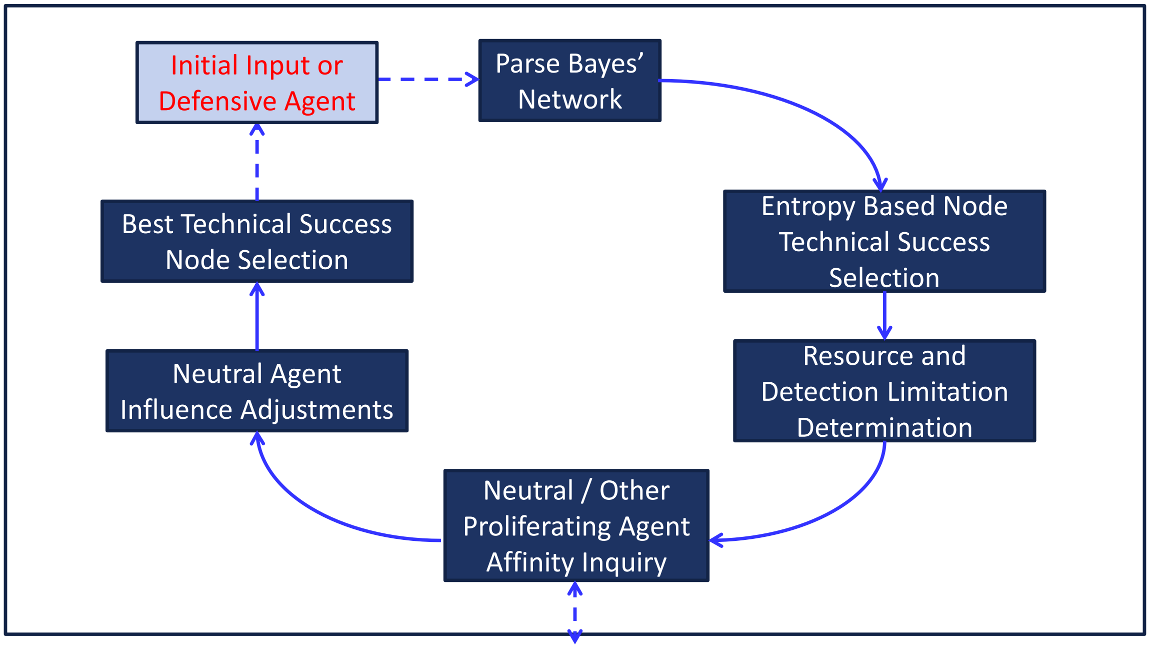


Figure 3-2. Proliferating agent decision making flow on a time step basis

During the first iteration of a BANE simulation, the proliferating agents review the state of their proliferating networks based on the input conditions specified. Figure 3-2 outlines how the proliferating agents then progress each time step. The proliferating agents next parse through their respective Netica Bayesian .dne files to gather the needed data based on their objectives. The heart of proliferating agent technical success pathway selection is through entropy analysis, which amounts to assessing the information content associated with different options relative to a given preference. After ranking its proliferation pathway preferences, the proliferating agents assesses whether they have sufficient resources and can risk the associated detection for progressing down a preferred proliferation pathway.

The proliferating agents then seek out other proliferating agents and also neutral agents with positive affinity relationships. The other agents are engaged to determine whether they can provide capabilities to advance down the desired proliferation pathway. Adjustments to the proliferating agent influence levels are made following the other proliferating and neutral agent inquiries. If another proliferating or neutral agens can provide a greater probability of technical progress on the preferred proliferation pathway, then the proliferating agent makes the connection transaction. When the proliferating agent cannot obtain the technical advancement through other agents they advance based on their indigenous capabilities within the resource and detection constraints permissible.

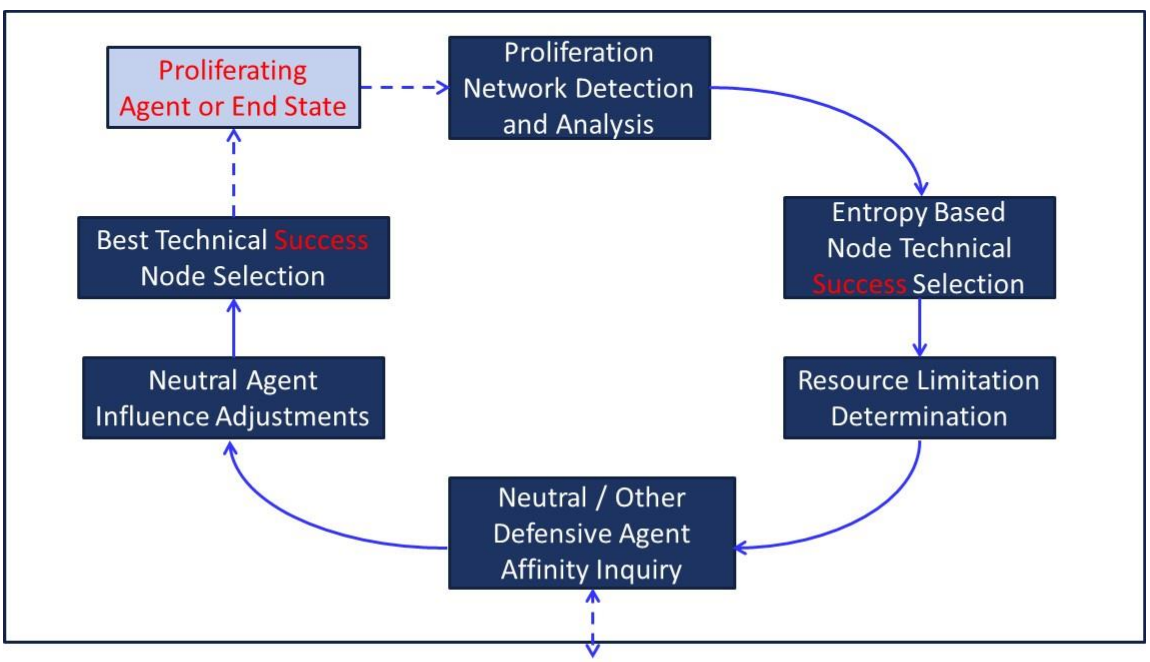


Figure 3-3. Defensive agent decision making flow on a time step basis

Once all the proliferating agents have finished, then the defensive agents are allowed to run as indicated in Figure 3-3. Defensive agents rely upon their different proliferation detection strengths to make them aware of proliferating agents. Once a proliferating network is located, the defensive agents input the .dne files for parsing to detect and assess proliferation pathway development. Like the proliferating agents, the defensive agents use entropy for determining what constitutes technical "success" within a proliferation scenario. However, the defensive agent technical success is based on hindering, rolling back, or eliminating proliferation networks. Immediate and expected future resource limitations are measured by the defensive agent when considering which proliferating activities to address.

Neutral and proliferating agent interactions are important from a counter proliferation perspective because outside assistance might rapidly increase proliferating agent abilities. The affinity levels of different defensive agents affect their ability to ensure neutral agent compliance with nonproliferation regimes. Working together allows aligned defensive agents to further spread the nuclear nonproliferation reach.

Once a defensive agent perceives a particular proliferator has a key pathway bottleneck it can proceed independently or elicit assistance from other appropriate defensive agents. Defensive agents then attempt to reverse proliferating agent influence and affinity levels with potential neutral agent sources of nuclear information, equipment, technology, or material. The defensive agent influence and affinity levels are then adjusted to reflect time step changes. Afterwards the defensive agent uses its indigenous capabilities where it best deems possible to prevent nuclear proliferation.

III.B.1. BANE Network Arrangement

In a Netica GUI Bayesian network, making evidence additions is analogous to increasing certainty in proliferator activities. Proliferation network priors facilitate understanding how proliferators weigh nuclear weapon acquisition pathways. Netica Bayesian networks priors provide insights into proliferator technical choices by bounding the benefit range of agent decisions. The priors are a major consideration, as new intelligence sources can indicate proliferator progress in a few areas that insinuates a shift in the currently expected proliferation pathway. The extrinsic physics governing progress along a particular proliferation pathway does not change. Therefore, grounding the Netica GUI proliferation network in scientific realities is advantageous. Updates to Netica GUI networks are still required as promising innovations that might overcome existing proliferation hurdles develop. New proliferation technologies and enhanced capabilities, such as in the laser uranium enrichment or pyroprocessing fields, can be adaptively considered within an ABM context.

Expert elicitation from available nonproliferation technical experts can relate the contribution of different node components to the total likelihood a node is true. The Netica GUI provides its technical success probability using repeated Bayesian analysis linkages. Therefore, priors are key for Bayesian nonproliferation analysis in an information denied environment. More detail about the setup, building, and modification of a Netica GUI nuclear proliferation model is shown in the thesis for Cory Freeman and Michael Mella.[10,11] Figure 3-4 shows the full version of the Freeman-Mella initiated Bayesian Netica GUI proliferation network references 10 and 11 articulate.

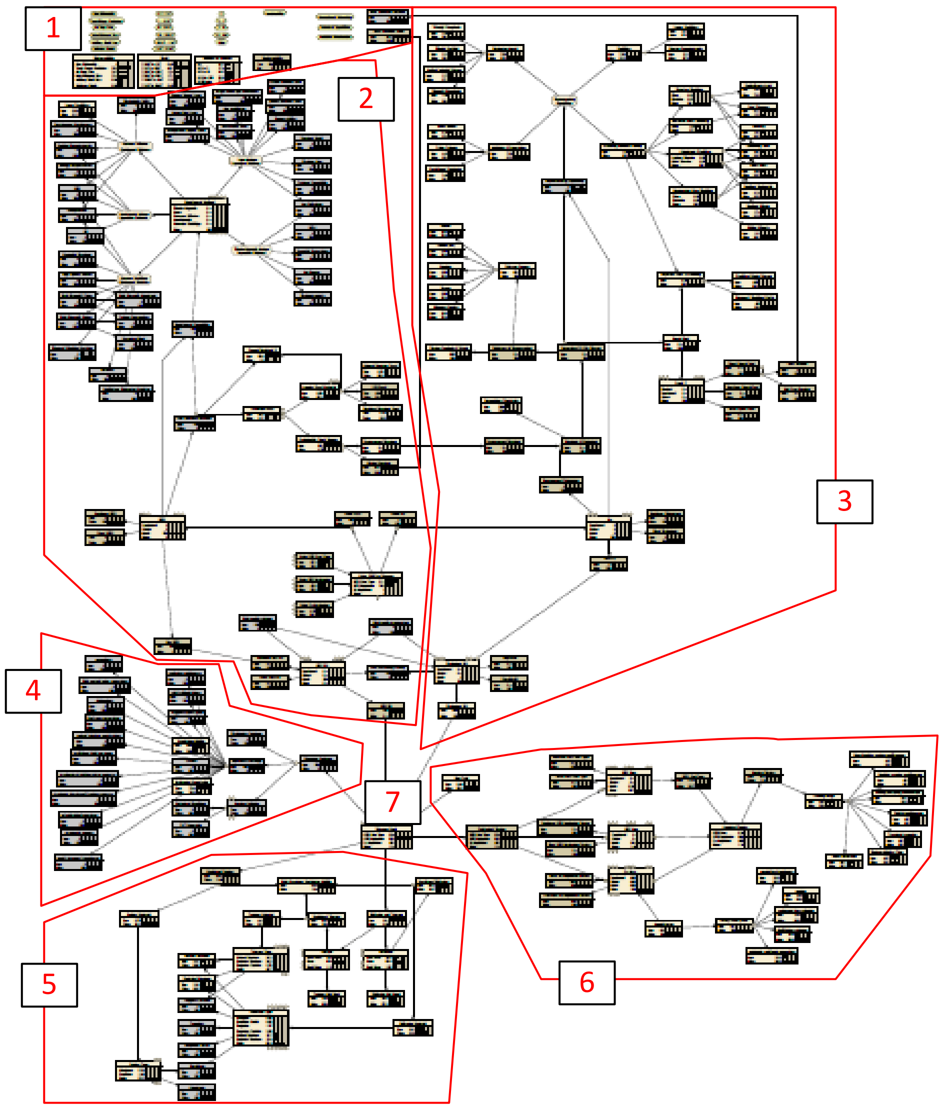


Figure 3-4. Full Netica GUI Bayesian proliferation network

Within BANE, the Bayesian model is broken up into 7 sections. A key objective for the BANE sections is to be flexible and allow additional section categories to be added in the future. Section 1 in Figure 3-4 is the proliferator specific characteristics associated with resources, technical knowledge, infrastructure, and desired nuclear arsenal arrangement. Uranium enrichment comprises section 2 and plutonium reprocessing makes up section 3. Processing of transformed special nuclear material (SNM) is section 4. Section 5 includes the non-SNM nuclear weapon fabrication, while section 6 encompasses the creation of usable SNM weapon pits. The complete nuclear weapon arsenal yield, size, delivery, and other aspects are considered in section 7. A more detailed view of section 1 is provided in Figure 3-5.

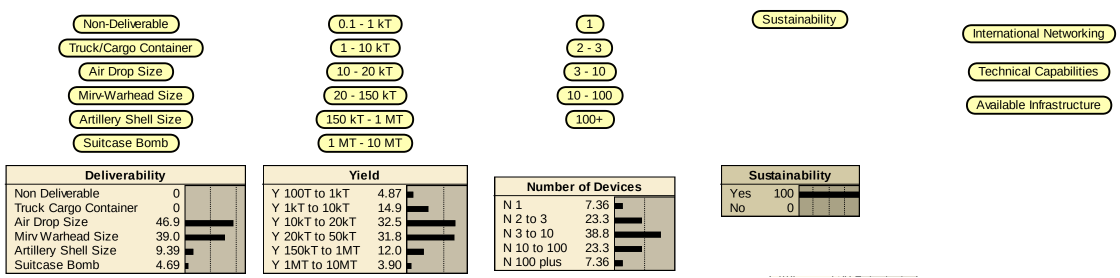


Figure 3-5. Bayesian proliferator specific attributes

The traditional nuclear fuel cycle for civilian, and with adjustment military, purposes is covered in sections 2 and 3. The front end of the nuclear fuel cycle with uranium mining or acquisition is closely associated with section 2. Plutonium reprocessing is a part of the nuclear fuel cycle back end. An image of a commercially oriented nuclear fuel cycle is shown in Figure 3-6.

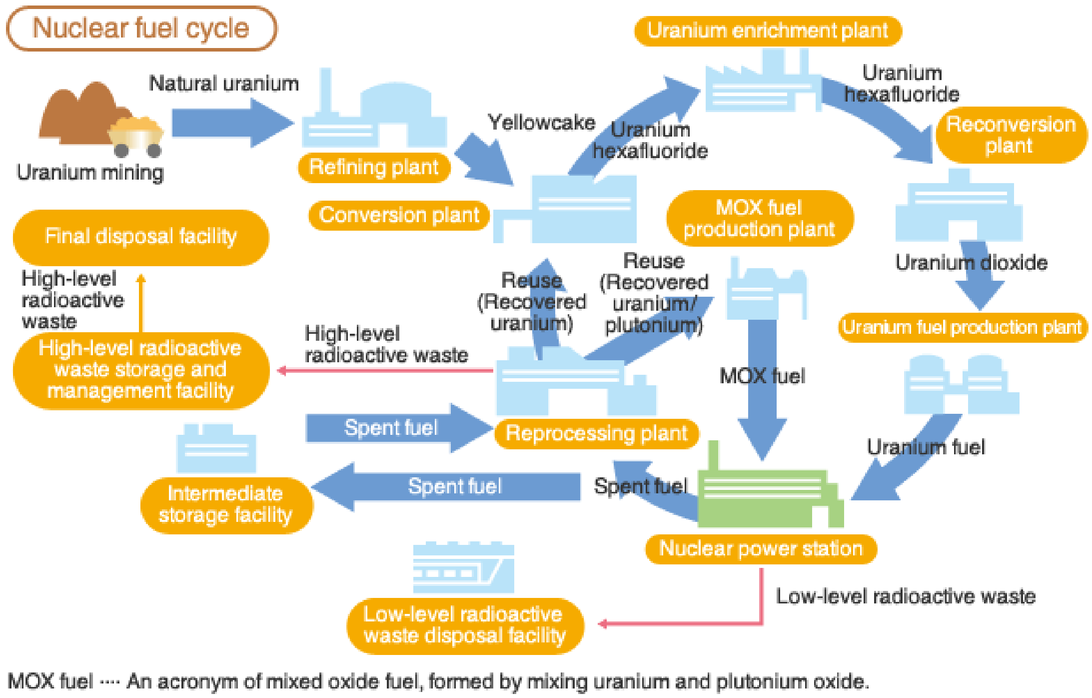


Figure 3-6. Nuclear fuel cycle with commercial emphasis.[76]

The commercial nuclear fuel cycle in Figure 3-6 undergirds peaceful nuclear energy generation. Whether a country needs to domestically possess all the components of a nuclear fuel cycle is a major source of international contention. The commercial nuclear fuel cycle can be broken up into a front and back end as shown in Figure 3-6. Generally, the front end covers uranium mining, milling (refining), conversion, enrichment, and fuel fabrication prior to usage in a nuclear power plant. Correspondingly, the back end includes spent nuclear fuel separation to recover valuable isotopes for future nuclear power generation.

BANE incorporates the commercial nuclear fuel cycle shown in Figure 3-6 through its 7 sections. The uranium enrichment portion of the Netica Bayesian network is section 2. In broad terms, section 2 can be broken up into the uranium enrichment methods and the associated precursors and post material management requirements. The methods for uranium enrichment are shown in Figure 3-7.

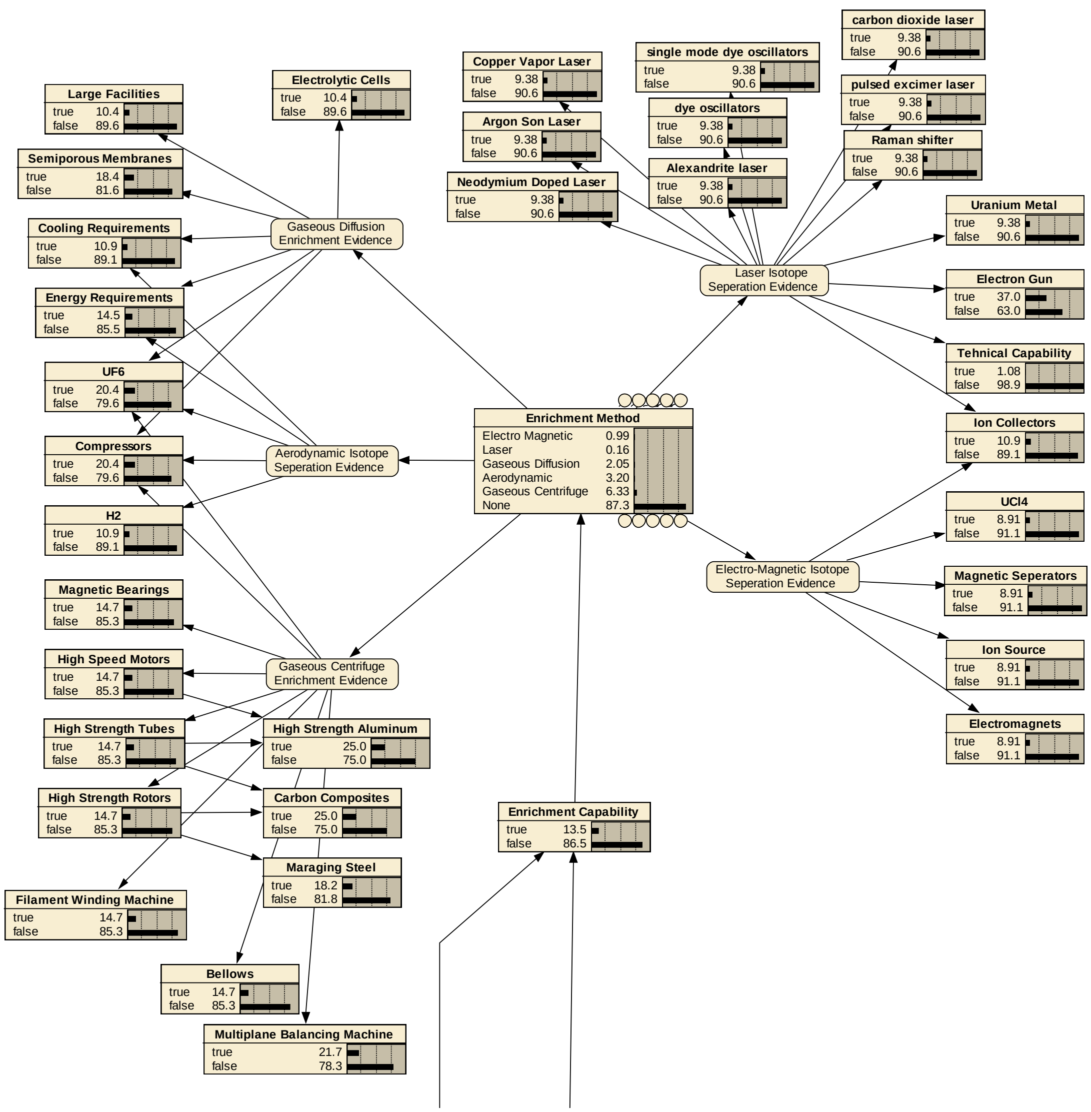


Figure 3-7. Uranium enrichment methods

The uranium enrichment network in Figure 3-7 has several parent and child relationship levels. Many uranium enrichment network parents have a large number of branching children. The parent success link is a non-uniform mix of "and" and "or" child nodes depending upon the necessity of individual or sets of technologies to achieve a particular type of uranium enrichment. The uranium management before and after enrichment is included in Figure 3-8.

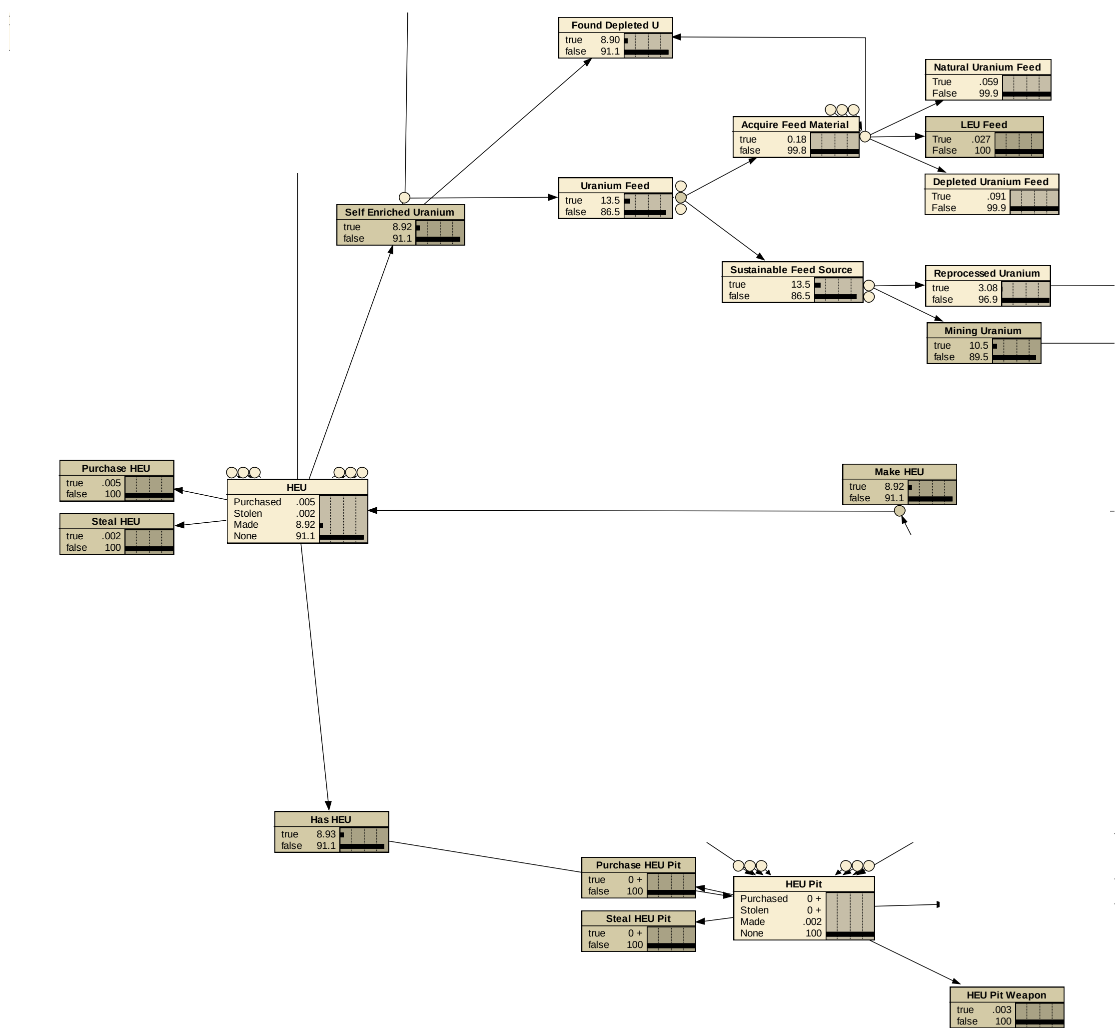


Figure 3-8. Uranium enrichment precursors and post material management

Creation of uranium based nuclear pits is grouped in Figure 3-8 into section 2. Figure 3-8 also covers the potential theft or obtaining of uranium from another entity. Plutonium reprocessing makes up section 3; and it predominately spans the back end of the fuel cycle in Figure 3-6 after nuclear reactor fuel production.

For comparison purposes relative to the BANE general to specific network methodology, a notional specific to general Netica proliferation network is depicted in Figure 3-9. The Figure 3-9 example is for a proliferator seeking reprocessing capabilities. Cladding removal precedes spent fuel dissolution, as depicted in Figure 3-9, with the subsequent radioactive gas release signature.

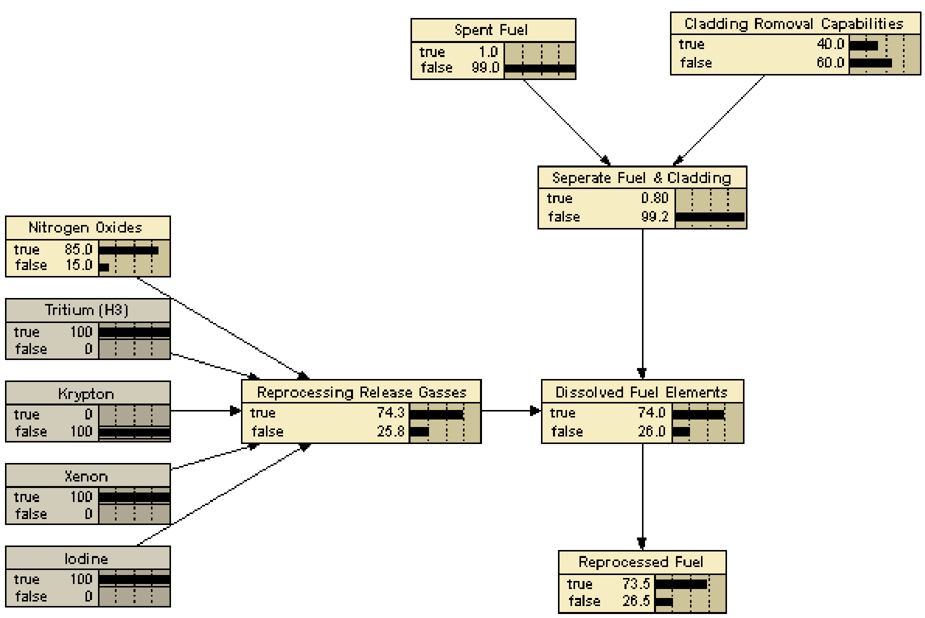


Figure 3-9. A pre-BANE specific to general reprocessing section with evidence

From a counter proliferation standpoint, uncovering a spent fuel diversion and clandestine cladding removal capability predisposes a broader covert reprocessing program. The detection of significantly elevated noble and radioactive gas via a wide area environmental sampling (WAES) system all but confirms the covert reprocessing Bayesian inference assertion.[77,78] An issue with the specific to general network arrangement in Figure 3-9 appears for the child node, Dissolved Fuel Elements, relationship to its parent nodes, Separate Fuel & Cladding and Reprocessing Release Gas. The parent Spent Fuel possession and Cladding Removal Capabilities fail to undergo the requisite alteration because Dissolved Fuel Elements is part of a child node chain. Realistically, a counter proliferation effort learning through WAES of reprocessing gas release should highly suggest reprocessing precursor steps occurred.

In contrast, the current BANE Netica plutonium reprocessing network using the general to specific network is more responsive to evidence additions. The BANE Netica proliferation network focuses on aqueous plutonium separation pathways as indicated in Figure 3-9. A subset of Figure 3-10 demonstrates the more evidence responsive general to specific BANE network incorporating reprocessing signatures from volatile compounds and different noble, radioactive, and other gas emissions.

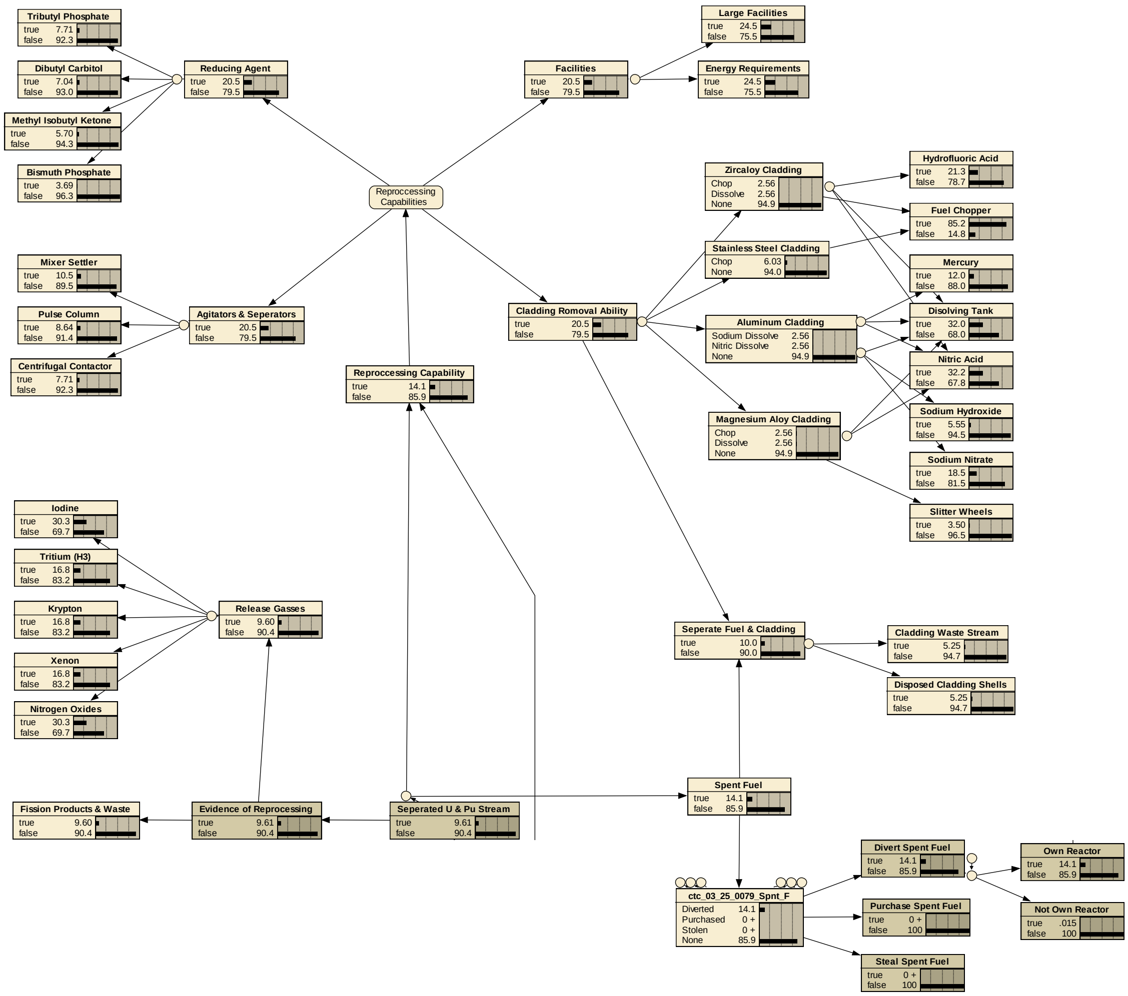


Figure 3-10. Plutonium reprocessing options

Aqueous plutonium reprocessing began by housing tall pulse columns and large volume, concrete lined separation facilities with heavy radiation shielding. Over time the reprocessing facilities could accommodate smaller and more efficient centrifugal contactors and other upgrades that shrank the physical and support requirements. Preprocessing and post processing are required for plutonium proliferation pathways following separation as shown in Figure 3-11.

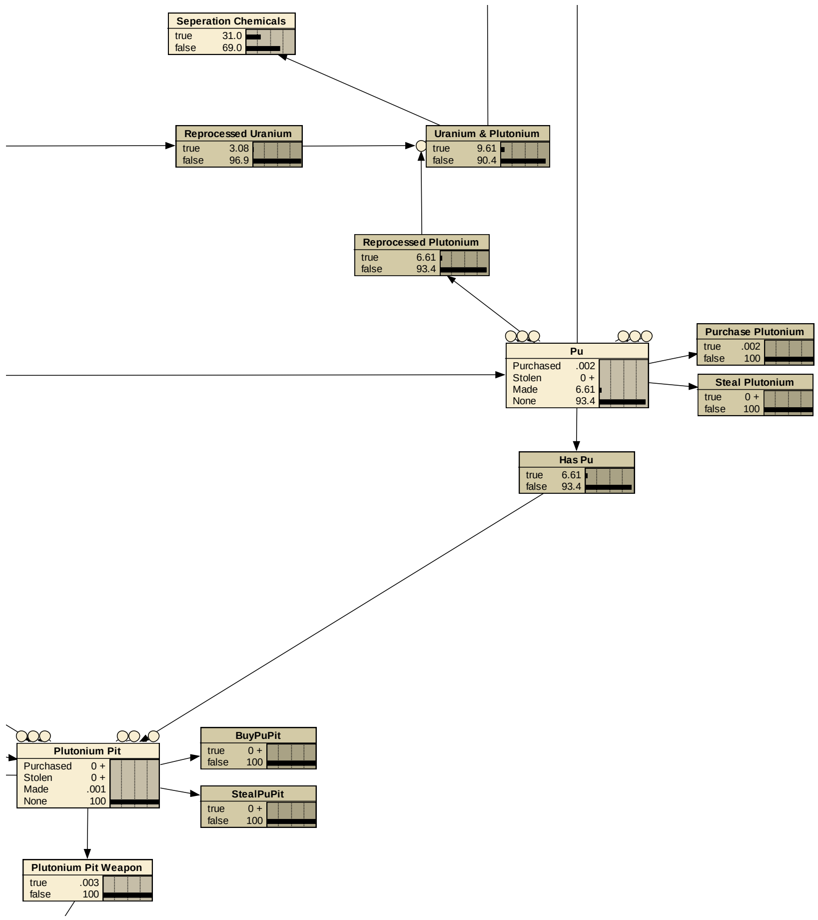


Figure 3-11. Plutonium reprocessing precursors and post material management

The non-nuclear aspect for nuclear weapon deployment is section 4 in Figure 3-4. Greater proliferation network detail for non-nuclear component connections exist in Figure 3-12.

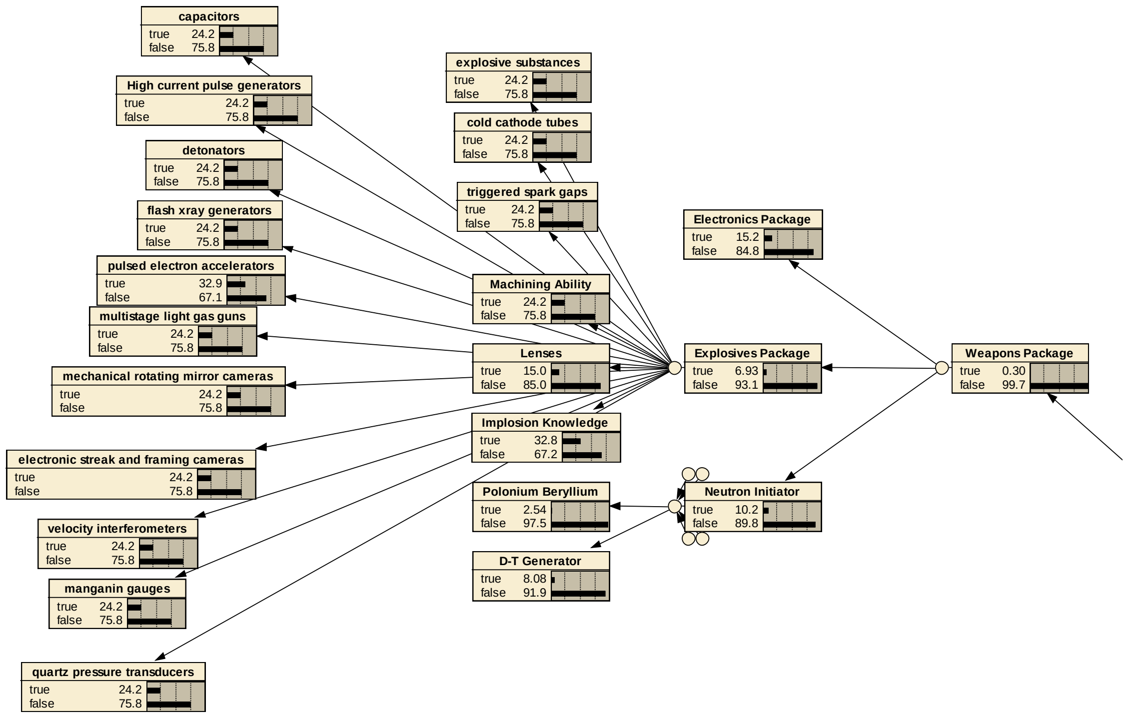


Figure 3-12. Non-nuclear weaponization

Research and development (R&D) associated with Figure 3-12 are mostly non-nuclear outside of the initiator systems. Activities undertaken by a proliferator in Figure 3-12 could be pursued prior to, concurrently with, or following efforts to obtain sufficient SNM to initiate a nuclear weapons programs. The pusher and reflector parts of nuclear weapon fabrication are outlined in Figure 3-13, and part of Figure 3-4 section 5.

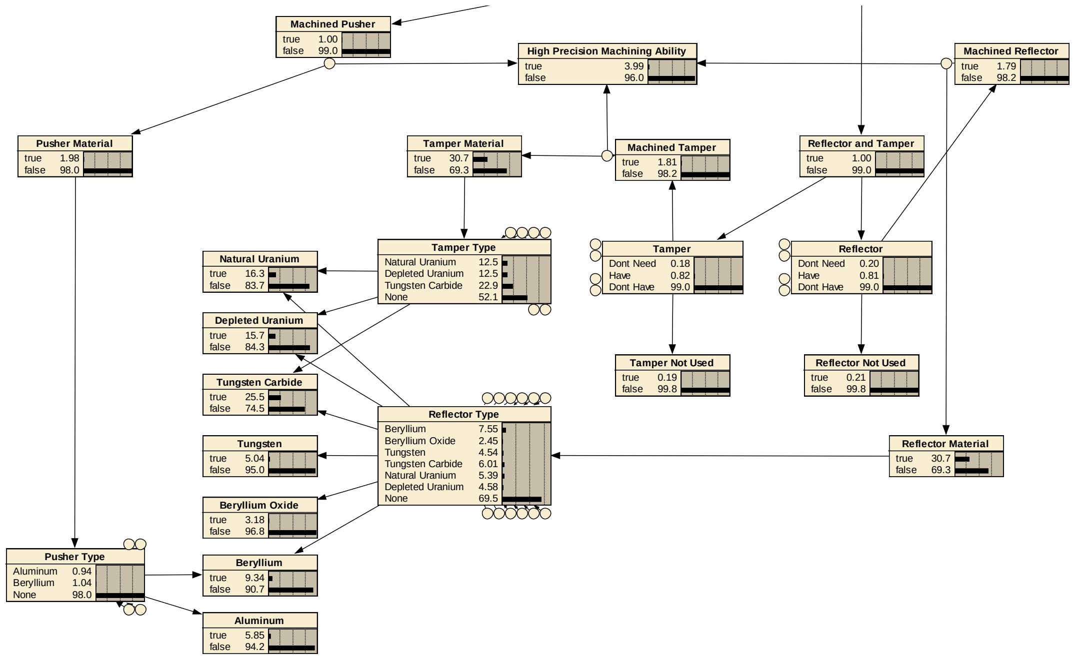


Figure 3-13. Nuclear weapon reflector and pusher components

Similar to non-nuclear R&D in section 4, some aspects of the pusher and reflector portions of nuclear weapons can proceed or follow SNM acquisition. Depending upon the preferred pusher and reflector, the material might be non-nuclear in nature and routinely used in legitimate commercial products. The creation of usable SNM weapon pits with different configurations is section 6. More depth on the section 6 network is shown in Figure 3-14.

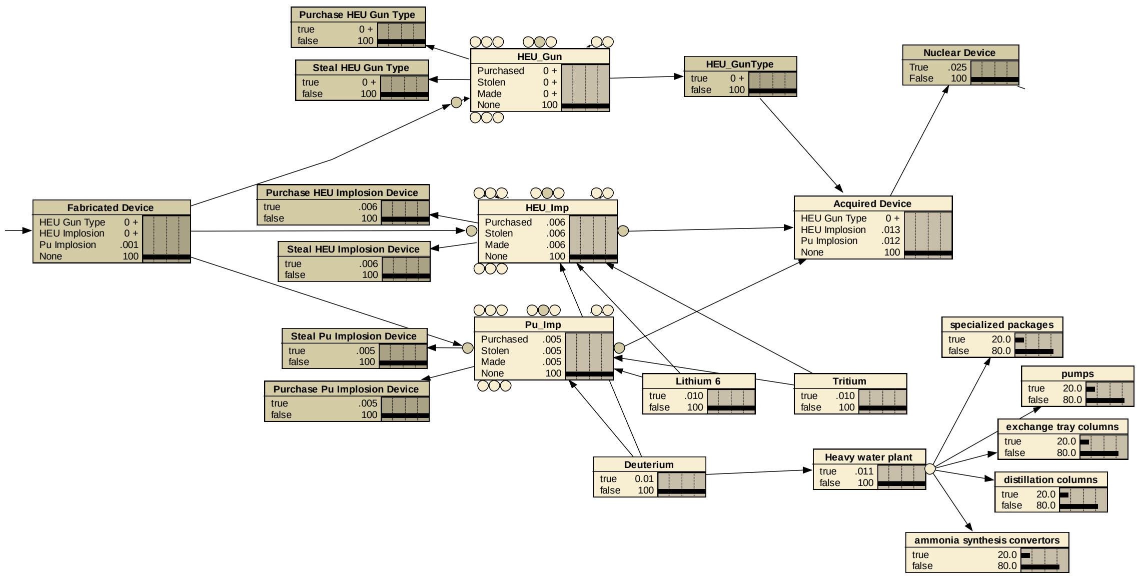


Figure 3-14. Nuclear weaponization configurations

The nuclear weaponization process in Figure 3-14 addresses generalities associated with different horizontal nuclear warhead proliferation options. New nuclear weapon states are a horizontal proliferation issue. Vertical proliferation covers improvements to existing nuclear weapon arsenals. Aspects of vertical proliferation nuclear weapon efforts are addressed in section 6. Nuclear weapon component testing is considered in greater detail separately from other parts of section 6 and provided in Figure 3-15.

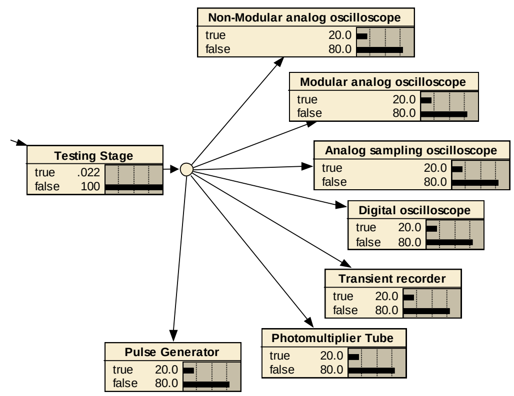


Figure 3-15. Nuclear weapon testing

Whole or component weapon testing shown in Figure 3-15 may or may not be optional for a proliferator. Indications of some nuclear weapon testing equipment leaking out raises major questions about final proliferation intentions. In Figure 3-4, section 7 is the node, and associated prior nodes, where all the other sections intersect for nuclear weapons program development.

III.C. Netica GUI Node Level Verification Testing

Considering a small subset of a full Netica GUI nuclear proliferation model demonstrates how small changes in constituent capabilities can alter proliferation decision making. Figure 3-7 shows the uranium enrichment network as a starting point for discussing Netica GUI network verification testing. Verification of components comprising the Netica GUI nuclear network can be tested by checking the truth tables to ensure the final probabilities match expected calculations. If smaller nuclear network parts are verified as part of increasingly large sections, then trust is built in the correct operation of the network.

Five uranium enrichment capabilities (Gas Diffusion, Aerodynamic Isotope Separation, Gas Centrifuges, Laser Isotope Separation, and Electromagnetic Isotope Separation [EMIS]) are available options for a potential proliferator in Figure 3-7. Each uranium enrichment proliferation option has several key components needed for their successful operation. Depending upon the potential proliferator, the likelihood of possessing the constituent technology as indicated by the “true” percentage in the Netica GUI model will vary. With the Netica GUI, each higher level node becomes a constituent for the next node and affects its chances of occurrence.

The components associated with a successful gas centrifuge program demonstrate the importance of Equation 2-8 within the Netica GUI. The high probability acquisition of advanced composite filament winding machines provides one of several crucial gas centrifuge technical requirements, B. The presence of the filament winding machines escalate the chances a proliferator could successfully obtain gas centrifuges, A_i, relative to several uranium enrichment technologies, A_j.

Proliferation technical success predicted by the Netica GUI occurs for a snapshot over a relatively short time frame. Changes in capabilities from a resource, time, or outside detection standpoint can impact the nuclear proliferation technical aptitude for an entity. As a result the Netica GUI module needs to be updated and run repeatedly by each agent every time step to address perturbed nuclear proliferation situations. The Netica .dne files may be generated for every proliferation update as part of robust verification operational testing.

III.C.1. Netica GUI Visualization Tool

The Netica Application GUI is invaluable for BANE .dne file creation, updating, and visualization elements. Viewing relationships between proliferation network nodes prior to updating them is typically handled with the Netica GUI. Depending upon the BANE user background, the Netica GUI visualization facilitates easy comparisons between different proliferation network progressions. Visualization within the BANE context is based on successive Netica .dne file generation and subsequent Netica GUI viewing. Human Netica GUI and agent based Netica API alterations to nodes in an existing .dne file change the normally beige colored nodes gray. The gray color aids rapid assessment of proliferation network changes.

The uranium enrichment model example from Figure 3-7 is shown in Figure 3-16 after several dozen time steps have occurred. The deviations in the Figure 3-16 uranium enrichment network subset reflect evolving decision making by a proliferating agent. Note the grayed out nodes indicate the proliferating agent hedging strategy of focusing first on UF_6 and Compressors improvements. The rationally based proliferating agent emphasizes obtaining uranium enrichment foundational capabilities of UF_6 and Compressors. Investing in UF_6 and Compressors opens up the Gas Diffusion, Aerodynamic, and Gas Centrifuge sectors for later proliferation exploitation.

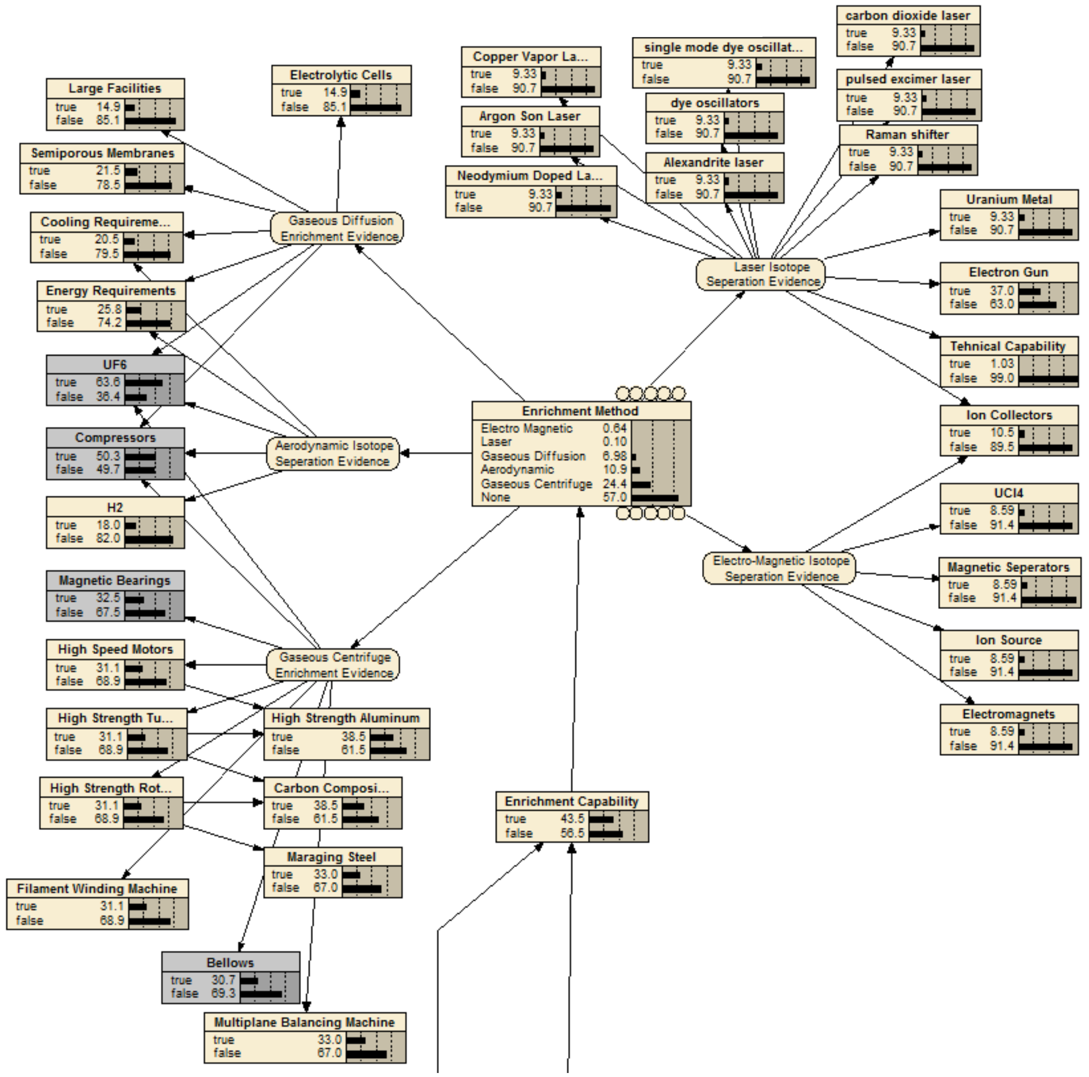


Figure 3-16. Updated Netica uranium enrichment model from proliferating agent perspective after several dozen time steps

Beyond a certain technical success threshold, the proliferating agent selects a more specific proliferation pathway. Proliferating agent attributes in the Figure 3-16 example depict a proliferation preference for gas centrifuge enrichment. Once the underpinning gas centrifuge UF_6 and Compressors mastery is sufficiently advanced, then the proliferating agent begins researching Magnetic Bearings and Bellows. Committing to the Magnetic Bearings and Bellows, which are only applicable for gas centrifuges, makes the desired proliferation pathway clearer.

The rate .dne files are generated by BANE for cataloging agent histories can be adjusted. Obtaining necessary agent information is balanced against computational storage and efficiency for selecting the number of .dne files produced. For MAS oriented simulations emphasizing in-depth analysis of a particular agent, producing more .dne file histories may be appropriate. Larger simulations along ABM lines would generally operate with fewer .dne files per agent with longer time intervals in between.

III.C.2. Netica Application Programmer Interface Parser

The nuclear proliferation networks contained within the .dne files are the backbone of BANE. Agents dynamically accessing the .dne files use the Netica API Parser module. The Netica API Parser allows agents with widely different objectives to determine, from their perspective, the state of nuclear proliferation.

The Netica API Parser can be broken up into several key functions. First, the Netica API Parser helps the agents breakdown the Netica network nodes based on their assigned category, type, and component. Second, the Netica API Parser handles the best node technical selection for the agent using Shannon entropy. Third, the Netica API Parser provides the mechanism for agent adjustment of Netica networks and .dne files considering resource and detection limitations for a given set of time steps.

Netica API Node Classification

Each Netica node in BANE has a unique category, type, component (CTC) classification identifier at the start of its name. From a visualization standpoint the 30 character Netica node name differs from the node title, which is not length limited. Fortunately, a human user looking at a node in the Netica GUI sees the node title. The CTC identifier allows agents to associate particular knowledge, technologies, equipment, and signatures to various nuclear proliferation pathways. Figure 3-17 outlines how the CTC is structured.

01	-	*01*	-	*0001*
Category		**Type**		**Component**

Figure 3-17. CTC classification arrangement.

The CTC classification system is designed for expansion as additional functionality is added to BANE. The CTC category currently consists of seven sections corresponding to a different nuclear weapon program proliferation aspect. The names and matching numbers for the CTC Category are shown in Table 3-IV. The CTC type is broken up into 38 sections based on node association such as prior node input, knowledge, material, signature level, etc. Within each CTC category a unique component number is assigned for numerical referencing and to speed up node access.

Table 3-IV. CTC Category names

Number	Category Name
1	Shared Category Node
2	Enriched Uranium
3	Plutonium
4	Non-Nuclear Weapons Package
5	Pusher, Reflector, Tamper
6	Device Fabrication
7	Completed Device

The seven category sections cover the major mainstream and contemporary portions of a proliferating entity nuclear weapons program. The Netica proliferation network overview in Figure 3-4 is apportioned by CTC category. The subsequent Figures 3-6 to 3-8 and 3-10 to 3-15 were finer breakout images of the CTC categories used in BANE.

The Shared Category node CTC category, category 1, is the catch-all classification for nodes not located in a particular section. Proliferating agent specific nuclear weapon posture nodes fall within the Shared Category. The second CTC category is for enriched uranium production, along with the requisite uranium ore feedstock, tails, and other associated processes. Specifically CTC category 2 covers uranium-235 enrichment. Sections of the proliferation network for uranium enrichment are shown in Figures 3-7 and 3-8.

Plutonium reprocessing through aqueous methods is addressed within CTC category 3. Figures 3-10 and 3-11 illustrate the proliferation network detail for aqueous derived plutonium reprocessing. Uranium ore for plutonium production is contained in category 2. However, the irradiating nuclear reactor is part of category 3.

CTC category 4 encompasses the non-nuclear weapon package portion for a nuclear posture. The proliferation network section linked to the non-nuclear weapon requirements are in Figure 3-12. The more nuclear related pusher, reflector, and tamper are in CTC category 5. The depiction in Figure 3-13 is for the pusher, reflector, and tamper nodes.

Nuclear weapon device fabrication is CTC category 6, which also includes any nuclear weapon device testing needed. Category 6 nodes depict the growth of horizontal and vertical proliferation capabilities for various nuclear weapon postures. The device fabrication nodes are provided in Figure 3-14, while the nuclear testing nodes are in Figure 3-15. The completed nuclear weapon category 7 is an interface node for categories 2, 3, 4, 5, and 6. Category 7 nodes are for quickly indicating the state of proliferating agent overall nuclear weapon technical success.

The CTC Type is broken into several sections based more loosely on what the node represents. The node sections are based on prior nodes, education level for attaining certain equipment and knowledge, SNA and SNT, nuclear and non-nuclear materials, and signatures. A node requires a type, and the best fit is used to place nodes that could fit into multiple types. The first 8 nodes are placeholder and prior nodes, and are shown in Table 3-V.

Table 3-V. CTC Type prior nodes

Number	Sub-ID	Type Name
1	--	*Placeholder Node*
2	Prior	[Desired Weapon(s)] Deliverability
3	Prior	[Desired Weapon(s) Most Challenging] Yield
4	Prior	[Desired Weapon] Number
5	Prior	[Desired Weapon] Sustainability
6	Prior	International Networking
7	Prior	Technical Capabilities
8	Prior	Available Infrastructure /Ability

Placeholder nodes are generally visualization nodes that should not be modifiable by agents through the Netica API. The prior nodes are heavily equated with the proliferating agent objectives and attributes in Figure 3-5. Prior nodes attached to other nodes serve as proliferating agent specific modifiers allowing for flexible usage of the same Bayesian inference network architecture. Deliverability relates to relative distribution of nuclear weapon arsenal, with the most difficult weapon configuration dominating technical difficulties. The most challenging obtainable yield dictates minimum technical requirements for nuclear weapon. Nuclear weapon arsenal size is a function of demand and supply proliferating agent drivers. Nuclear weapon sustainability posture varies significantly for non-state actors and state actors seeking latent deterrence versus medium to large stockpiles.

With ABM nodes types 6 through 8 are handled in the Bayesian network for agent specific possessions. International networking is a supply side determinant for proliferation technical success. The technical capabilities of an agent are a function of its indigenous human capital. The availability infrastructure, or acquisition ability, deals with the industrial and scientific agent nuclear proliferation prowess. CTC Type 9 through 16 address proliferation equipment industrial abilities as defined in Table 3-VI.

Table 3-VI. CTC Type equipment nodes

Number	Sub-ID	Type Name
9	Base	Unskilled Equipment
10	Base	Skilled / Technician Equipment
11	Base	BS / MS Level Equipment
12	Base	PhD Level Equipment
13	--	Unskilled Equipment
14	--	Skilled / Technician Equipment
15	--	BS / MS Level Equipment
16	--	PhD Level Equipment

The BASE sub-type identification (ID) is important for nuanced agent interactions with the Bayesian network. Predominately, the BASE sub-ID restricts proliferating agents to internally pursuing foundational capabilities. Accumulated investments in BASE nodes then drive more advanced proliferation acquisitions. The BASE sub-ID limitation mirrors proliferator incremental research challenges. Ensuing proliferation desires to obtain international research and development (R&D) and SNA are predicated on rapidly overcoming proliferation hurdles requiring major time and resource investments.

There are four CTC Type classes for equipment based on the educational attainment needed. The CTC Type classes are duplicated because half are fundamental

BASE nodes and the others depend on BASE nodes to exist. The unskilled level equates to equipment attainable by those with a high school education. Equipment at the skilled / technician education needs a workforce with a trade or associates level degree background. The bachelor's (BS) and master's (MS) degrees include most common place high technology equipment. Doctoral (PhD) level equipment is cutting edge for its respective field, but complicated to develop and maintain. The proliferation knowledge CTC Types are depicted in Table 3-VII, and similar to the CTC Type equipment classes.

Table 3-VII. CTC Type knowledge nodes

Number	Sub-ID	Type Name
17	Base	Unskilled Knowledge
18	Base	Skilled / Technician Knowledge
19	Base	BS / MS Level Knowledge
20	Base	PhD Level Knowledge
21	--	Unskilled Knowledge
22	--	Skilled / Technician Knowledge
23	--	BS / MS Level Knowledge
24	--	PhD Level Knowledge

Paralleling the CTC Type equipment, the CTC Type knowledge breaks down proliferation knowledge into BASE and BASE dependent nodes. A high school education leads to unskilled knowledge. With a technical trade or associates degree workforce the skilled / technician level nodes are available. College BS or MS educated science, technology, engineering, or math (STEM) personnel engaged in proliferation grant access to BS / MS level knowledge. At the upper tier, doctoral SETM experts are required for PhD level knowledge. Specialized nodes 25 through 27 are provided in Table 3-VIII.

Table 3-VIII. CTC Type specialized nodes

Number	Sub-ID	Type Name
25	--	Network Major Multiple Node
26	--	Special Nuclear Theft (SNT)
27	--	Special Nuclear Assistance (SNA)

A network major multiple node is a central connecting node with major implications for direct agent access. The central enrichment node in Figure 3-6 is a CTC Type 25 node. The SNT CTC Type 26 node is crucial for non-state agent nuclear nonproliferation lacking the sophistication of a state proliferating agent. The non-state agent seeking a single nuclear weapon prefers the acquisition pathway with the least work to a functional and deliverable weapon. Enclosed within SNT is taking SNM, stealing a nuclear pit, or even absconding with a completed nuclear weapon.

The SNA is state centric and covers a wider range than SNT. With SNA a proliferating state agent could receive crucial nuclear weapons design information. Providing a large quantity of SNM for a proliferating state also constitutes SNA. Supplementing a proliferating state with major equipment and knowledge is SNA if it enables creation a SNM reprocessing or enrichment facility for HEU production. Directly supplying nuclear weapons would be another form of SNA. Nuclear materials CTC Types for proliferation are provided in Table 3-IX.

Table 3-IX. CTC Type nuclear material nodes

Number	Sub-ID	Type Name
28	--	Raw [Ex. Uranium Ore]
29	--	Refined [Ex. Purified Uranium Yellowcake and Uranium Dioxide]
30	--	Processed [Ex. Uranium Hexafluoride, Natural Uranium Metal]
31	--	Enriched [Ex. Low Enriched Uranium, Highly Enriched Uranium, Plutonium, Depleted Uranium]

There are four CTC Type nuclear material classes based on the level of processing to create. Raw nuclear materials need minimal alteration. With refined nuclear materials chemical processing was used. Processed nuclear materials have been purified and transformed for easy usage in more advanced nuclear endeavors. Enriched nuclear materials underwent isotopic enrichment or irradiation leading to another element or isotope being generated. In Table 3-X the CTC Types for non-nuclear materials are listed.

Table 3-X. CTC Type non-nuclear material nodes

Number	Sub-ID	Type Name
32	--	Raw [Ex. Seawater]
33	--	Refined [Ex. Hydrogen]
34	--	Processed [Ex. Steel, Composite Material such as Carbon Fiber]
35	--	Enriched [Ex. Heavy Water]

The four CTC Type non-nuclear material classes parallel the CTC Types 28 to 31. Non-nuclear materials that are raw exist naturally without human activity. Obtaining refined non-nuclear material requires at least chemical processing. There is a big differential between refined and processed non-nuclear materials. Manufacturing processed non-nuclear material needs advanced industrial processing across polymer, ceramic, or metallurgy fields. The enriched field for non-nuclear materials equates to isotopic composition alterations. Nodes that are signatures for activities are included in Table 3-XI.

Table 3-XI. CTC Type non-nuclear material nodes

Number	Sub-ID	Type Name
36	--	Easily Apparent Facility Signatures
37	--	Discernable Facility Signatures
38	--	Difficult Facility Signatures

Several nuclear proliferation areas, but particularly reprocessing, yields detectable signatures potentially alerting defensive agents. Easily apparent signatures encompass issues such as large facility and complex footprint. Discernable signatures include radioactive and non-natural concentrations of noble and volatile gas products. Within the difficult signatures CTC Type are precursor materials and compounds suggestive of a nuclear proliferation effort. The signature nodes represent proliferation features that vary in technical difficulty to achieve for agents. However, the signature nodes have a far greater impact on nuclear counter proliferation for defensive agents.

Netica API Node Technical Selection

Focusing only on node technical selection illustrates the underlying mechanism for Netica API operation. The uranium enrichment network shown in Figure 3-7 works as a technical selection starting point. A proliferating agent perturbing the UF_6 capabilities in the Figure 3-7 proliferation network could occur. Increased UF_6 technical aptitude might be based on applying resources to eventually overcoming domestic research hurdles. Another option could be the proliferator makes contact with an entity inclined towards nuclear cooperation with it based on economic, religious, ideological, or other affinity.[17,79]

Figure 3-7 shows the UF_6 technology connection to gas diffusion, aerodynamic, or gas centrifuge uranium enrichment methods. Advances in UF_6 mastery broaden the proliferation pathways and increase the chances the proliferator could obtain enriched uranium. At higher levels of UF_6 advancement, BANE demonstrates in Figure 3-18 the expectation that the proliferating agent receives greater proliferation benefit. Growing UF_6 abilities enable enhanced testing and development of other proliferation pathway components dependent on UF_6.

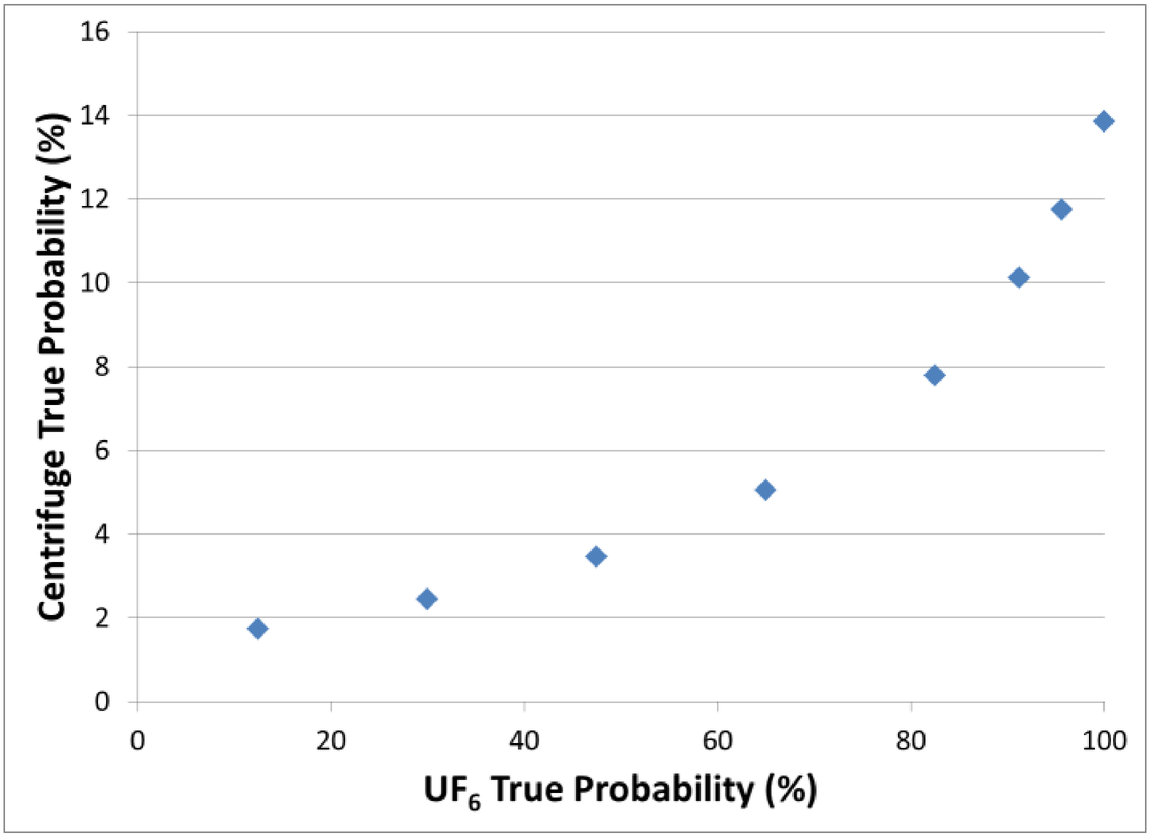


Figure 3-18. Alterations in UF_6 capabilities change proliferating agent gas centrifuge technical success. Reprinted with permission from 75.

In BANE the determination to pursue UF_6 research for proliferation technical success over other uranium enrichment options uses Shannon entropy. Priors in Bayesian inference create data networks. With Shannon entropy the "information content" is analyzed to determine relationships between a specific option / BANE node and the range of additional choices / remaining BANE nodes. The node with the greatest information content uncertainty, relative to the node of interest, matters most when using Shannon entropy.

A proliferating agent applying resources towards mastering a proliferation pathway node in one time step reduces the overall information content uncertainty. Certain proliferation pathways become relatively more favorable, and the information content uncertainty on nodes down the proliferation chain increase. Conversely, other proliferation pathway options become less advantageous and their information content uncertainty declines. The declining information content uncertainty is linked to the diminished benefit of selecting those pathways for achieving the desired proliferation objective. Therefore, the Shannon entropy methodology allows for intelligent agent identification of the BANE proliferation network nodes with the greatest technical success impact.

An advantage of Shannon entropy is its reversibility ease. Proliferating agents with an objective can determine the BANE nodes most valuable for attaining their goals. Defensive agents can employ the same Netica API Parser technical “success” functions with Shannon entropy for ascertaining the best BANE nodes to hinder, reverse, or dismantle proliferation networks. Keeping the same BANE Shannon entropy technical success methodology for all applicable agent classes helps prevent biasing for proliferation or counter proliferation.

Netica API Network Adjustment

The Netica API Parser is the BANE focal point for agents, since it performs agent dictated alterations of Netica .dne files. Agents can interface with other modules, such as the SQL Server or Optimization Solver, but the information is still transferred back to the Netica API Parser. Each BANE agent action during a time step relies on the

Netica API Parser for any operation. An illustration of the Netica API Parser importance for coordinating agent specific in BANE is shown in Figure 3-19.

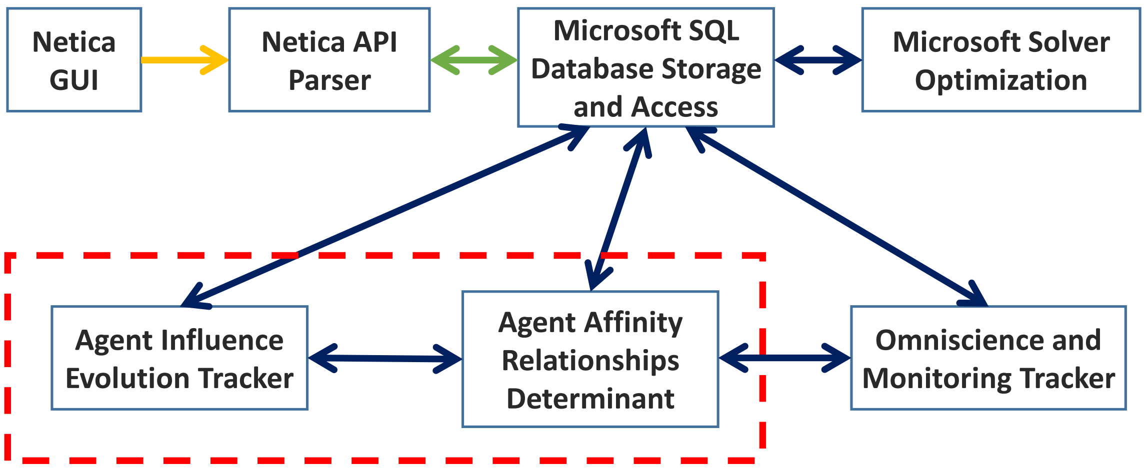


Figure 3-19. Netica API Parser role for directing agent specific information in BANE

The movement of BANE information in Figure 3-19 is for a single agent during one time step. The yellow arrow going from the Netica GUI indicates the interaction is only for the first time step when the starting agent parameters are provided. The green two sided arrow represents the Netica API Parser modules being used to repeatedly ping the other modules groups for ALL time steps. The dark blue two sided arrows represent connections that MAY transfer information during a given time step run depending upon the agent.

An internationally isolated agent might not receive any assistance if its affinity with other agents is low and its influence is further declining. In that situation the affinity and influence modules within the dashed red box from Figure 3-19 would not provide proliferation usable benefits for the agent. Substantial resources and international influence can help insulate a country from resource and detection proliferation restrictions. Over a short time span, a wealthy and well-connected proliferating agent can ignore resource and detection “Optimization Solver” requirements. The “Omniscience and Monitoring Tracker” modules are designed for defensive agents checking proliferating agent progress.

Once the agent has selected the needed modules the information is routed through the agent specific SQL databases and concentrated in the Netica API Parser. The Netica API wrapper translates the new data into means for adjusting the agent .dne file. An example of Netica API Parser control considers the case of an agent deciding to pursue indigenous proliferation research on a node. Upon agent node selection functions with Netica commands are selected that take inputs such as agent research capabilities in the desired area. The node probability for technical success being true is then adjusted based on the research formula inputs.

During a single time step for an agent, the Netica API Parser modules might operate iteratively several times. The agent starts by using Shannon entropy to decide on the node with the best technical success. However, the first choice node might be rejected due to resource limitations. For the subsequent iteration, the next best node is infeasible because it raises the proliferation detection level to an unacceptable level. Finally, a permissible node is selected by the agent. Updating the .dne file occurs with the Netica API parser modules; and, BANE progresses to the next agent or time step.

III.C.3. SQL Server Access and Storage

Creating a BANE architecture designed for handling thousands of agents with different classes, types, postures, competencies, etc. required a robust information storage system. SQL provides a means to store, access, and update the large databases required for fully exploring BANE capabilities. SQL Server is the Microsoft program for using SQL to interface with databases and is integrated within BANE.

The importance of SQL is shown in Figure 3-19 for BANE agents. Several different agent parameters and attributes are stored in SQL databases. Table 3-XII breaks down a few of the key SQL database data sub-sections associated with agents in BANE.

Table 3-XII. Agent data kept within SQL databases

Agent Information	Affinities	Node Levels
Agent ID	Allegiance	Node CTC
Agent Type	Security	Resources
Agent Posture	Economic	Detection Probability
Agent Goals	Political	
Agent Goal Levels	Religious	

Initial agent information is contained within one SQL database as indicated in Table 3-XII. Also, the starting agent objectives and success thresholds are in SQL databases and loaded to start simulations. Across a broader spectrum the unique agent abilities, affinity tables, etc. are all handled through SQL databases. A first generation BANE basic database for the extrapolation of technical success is shown in Table 3-XIII for the UF_6 node.

Table 3-XIII. Database table for initial node technical success extrapolation

ID	Field1	Field2	Field3
1	AlteredNode	true	false
2	UF6	0.1	0.9
3	UF6	0.2	0.8
4	UF6	0.3	0.7
5	UF6	0.4	0.6
6	UF6	0.5	0.5
7	UF6	0.6	0.4
8	UF6	0.7	0.3
9	UF6	0.8	0.2
10	UF6	0.9	0.1
11	UF6	0.95	0.05
12	UF6	0.975	0.025

Interpolation ranges for individual node alteration of attributes, such as resource requirements, can rely upon SQL databases for storing the large data quantities. The database frameworks are all repeatable, but the specific BANE node values are adjustable. Without SQL databases, or some other model like HDF5, holding agent specific parameters and attributes BANE could only handle very generic agents. Unique data storage is necessary for creating agent granularity to gain benefits from ABM and MAS paradigms.

The SQL access and data manipulation modules are designed for use with as many databases tables as possible. Interfacing with agent operational modules, as described in Figure 3-19, makes the SQL databases modules information nexus even when no changes are made to them. Modules performing multiple SQL database interactions decrease BANE code complexity.

Beyond similar data employment within agent types, SQL modules allow different agent types to often use the same database tables. Keeping as uniform a data framework ensures computational equality between agent types. One agent type is not allowed to unintentionally make more decisions simply based on different rules for database access.

III.C.4. Optimization Solver

Historical proliferation efforts show intelligent proliferator decision making being pursued. Agent optimization in the BANE paradigm informs proliferation choices in an analogous manner. First generation BANE efforts centered on the proliferating agent seeking the highest technical success probability for a major nuclear weapons program. A 100% barrier was implemented for the proliferating agents. Still, there are additional historical precedents for proliferators greatly exceeding their initial nuclear weapon program budgets. Adding to the nuclear weapons budget means national resources are potentially removed from other productive enterprises like economic growth or conventional military operation. Short term, negative implications of adding to the nuclear weapons program may be minimal. Over an extended timeframe the degraded economic growth or weakened conventional capabilities could decrease the proliferator's national security, prestige, and influence.

The optimization process allows agents to select proliferation pathways while weighing multiple constraints. The linkage in BANE between economic resources and proliferation technical success probability is demonstrated in Figure 3-20. The 100% threshold in Figure 3-19 represents the notional budget available for the proliferator's national defense. The allocated proliferation resources clearly affect the ability of the proliferator to reach its nuclear posture. Therefore, BANE shows the compromises being made by a proliferator to satisfy national security and economic importance connections. The trade-off dynamics play an integral role in identifying and understanding potential proliferator responses under various conditions.

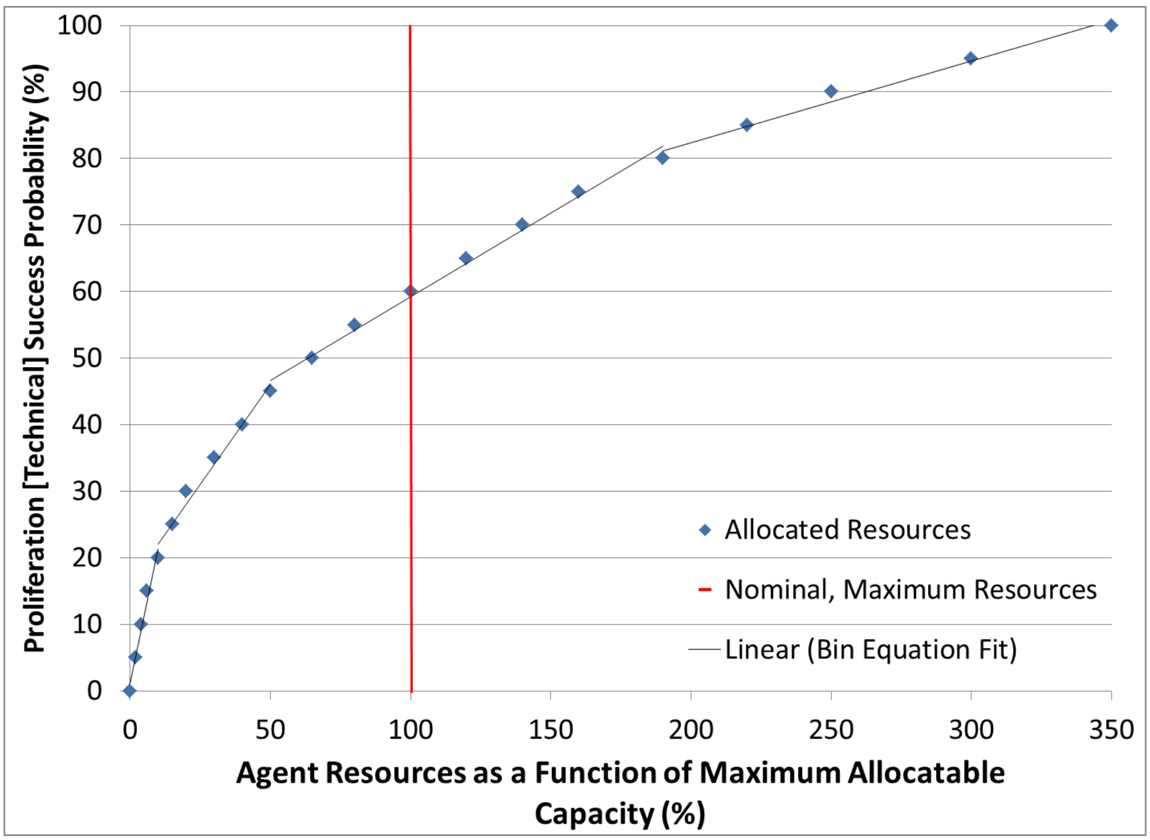


Figure 3-20. Proliferation technical success for a proliferating agent based on resource allocation. Reprinted with permission from 75.

The BANE optimization solver module uses a linear programming based method. Handling different proliferation success regions was accomplished through breaking the technical success sections into "bins." Linear best fits were taken over each "bin" section and passed to the solver as articulated in Table 3-XIV. Figure 3-20 makes the optimal, 60% technical success probability apparent, provided the proliferator does not exceed the nominal 100% resource allocation level.

Table 3-XIV. Linear optimization bins for ABM resource and detection interference

Bin	Agent Resource Allocation Capacity [%]	Linear Equation for Proliferation Technical Success Probability [%]	Bin	Category	Probability of Detection by Outside Agent [%]	Linear Equation for Proliferation Success Probability Considering Interference [%]
1	$0 < x \leq 10$	2.0x + 1.1	1	Conceptual	$0 < x \leq 10$	-0.17x+100
2	$10 < x \leq 50$	0.6x + 16	2	Lab Scale	$10 < x \leq 40$	-0.29x + 100
3	$50 < x \leq 190$	0.25x + 34	3	Pilot Scale	$40 < x \leq 70$	-0.64x + 110
4	$190 < x \leq 350$	0.12x + 58	4	Small Covert Production	$70 < x \leq 98$	-1.2x + 150
			5	Large, Overt Production	$98 < x \leq 100$	-17x + 1700

The proliferation detection, and associated interference, probability for defensive agents is shown in Figure 3-21. Outlining a major assessment benefit from the interaction between proliferation and defensive agents helps indicate BANE's analytic nonproliferation utility. Counter proliferation entities possess several means of identifying proliferation including wide area and localized environmental sampling, multiple intelligence assets, etc. As a proliferating agent progresses through nuclear weapon programs stages (e.g. conceptual, lab scale, pilot scale, small covert production, or large overt production) the defensive agent detection opportunities grow. Table 3-XIV indicates the "bin" category linkage between proliferating agent nuclear weapon program stages and the associated defensive agent detection probability. Nuclear proliferation intuition is again satisfied by BANE. More successful nuclear proliferation activities incur heightened exposure to counter proliferation efforts.

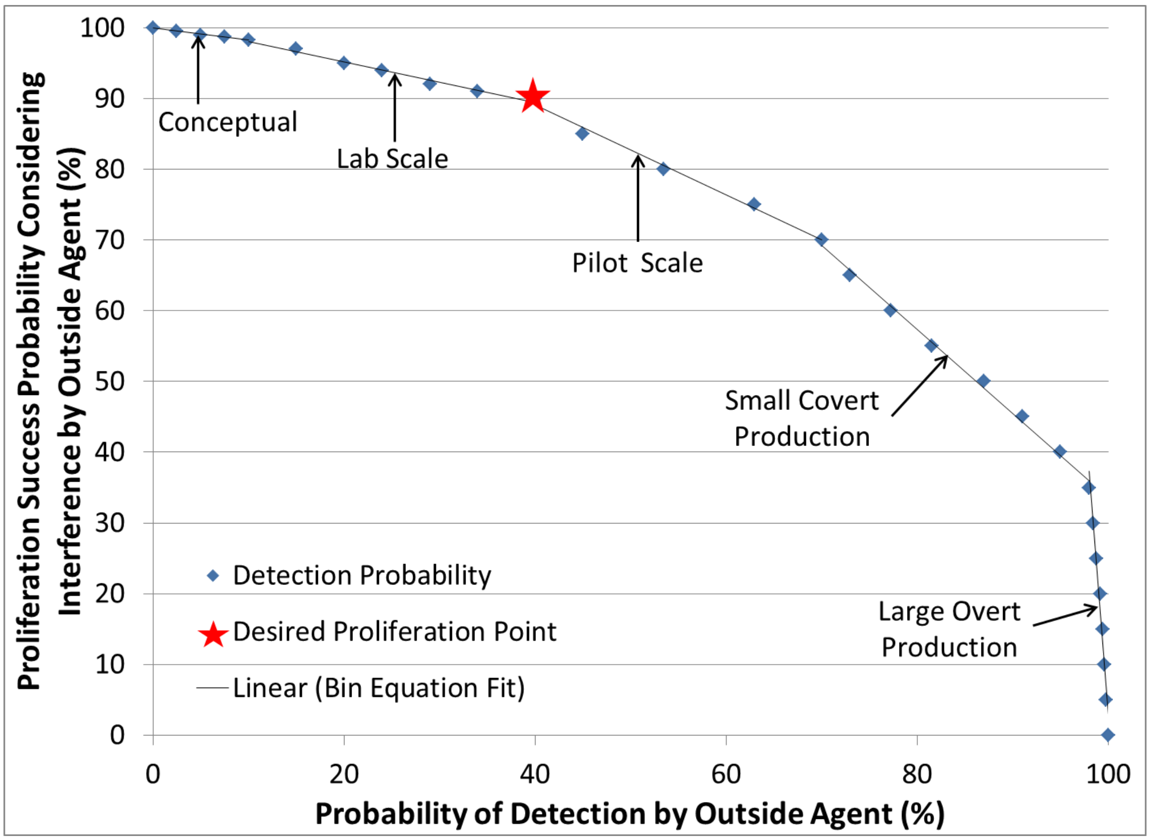


Figure 3-21. Defensive agent interference considerations for a proliferating agent. Reprinted with permission from 75.

In the early BANE methodology, defensive agents discovering proliferation operations have a particular intervention probability. The proliferation level attained by the proliferating agent when discovered will play a major driving role in future versions of BANE for the defensive agent response. Advanced proliferation activities will yield more vigorous, and multi-pronged, defensive agent efforts to roll back, or outright eliminate, nuclear weapons programs. Therefore, all proliferation decisions under the BANE framework have a corresponding risk if located by a defensive agent.

The example in Figure 3-21 is for a BANE scenario with a proliferating agent seeking pilot reprocessing or uranium enrichment facilities. Such a nuclear weapons program objective results in a 40% chance the defensive agent ascertains the existing proliferation. The BANE corresponding incurred proliferation risk probability from defensive agent interference is 10%. Defensive agent intervention might encompass economic, political, or potentially military responses. The assessed proliferation advancement, along with the defensive and proliferating agent rapport, will also affect how the defensive agent attempts to intervene.

In BANE, the first option for handling proliferation detection along a pathway, D_{Path}, focused on using the largest single detection probability, D_i. The detection probability of the largest single time step could be used to define the proliferation signature for a defensive agent. The initial pathway detection probability is:

$$D_{Path} = \max\left(D_i\right) \qquad 3\text{-}1$$

However, Equation 3-1 failed to consider the implications of defensive agent proliferation pattern recognition. The next level of proliferation pathway analysis used a form of time based learning. A product formula for proliferation learning was explored. With the product formula, the defensive agent develops increased proliferation awareness the longer the identified proliferation program is in existence. The equation form for the product detection probability formula is:

$$D_{Path} = 1 - \prod_{i=1}^{j} \left(1 - D_i\right) \qquad 3\text{-}2$$

The increased intelligence attributed to the defensive agent for Equation 3-2 aided in developing and improving BANE realism. A proliferator might decide early in the lab scale stages to pursue research with application for multiple proliferation pathways. Two explored proliferation routes are shown in Figure 3-22 that suit the proliferator nuclear weapon objective.

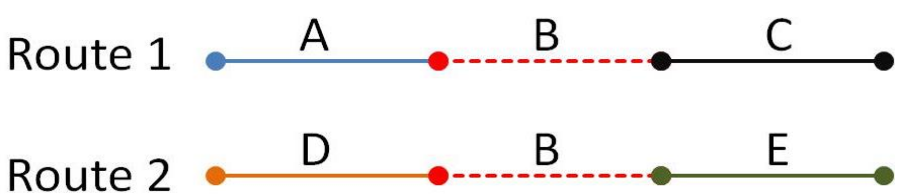


Figure 3-22. Proliferation pathway with step commonality

The common step in routes 1 and 2 for Figure 3-22 represent proliferation hedging behavior. Table 3-XV shows the advantage of Equation 3-2 when a proliferator is hedging by pursuing proliferation pathways with a technical step in common.

Table 3-XV. Multiple proliferation step detection progress

Proliferation Pathway	Detection Probability	Non-Detection Probability
Path A - Centrifuge Rotors	0.20	0.80
Path B - Uranium Hexafluoride	0.30	0.70
Path C - Magnetic Bearings	0.40	0.60

Aggregate Proliferation Assumption	Aggregate Detection Probability
Single Pathway Analysis	0.40
Simultaneous Pathway Analysis	0.66

The uranium hexafluoride (UF_6) research has application to route 1 for gas centrifuges and also for gas diffusion research along route 2. The higher aggregated detection probability with Equation 3-2 makes the defensive agent more effective at proliferation suppression in the Figure 3-22 case. If a defensive agent can avoid stove pipes and share obtained proliferation information effectively it will more closely resemble knowledge governed by Equation 3-2. However, in a highly data sectioned environment decreased defensive agent abilities will manifest as illustrated by Table 3-XV. The defensive agent then functions as though Equation 3-1 represents its proliferation detection probability.

The linked proliferating and defensive agent relationship modeled in BANE is done in Figure 3-23. The resulting analysis of how the defensive agent can curtail proliferating agent proliferation technical successes is illustrated. Initially the technical success probability limitation, shown by the red dashed line in Figure 3-23, impedes the proliferator. In the BANE scenario the proliferating agent attempts to reach the highest proliferation technical success probability. However, the proliferating agent activities attract defensive agent awareness when establishing its small, covert SNM transformation facility. The defensive agent coercing influence then renders the proliferating agent expending 100% of its available proliferation resources, as shown by the Figure 3-23 red vertical line, less valuable. The constrained maximum optimal technical success probability is 55%; therefore, the intelligent proliferating agent would only seek to deploy 83% of its proliferation resources.

The defensive agent prevented proliferation region lies underneath the solid black lines in Figure 3-23. The proliferation prevented region is a function of defensive agent proliferation assessment capabilities. When the defensive agent interference line has a higher probability over a range than the technical success probability alone would indicate, a forbidden region exists.

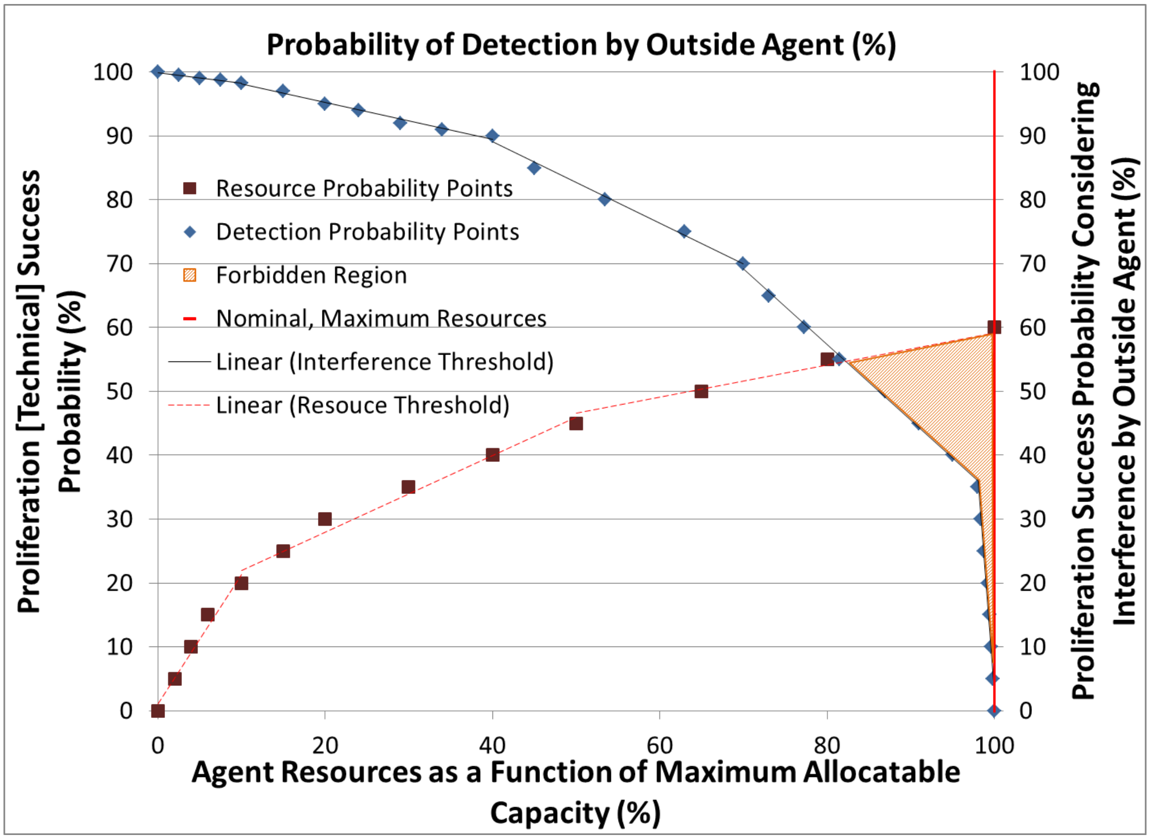


Figure 3-23. Interaction between proliferating agent preferences and defensive agent intervention for optimal nuclear proliferation scenario for proliferating agent. Reprinted with permission from 75.

In Figure 3-23 the BANE indicated forbidden region is represented by a dashed orange shape. Were the proliferating agent to enter the forbidden region its nuclear program would face rollback from the defensive agent. A constrained proliferating agent is less likely to generate a regional nuclear arms race, for instance; and, thus the counter-proliferation role played by a proactive defensive agent is highlighted using BANE.

III.C.5. Uncertainties

Nuclear proliferation predictions are fraught with uncertainty for proliferators, counter proliferation entities, and drawn in neutral agents. An adage often attributed to Albert Einstein is, “If we knew what we were doing it wouldn’t be called ‘research,’ would it?” Forecasting progress on intricate research coupled with potentially diffuse contributors operating to avoid drawing scrutiny is far from precise. BANE uncertainty modules are designed to emulate real world information gaps throughout nuclear proliferation programs.

Simulations in BANE can operate in deterministic mode or with varying uncertainty levels and methodologies. The level affects the number and type of agent decisions that use the BANE uncertainty modules. The two current BANE uncertainty methodologies are random range and Gaussian in nature. Figure 3-24 lays out the relationship between range and Gaussian uncertainty distributions used in BANE.

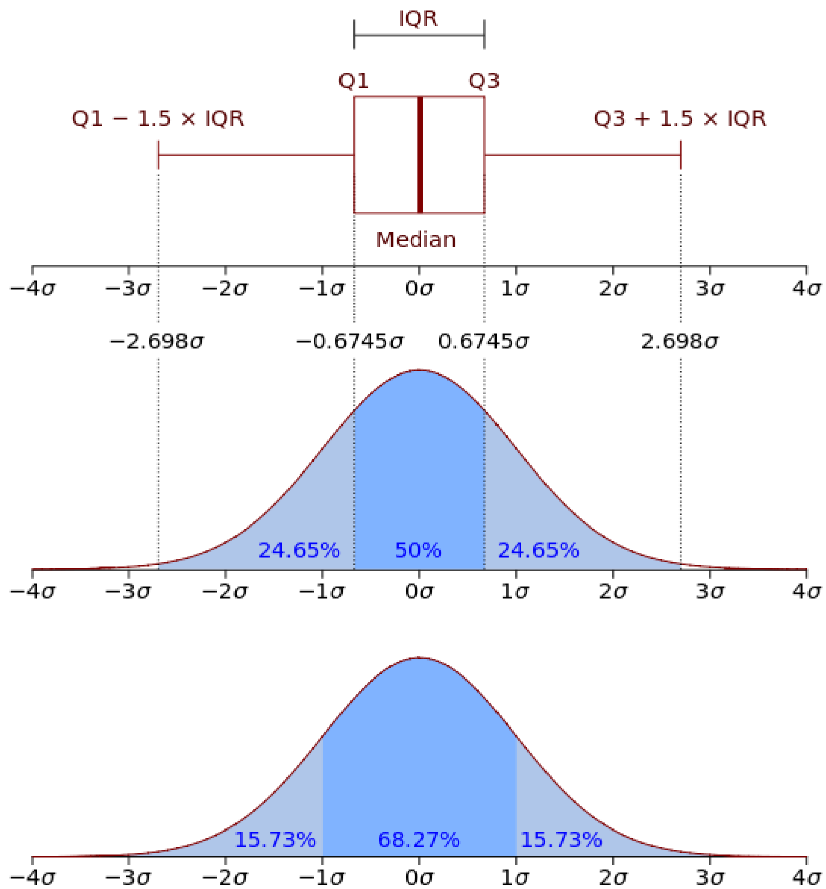


Figure 3-24. Uncertainties with boxplot and Gaussian distribution[80]

The top of Figure 3-24 shows a box plot with a central, deterministic value and an interquartile range (IQR). Within BANE, the uncertainty range methodology is used like the IQR as a bounding measure. Depending upon the agent, the same research might lead to higher or lower capabilities similar to enlarged boxplot whiskers.

The middle and bottom portions of Figure 3-24 are Gaussian distribution with the same mean value. The shaded Gaussian distribution regions correspond to the probability density function (PDF) for a given standard deviation, σ. Integrating PDFs with smaller σ yield lower probability values within the range. In the middle Figure 3-24 portion the integrated dark region is less than for the bottom portion. Using the smaller middle portion bound darker region instead of the bottom bound darker region in BANE corresponds to less uncertainty. With the BANE uncertainty modules the agent variations in action certainty have major proliferation repercussions.

Before embarking on a covert nuclear weapons program, a proliferator may believe a high research rate is sustainable. Only later will the proliferator realize additional progress will entail much higher resource and / or intellectual capital allocation. Conversely, a proliferator might run into indigenous proliferation R&D hurdles leading to its discouragement. The dejected proliferator could turn to SNA or pursue other less effective pathways rather than attempt to persevere down the pathway with only domestic means. When nearing completion of a research area, the proliferator might also face the risk of greater detection than expected during the initial project phases. Accurate awareness of potential technical hurdles in clandestinely acquiring nuclear material would shift proliferator decision making.

With a better understanding of proliferation challenges alternative pathways might have been followed years or decades earlier. For instance, pursuing latent deterrence can involve longer nuclear weapon time horizons. Enlarged resource cost and knowledge base breadth for pursuing civilian nuclear infrastructure is a potential downside for latent deterrence. When hedging against future security threats the increased technical success and diminished international suspicion for nuclear R&D may outweigh the negative latent deterrence concerns. Pairing other justifications, such as economic or political self-sufficiency arguments, with security threats can enhance proliferation attractiveness. The implications of leadership failures for all entities related to nuclear proliferation efforts is illustrated in Figure 3-25.

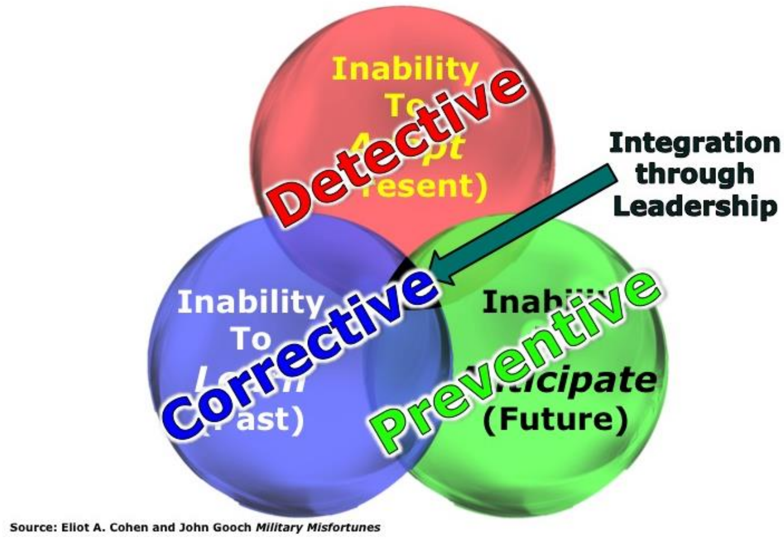


Figure 3-25. Leadership failures and associated remedies[81]

Effective leadership, and associated planning and mitigation strategy, is harder to marshal when confronting black swan type events. BANE uncertainty modules help incorporate strategic proliferation and counter proliferation planning while considering the Figure 3-25 leadership challenges. Relative to military and national security challenges, successful nuclear weapon development pathways could receive black swan classification. Particularly if new or unexpected scientific R&D was applied to circumvent expected and largely accepted proliferation protection barriers.[82] Allowing BANE simulations to fluctuate agent research and affinity connection investments through uncertainty propagation can aid in bounding rarer proliferation events. The accumulation of rare events in BANE simulations can mirror occurrences like multiple intelligence snippets not being aggregated to determine terrorist or state activities.

Nuclear proliferation models tend to treat proliferation leadership as possessing an “inability to learn” from past events. Historically this is not the case, and circumstances that led to early proliferation efforts rejecting EMIS for uranium enrichment might differ for a later proliferator. Another example is proliferators favoring certain types of gas centrifuge designs based on choices such as technical achievement, individual ego, and pride motivations.[83] In BANE, agents perform “corrective” learning by looking first at the technical and physical limitations for proliferation.[84] Other limitations such as resource needs are then considered.

Including uncertainty effects for most modules justified BANE maintaining proliferation network history. Agents facing unexpected, and seemingly insurmountable, proliferation system challenges gain a measure of credit for past proliferation choices. Detective agent work in BANE takes place as agents assess the best remaining proliferation decision fork along their chosen proliferation pathway. This adaptive BANE behavior is highlighted by the uncertainty modules creating non-linear variation in encountered proliferation challenges.

Historical inspiration for BANE agent decision methodologies was also instrumental for laying out the uncertainty modules’ operation. The expert Prussian military strategist Helmuth von Moltke coined the phrase, “no plan survives contact with the enemy.”[85] Therefore, the role of superb leaders is attempting to anticipate plan perturbations, their associated outcomes, and means to mitigate consequences. BANE addresses von Moltke's concerns by using uncertainty modules to create a range of options for counter proliferation decision makers to understand the impacts of their decisions. The anticipative nature and risks of BANE agent hedging also touches on von Moltke's quote, "strategy is a system of expedients." Technically and politically the grand strategy of obtaining or hindering proliferation advancements turns on operational and tactical choices. Proliferation uncertainties likely alter how operations and tactics are executed using a different set of constraints governing their optimization.

III.C.6. Affinities and Influence

No single individual can perform all the steps needed to create and deliver a nuclear weapon with a high order yield. A proliferating entity that is a state can perform all those tasks, but thousands of individuals are involved throughout the nuclear fuel cycle and militarization process. Relying on assistance outside the proliferating state, even if just for intellectual capital or raw materials, can significantly speed up nuclear weapon acquisition. A major BANE justification is capturing the affinities driving relationships between agents and how the influence wielded over each other changes with time.

Table 3-XII in the SQL database section indicates the allegiance, security, economic, political, and religious affinities categories agent can possess. For the affinity categories the BANE affinities modules have cooperation and animosity triggers. Agent affinity levels range from 0 to 10. Not all affinities are black and white and involve outright cooperation or affinity. Therefore, affinities have sub-categories which enable

nuanced agent postures. A breakdown of several affinities into sub-category used in the SQL database tables are shown in Table 3-XVI.

Table 3-XVI. Agent affinity sub-categories

Allegiance	Political	Religion
United_States	Liberal_Democracy	Muslim_Sunni
Russia	Capitalist_State	Muslim_Shia
China	Socialist_State	Chrisitan_Catholic
Pakistan	Socialist_Liberal	Christian_Protestant_A
France	Communist	Officially_Agnostic

BANE modules handle the affinity sub-categories based on creating real world approximations. Depending upon the affinity category, a level 0 sub-category affinity may represent absolute hostility or a refusal to trade. A level 10 sub-category affinity represents an overwhelming desire to interact. The specifics of sub-category affinity meanings are addressed with the following affinity category discussions.

The allegiance affinity stemmed from individuals having citizen, businesses being headquartered or having major operation locations, and governments ideally having geographic boundaries. Several major state sub-category allegiances used in BANE simulations are listed in Table 3-XVI. Agents sharing the same allegiance will cooperate until the affinity level is below 2. Allegiance represents the nationalism, regulations, family and friendship ties, values, and other normative factors that elicit adherence to governmental rules and objectives.

The security affinity covers issues such as alliances, state based relations, and non-state actor perceptions of the international environment. Security oriented demand side proliferation drivers and threats motivate proliferating and counter proliferation agents to seek a wider range of cooperative assistance. BANE couples demand side drivers to new supply side proliferation opportunities from affinity connections. Sub-categories for security are absent from Table 3-XVI because many security relationships can exist simultaneously and they are not necessarily mutually exclusive. Letters represent security alliance sub-categories, and agents then join or leave security alliances. Agents can also oppose particular security alliances and exhibit antagonistic behavior towards agents with high affinity levels for that sub-category.

Modern international trade is predominately driven by economics. Corporation and individual monetary persuasion susceptibility to engage in proliferation is captured in BANE. Even government entities face budgetary pressures. Except in dire national security circumstances, government agencies base their actions on fiscal resources. Economic sub-categories are straight-forward and affinity interactions occur once trigger levels representing sufficient monetary resources are present.

Historically, political and ideological alignments were strongly tied to nuclear assistance. Following the Cold War ending, security and economic rationales have eclipsed political affinities for nuclear cooperation with military dimensions. Particularly when tracing past ties for successful nuclear proliferation, BANE module consideration of ideological affinities is a crucial feature. Political sub-categories from Table 3-XVI are currently designed for constructive engagement. When a level of affinity towards the shared ideology is reached the agents will work together.

Non-state agents definitely share religious connections that bring them into contact and incline them to work with each other. For states, asserting pure religious nuclear connections devoid of strategic concerns is more tenuous. Whether those connections enable vis-à-vis facilitate usable nuclear assistance is more debatable. However, BANE provides the means to consider religion induced nuclear cooperation. The religion affinity sub-categories in Table 3-XVI operates with agents belonging to a single sub-category. The constructive affinity trigger system is then used when determining if shared religious beliefs are sufficient for cooperation.

A series of nuclear proliferation graphics are shown starting with Figure 3-26 for a normal, base example. The example series affinity category is generic and uses only constructive trigger thresholds.

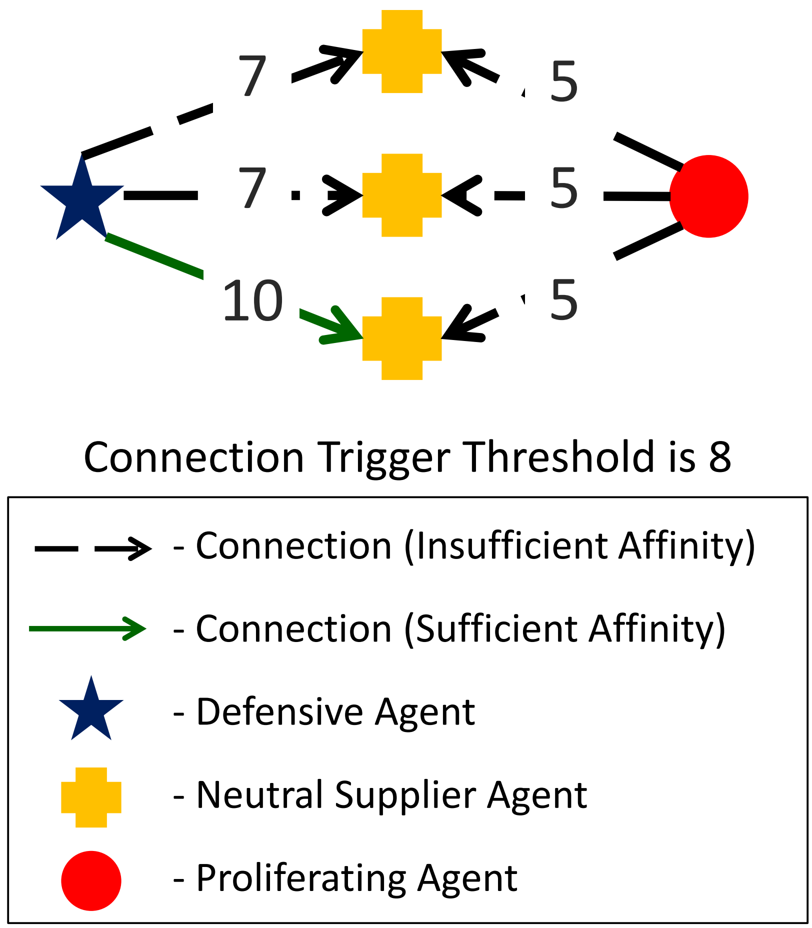


Figure 3-26. Base affinity connections

In Figure 3-26 the defensive agent has a strong affinity connection with the bottom neutral supplier agent. The existing level 10 affinity connection between the defensive and bottom neutral supplier agents cannot be broken in BANE. Even if the proliferating agent reaches a level 8 affinity the neutral supplier agent will not provide nuclear assistance. At the time the top and middle connection affinities favor the defensive agent over the proliferating agent.

Over several time steps the role of influence on BANE modules affinities grows in importance. If the proliferating agent influence is rising they can allocate influence to establishing a connection with the top or middle defensive agent in Figure 3-26. Although the defensive agent initial affinities are higher, careless monitoring and / or declining influence can prevent the defensive agent from first reaching the level 8 connection threshold. A strong proliferator situation in Figure 3-27 poses greater challenges for a defensive agent.

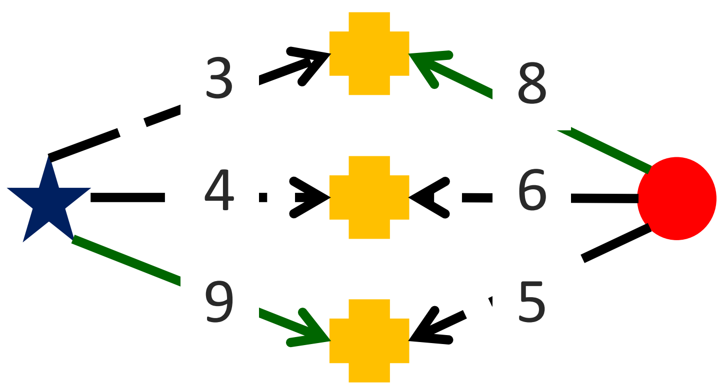


Figure 3-27. Strong proliferator affinity connections

Against a high level proliferator, a lower level defensive agent can be over matched on affinity and influence counter proliferation. The strong proliferating agent in Figure 3-27 has an affinity connection with the top neutral supplier agent. The defensive agent retains its affinity with the bottom neutral agent. However, for the middle neutral agent the strong proliferating agent holds the affinity advantage for reaching the connection trigger first. Conversely, a weak proliferator example version is shown in Figure 3-28.

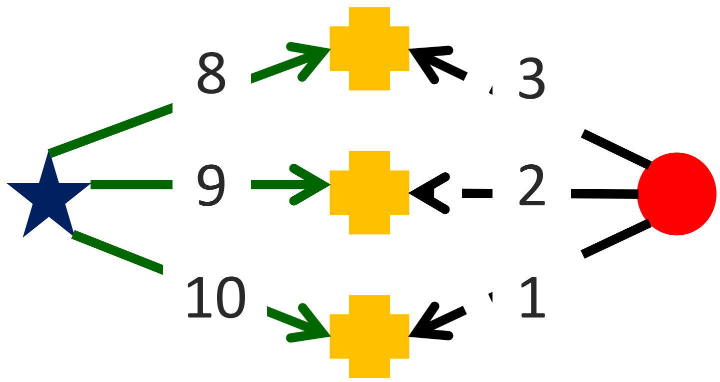


Figure 3-28. Weak proliferator affinity connections

In the weak proliferator example from Figure 3-28, the proliferator is outclassed on affinities for all three neutral agents shown. An international pariah that is a nuclear proliferator would have a network more closely approximating Figure 3-28. BANE affinity and influence modules using SQL database tables can keep thousands of proliferation associations mapped out. A weak proliferator in BANE can seize the chance for obtaining an affinity connection if presented the opportunity. Realistically, BANE is still tracking the limited number of opportunities for the proliferating agent to build international contacts.

Figures 3-26 to 3-28 indicated the substantial nuclear proliferation implications of affinity relationship diversity and strength. Higher affinity levels provide proliferating agents more chances to achieve technical success through resource and information acquisition from connections. The nonproliferation capabilities of defensive agents are severely strained by proliferators with strong affinity bonds. Traditional defensive agent advantages such as political and economic pressure are mitigated by active and passive assistance to the proliferator. The proliferation technical success of several proliferators analogous to those depicted in Figure 3-26 to 3-28 are shown in Figure 3-29.

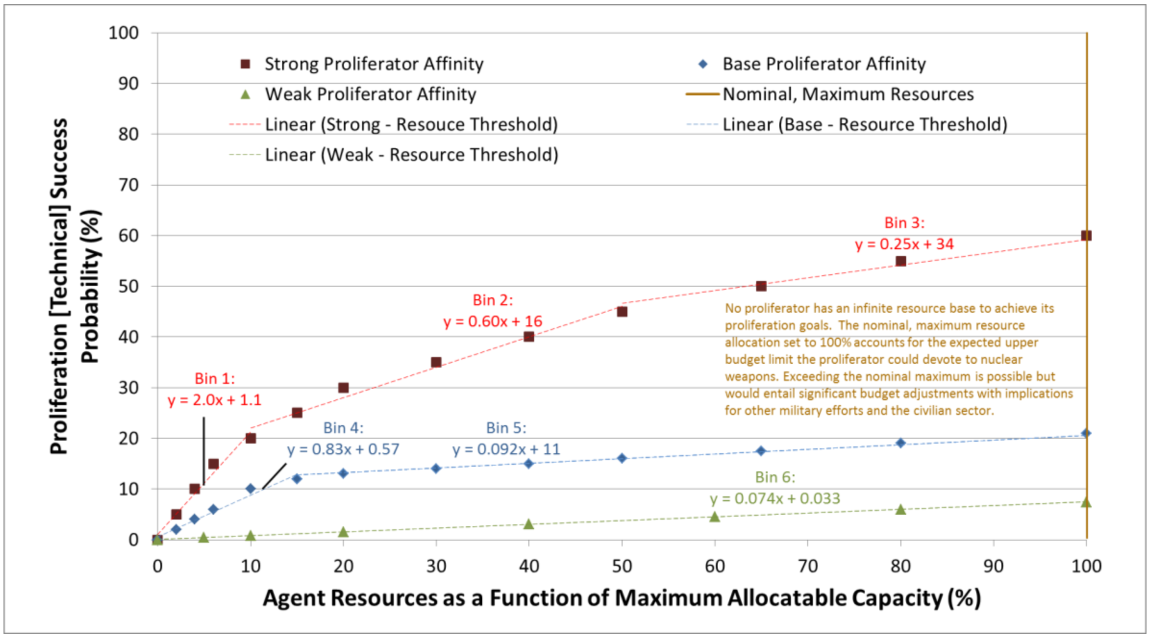


Figure 3-29. Proliferator technical success with affinity inclusion

A proliferator with significant access to global nuclear suppliers and deep research connections will pursue one set of proliferation paths. Figure 3-29 indicates how technical barriers are more readily countered by a proliferator with strong international affinities. Proliferators suffering more limited worldwide connections depend on indigenous research resources. For similar states, the lack of global resources in BANE is shown in Figure 3-29 to result in diminished nuclear proliferation progress.

III.C.7. Omniscience and Monitoring

The BANE omniscience and monitoring modules were designed specifically to capture counter proliferation defensive agents challenges. In BANE the omniscience and monitoring modules rely heavily upon linkages to other modules as shown in Figure 3-19. Perturbations from provided BANE module information then shape defensive agent decisions. The BANE operational flow diagram in Figure 3-1 indicates defensive agents are responsive by nature to proliferating agent activities.

Defensive agent monitoring efficiencies in BANE differ significantly depending upon its resources and technological prowess, proliferation efforts being uncovered, etc. Taking corrective action against unknown proliferation is very inefficient for defensive agents. Therefore, defensive agent preferences focus on first expending substantial effort on identifying proliferator pathways.

To enhance realism defensive agents suffer time delays in acquiring proliferating agent network information. Once proliferating efforts are detected the defensive agents still must analyze the signatures. The intelligence processing cycle the BANE omniscience and monitoring modules approximate is shown in Figure 3-30 from the Federal Bureau of Investigation (FBI).

Figure 3-30. FBI identified intelligence collection cycle[86]

The generation of Netica .dne proliferation network time histories is central for defensive agents. Although the .dne files have visualization roles, the BANE omniscience and monitoring modules restrict the access time. The FBI Figure 3-30 intelligence collaboration cycle provide a means of rating defensive agent proliferation attentiveness. Efficient intelligence efforts with superior proliferation recognition and exploitation competencies aid some defensive agents in lessening the proliferation awareness time delay gap.

In the optimization solver section, the defensive agent proliferation hindering shown in Figures 3-21 and 3-23 is for deterministic cases. Realistically, proliferation networks obtained by defensive agent have uncertainties. With BANE the uncertainty module configuration is adjustable for each defensive agent. When using the BANE omniscience and uncertainty modules together there are two main determinants of uncertainty. First, the level of proliferating agent openness and counter intelligence. Second, the defensive agent intelligence sources and capabilities. Several intelligence collection parameters impacting defensive agent omniscience limitation are provided in Table 3-XVII.

Table 3-XVII. Counter proliferation intelligence collection sectors

Intelligence Method	Cost	Technical Difficulty	Access Difficulty
Human Intelligence (HUMINT)	Low	Low	High
Signals Intelligence (SIGINT)	Medium	Medium	Medium
Imagery Intelligence (IMINT)	High	High	Low
Measures and Signature Intelligence (MASINT)	High	High	Medium
Open Source Intelligence (OSINT)	Low	Low	Low

The uranium enrichment proliferation progress example using Figures 3-7 and 3-16 can demonstrate defensive agent monitoring practices. A defensive agent can possess the proliferator uranium enrichment proliferation network in Figure 3-7. After a monitoring campaign, the defensive agent can acquire updated the more recent Figure 3-16 proliferation network. The available Table 3-XVII intelligence collection methods help dictate the defensive agent Figure 3-16 acquisition delay. When parsing the new network the defensive agent recognizes a preference for gas centrifuge uranium enrichment based on detected magnetic bearings and bellows research.

The BANE omniscience and monitoring modules are also integrated into the affinities and influence modules. A defensive agent with intelligence gathering difficulties might confront several proliferators that appear stronger in narrow areas. The affinity situation in Figure 3-27 could then occur as a subset of the existing international connections where the defensive agent is particularly vulnerable. A more powerful defensive agent, or coalition of defensive agents, confronting a proliferator would more closely approximate Figure 3-28.

III.D. Justification of BANE Modular Development and Upgrade Potential

BANE was developed using a modular paradigm for creating an ABM and MAS nonproliferation assessment computational ecosystem. Entities involved in proliferation are not monolithic; but, rather proliferation involves collections of individuals simultaneously working together or at odds to achieve a set of objectives. ABM facilitates granular agent definitions.

The BANE foundation is the Netica Bayesian inference methodology. The original static Bayesian inference proliferation assessment models were built using the Netica GUI. However, BANE really became modular and dynamic when the Netica API based wrapper modules were created. The Netica API modules allowed agents to modify the Netica .dne files underlying the Netica GUI proliferation models.

Intelligent agents make multiple decisions informed by the best proliferation information available to them. With modules each major type of intelligent decision making can be sectioned off for independent testing and exploration within BANE. New ways to further define agent choices lead to the development of additional linked modules. Agents can consider data across a range of categories such as resource expenditures versus detection risks to select the best proliferation posture suiting their goals.

In BANE the modules were developed with the goal of being agent reusable to reduce computational loads. SQL interface modules access and alter database tables that store a wide range of information types. Agent predictions and accessing information on other agents incurs uncertainty penalties. Cooperation and animosity between agents is governed by affinity and influence modules. Omniscience and monitoring modules capture defensive agent realism struggles for ascertaining and addressing proliferation.

Upgrades across all BANE modules in response to new proliferation or counter proliferation technologies and methods is easily performed. Emerging proliferation technologies can be added to the Netica .dne proliferation network files using the Netica GUI or Netica API text configuration. Handling uranium-233 proliferation pathways is an upgradable BANE possibility. New technologies and associated signatures for pyroprocessing proliferation can be incorporated into BANE to expand its utility.

Counter proliferation decision makers will always face being caught by a black swan proliferation event. An upgradable BANE tool will let them explore how different international treaty engagements, technology controls, and monitoring regimes can reduce proliferation risks. Policy and technical analysts can contribute to BANE improvements by providing module input in the area of expertise.

III.E. BANE Tiered Operations and Input Data

BANE is currently built and run using Microsoft Visual Studio 2013 and SQL Server Management Studio 2012. Proprietary software such as the Netica API and GUI is used for the Bayesian inference BANE core. However, there are no restrictions on owning the Microsoft products or Netica. The cost of Visual Studio and SQL Server is not prohibitively high. The low educational, or even commercial, costs of the Netica API and GUI should not be major barriers for more open source BANE contribution and development.

Including a wide array of social science, nuclear and related technical experts, and machine learning specialists will definitely benefit BANE upgrades. Global proliferation awareness varies significantly between entities. With BANE, proliferation system information is used to tune agent, and in turn simulation, fidelity. Developing and enhancing BANE decision making mechanics requires nothing more than readily available proliferation reports. Allowing a broad range of code developers to enhance BANE is another option.

Tiered operation of BANE is possible for users with proprietary information. Different paths forward could happen for those BANE users. They could directly develop specialized BANE modules that meet their specific needs. A partnership with a BANE developer could allow the funding entity to direct module additions by providing guidance on a range of future needs. It would then be the BANE developer's job in the partnership to provide newly empowered BANE modules. If appropriate some of the developed BANE modules, but probably not the input information, would be made available to a wider audience. The sharing of upgrade modules will help maintain the BANE nonproliferation ecosystem.

CHAPTER IV

AGENT EMPOWERING BANE MODULES IN ABM CONTEXT

Technical success varies based on the agent class and their desired nuclear proliferation, or nonproliferation, posture. This is fundamental to BANE. Intelligent agent actions are a requirement of ABM and provided modularly within BANE. Technical decision making is linked to the calculations agents make in other modules regarding real world proliferation trade-offs.

IV.A. BANE Agent Technical Success Decision Making

The field of information theory evolved from communication theory proposed by Claude E. Shannon in 1948.[87] Information theory began as a means to determine information content attributes along the lines of data compression, storage, and communication.[88] Two integral parts of information theory are Claude Shannon's entropy measure for a random variable's information content and the area of mutual information between random variables. Shannon entropy, or just entropy, quantifies information compression and associated uncertainty. Mutual information considers rates of information exchange.

Numerous fields have employed cutting edge information theory and research. Several major areas include economics, social sciences, intelligence, communications, electronics, and nuclear engineering. Within the nuclear engineering field, one application of information theory is improving fuel cycle material flows for possible reprocessing extraction candidates associated with repository loading schemes.[89] For

BANE agent technical success decisions, entropy reduction and mutual information are valuable and complementary information theory aspects for proliferation analysis.

IV.A.1. Shannon Entropy and Mutual Information Based Technical Success

The BANE Bayesian inference network approach for managing agent technical progress is based on physics defined proliferation constraints. Agents make decisions by considering their perceptions for achieving technical success meeting their objectives. Proliferation pathways evolve as aggregated agent decisions introduce more data indicating proliferation intentions and corresponding key technology investments. The additional information reduces the entropy associated with a particular agent goal being achieved. The Netica GUI and APIs can be configured for entropy reduction through mutual information determinations of the Netica network node proliferation relationships.

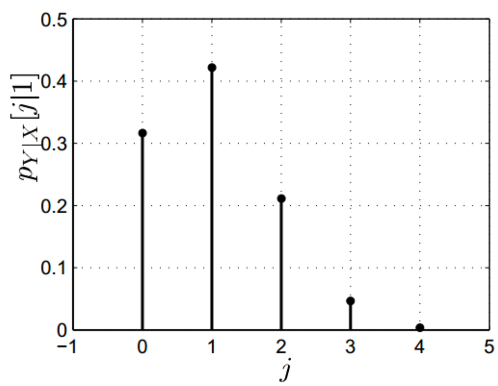
Shannon Entropy Overview

The probability and statistics basis of entropy meshes well with the BANE Bayesian inference framework for guiding agent technical success choices. Entropy, H, can be written in a generic form that is the foundation of more advanced entropy equations used in BANE. The general entropy equation is:[90]

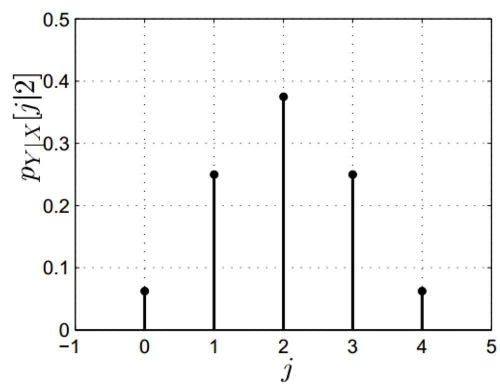
$$\mathrm{H}(X) = E\left[I(X)\right] = E\left[-\ln\left(p_f(X)\right)\right] \qquad 4\text{-}1$$

where A is a discrete random variable with state mapping values $\{x_1, \ldots, x_{\|X\|}\}$ and probability mass function (PMF), p_f (X); expected value operator, E; and, information content, I, comprising the discrete random variable information content.

Equation 4-1 introduces formatting useful for entropy information processing. Random variables that are discrete have set value ranges that lend themselves to PMFs. Continuous random variables, by contrast, require probability density functions (PDFs). In information theory, the emphasis on a "particular" random variable's uncertainty under specific different conditions lends itself to using PMFs.[91] Two different PMF sets are shown in Figure 4-1 for the probability of variable Y with respect to variable X.



(a) $i = 1$, $p_1 = 1/4$



(b) $i = 2$, $p_2 = 1/2$

Figure 4-1. Probability mass functions.[91]

PMFs cannot have negative probabilities for any discrete state and the summation of all states must be 1. A straight forward PMF example for any side x of a fair six sided dice X is:

$$p_X\left(x_i\right)=\begin{cases} 1/6, & x\in\{1,2,3,4,5,6\} \\ 0, & x\notin\{1,2,3,4,5,6\} \end{cases} \qquad 4\text{-}2$$

In Equation 4-2 the PMF $p_X(x_i)$ differs from $p_f(X)$ because $p_X(x_i)$ is the PMF for a single discrete state, x_i. The $p_X(x_i)$ dictates that for any of the six dice sides, 1 through 6, there is a 1/6 probability any particular side turns up. The bottom part of Equation 4-2 defines the sample space being only 1 through 6. Since no other option is available the PMF is zero everywhere else outside the sample space. A PMF can contain the information content for a random variable with the form:

$$I\left(X\right)=-\log_b\left(p_f\left(X\right)\right) \qquad 4\text{-}3$$

The $\log_b$ in the Equation 4-3 is the generic form used in Equation 4-1 for information content. Using ln is based on the assumption of a natural logarithm base. Other logarithmic bases, such as binary with a b = 2, are valid. The entropy thus maintains a functional relationship with a random variable PMF or other distribution. The expectation value for information content in X is encompassed by:

$$E(X)=\sum_{i=1}^{\infty}x_i\,p_X\left(x_i\right) \qquad 4\text{-}4$$

For n evenly distributed possible events, like the six sided fair dice, $\{x_1, \ldots, x_{\|n\|}\}$ the probability is 1/n. The entropy uncertainty, u, needed to define the set of n outcomes for x is:

$$u = \log_b(n) \tag{4-5}$$

In BANE, entropy and uncertainties stack on each other. The additive property of logarithms makes combing Equation 4-5 event uncertainties possible. If the uncertainty associated with m evenly distributed possible events is pooled with n events then:

$$u = \log_b(nm) = \log_b(n) + \log_b(m) \tag{4-6}$$

Decomposing the uncertainty for a single event yields the surprisal, u_i.[92] The surprisal for a single event in a uniform set is defined as:

$$u_i = \log_b\left(\frac{1}{p_X(x_i)}\right) = -\log_b\left(\frac{1}{n}\right), \ \forall i \in \{1, \ldots, n\} \tag{4-7}$$

Another form of Equation 4-7 is needed to handle non-uniform events. The surprisal for a single non-uniform event is:

$$u_i = -\log_b\left(p_X(x_i)\right) \tag{4-8}$$

For a lower probability $p_X(x_i)$, the result is $p_X(x_i) \to 0$. This causes higher uncertainty and surprise leading to $u_i \to \infty$ for event x_i. The average outcome set uncertainty is $< u >$:

$$\langle u \rangle = \sum_{i=1}^{n} p_X(x_i) u_i = -\sum_{i=1}^{n} p_X(x_i) \log_b\left(p_X(x_i)\right) \tag{4-9}$$

The derivation for individual and aggregate entropy and information content uncertainty is needed for defining more advanced entropy equations forms. When formulating his entropy theory, Shannon proved the exchangeable nature of information entropy and uncertainty.[93] The explicit entropy using Equation 4-1 can be written as:[94]

$$\mathrm{H}(X) = -\sum_{i=1}^{n} p_X(x_i) I(x_i) = -\sum_{i=1}^{n} p_X(x_i) \log_b p_X(x_i) \quad \text{4-10}$$

The joint entropy of the discrete random variables X and Y are:[95]

$$\mathrm{H}(X,Y) = -\sum_x \sum_y p_{X,Y}(x,y) \log_b \left(p_X(x,y) \right) \quad \text{4-11}$$

In Equation 4-11 $p_{X,Y}(x,y)$ is a joint PMF (JPMF), sometimes called a joint probability distribution function. The JPMF captures the probabilities for the combined state possibilities when considering multiple discrete variables together. The additive property of independent random variable entropy builds on the logarithmic additive property from Equation 4-6. The entropy additive form follows:

$$\mathrm{H}(X,Y) = H(X) + H(Y) \;\; \mathit{if} \;\; p_{XY}(x,\mathrm{x}) = \mathrm{p}_X(x)\,\mathrm{p}_Y(\mathrm{y}) \quad \text{4-12}$$

For a set of variables X_1 to X_n, the joint entropy is greater than or equal to any of the individual, X_i, entropies:

$$\mathrm{H}(X_1, \ldots, \mathrm{X}_n) \geq \max\left[H(X_1), \ldots, H(X_n) \right] \quad \text{4-13}$$

The joint entropy is less than or equal to the summation of individual, statistically independent variables entropies:

$$\mathrm{H}(X_1, \ldots, \mathrm{X}_n) \leq \sum_{i=1}^{n} H(X_i) \quad \text{4-14}$$

Conditional entropy is based on the joint entropy definition. The entropy conditional probabilities link to conditional Bayesian analysis for two independent, and discrete random variables X and Y. The information required to determine variable X's state given the state of variable Y is the conditional entropy and given by:

$$\mathrm{H}\left(X \mid Y\right) = H(X,Y) - H(Y) \qquad \text{4-15}$$

Rewriting the conditional entropy Equation 4-15 using the PMF definition of entropy in Equation 4-10 yields:

$$\mathrm{H}\left(X \mid Y\right) = \sum_{y \in Y} \sum_{x \in X} p_{X,Y}\left(x, y\right) \log_b \left(\frac{p_Y\left(y\right)}{p_{X,Y}\left(x, y\right)} \right) \qquad \text{4-16}$$

The conditional Bayes probability in Equation 2-6 for knowing A if B is known is very similar to Equation 4-16 for conditional entropy. The similarities between the two probability types is fundamental to why using entropy reduction can inform agents within a BANE Bayesian framework.

Mutual Information Overview

The mutual information, I, is a relationship of the information content shared between two or more variables. For discrete random variables X and Y the mutual information is:

$$I\left(X;Y\right) = H(\mathrm{X}) - H(X \mid Y) \qquad \text{4-17}$$

Constraints on Equation 4-17 include I(X; Y) = I(Y; X) and I(X; Y) ≥ 0. Mutual information can be used almost synonymously with entropy reduction. Therefore, mutual information can be written as:

$$I\left(X;Y\right) = \sum_{y \in Y} \sum_{x \in X} p_{X,Y}\left(x, y\right) \log_b \left(\frac{p_Y\left(y\right)}{p_{X,Y}\left(x, y\right)} \right) \qquad \text{4-18}$$

Mutual information quantifies the average reduction in uncertainty for X once the value of Y is learned. Conversely, mutual information relates the average information amount X provided regarding Y. Conditional mutual information allows for large data relationship interdependences to be analyzed. Understanding the conditional mutual information of X and Y based on a third random variable Z in an entropy context is:

$$I\left(X;Y\,|\,Z\right)=H(\mathrm{X}\,|\,\mathrm{Z})-H(X\,|\,Y,Z) \tag{4-19}$$

The three variable conditional mutual information can be rewritten in Equation 4-18 format using JPMFs:

$$I\left(X;Y\,|\,Z\right)=\sum_{z\in Z}\sum_{y\in Y}\sum_{x\in X}p_{X,Y,Z}\left(x,y,z\right)\log_b\left(\frac{p_Z\left(z\right)p_{X,Y,Z}\left(x,y,z\right)}{p_{X,\mathrm{Z}}\left(x,\mathrm{z}\right)p_{\mathrm{Y,Z}}\left(\mathrm{y,z}\right)}\right) \tag{4-20}$$

The conditional mutual information in Equation 4-20 still holds I(X: Y|Z) ≥ 0 as a requirement. The mutual information format I(X; Y|Z) may be modified only by adding conjunctive linkages in any location occupied by X, Y, or Z. Consider I(X, Y; U, V | Z, W) as a case in point. I(X, Y; U, V | Z, W) relates the average information U and V indicated for X and Y, carrying the assumption of knowing Z and W. Figure 4-2 provides a physical representation of the overlaps between entropy and mutual information.[96]

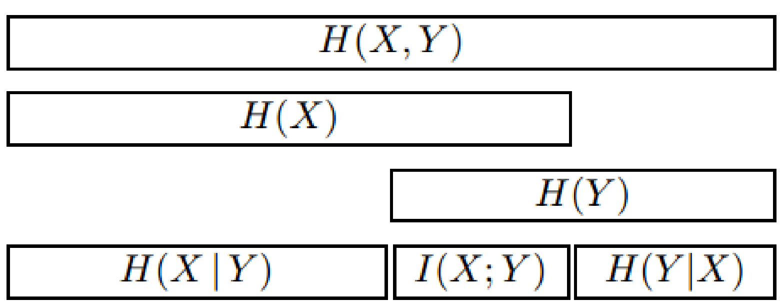


Figure 4-2. Entropy and mutual information overlap.[96]

The overlay from Figure 4-2 indicates how joint entropy for X and Y can be defined using single variable entropy, conditional entropy, and mutual information. The Figure 4-2 entropy equation overlaps mirror those for Bayesian probabilities. The similarity is particularly strong for conditional entropy and probability.

Agent Entropy and Mutual Information Guidance in BANE

Entropy and mutual information are integral to BANE agents' proliferation and counter proliferation decision making. From a BANE technical perspective, a major entropy reduction advantage is its consistency for positive or negative correlations. Assessing primarily the connection relationships between physics grounded technical nodes facilitates proliferating and defensive agents sharing the same technical selection methodology. The uranium enrichment pathways example is useful for understanding scientific determinants and their associated mutual information as they relate to proliferation options. A schematic for uranium enrichment nodes at a higher level is presented in Figure 4-3.

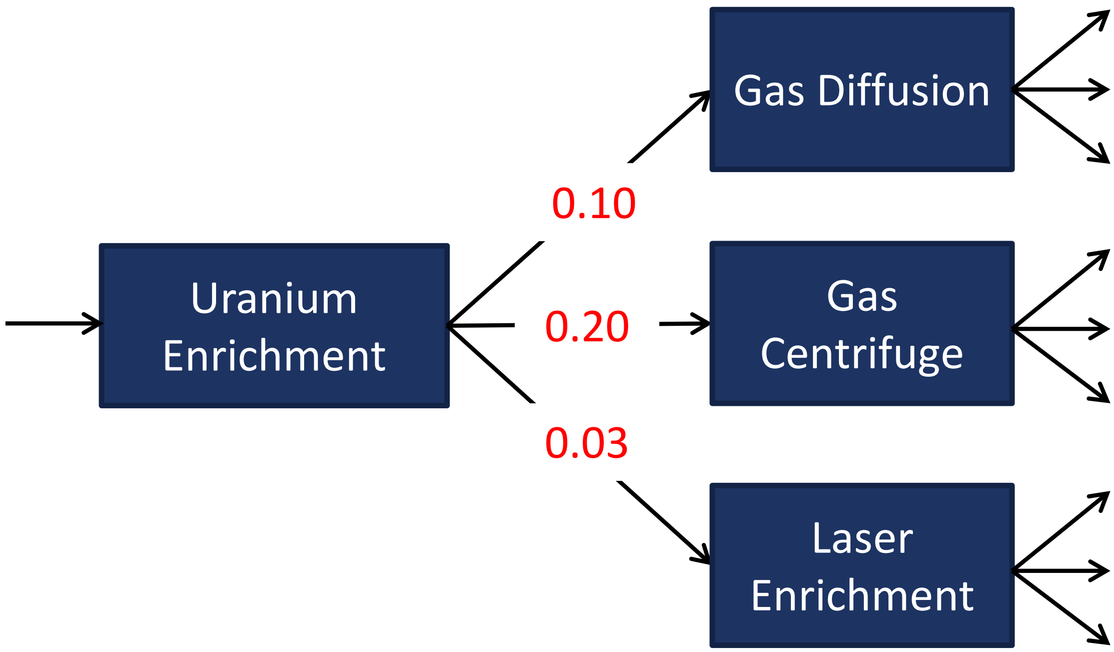


Figure 4-3. High level proliferation network level mutual information example

In Figure 4-3, an agent uses mutual information for assessing the pathways for a nuclear weapon acquisition. The proliferation network example shows the relationship that the uranium enrichment routes provide relative to the nuclear weapons acquisition objective. The mutual information values are not probabilities; and, therefore the values do not sum to 1.0. Other proliferation pathways options not shown in Figure 4-3 have mutual information values that balance the gas diffusion, gas centrifuge, and laser enrichment values shown.

Generally, but not always, the parent nodes have and higher mutual information levels than their children unless they are on a separate proliferation pathway branch. Intuitively this makes sense because Netica Bayesian network parent nodes are influenced by their children. However, to achieve mastery of a parent nodes means some set of children nodes were obtained.

The BANE uranium enrichment subset, in Figure 3-7 is used for illustrating actual Bayesian inference technical success options; and, the network subset is also applicable as an example of entropy and mutual information. In Figure 3-7 the proliferating agent exhibits a preference for pursuing gas centrifuges. Several moderate affinity assistance transfers in the laser enrichment realm shift the proliferator probability and entropy values. Figure 4-4 shows the Netica visualization perspective, and associated probability changes, from the laser enrichment probability assistance.

In the Netica visualization section III.C.1, Figure 3-16 shows how grey Netica nodes indicate network changes. The increased proliferator capabilities shown in Figure 4-4 illustrate the higher proliferation likelihood with laser enrichment over the time steps with laser enrichment technology transfers. Correspondingly, the gas centrifuges and the other enrichment technologies all declined. Table 4-1 indicates the entropy reduction for the top 25 proliferation network nodes for Figure 3-7 and Figure 4-4. The rule for mutual information values being real numbers between 0 and 1 was followed in Table 4-I.

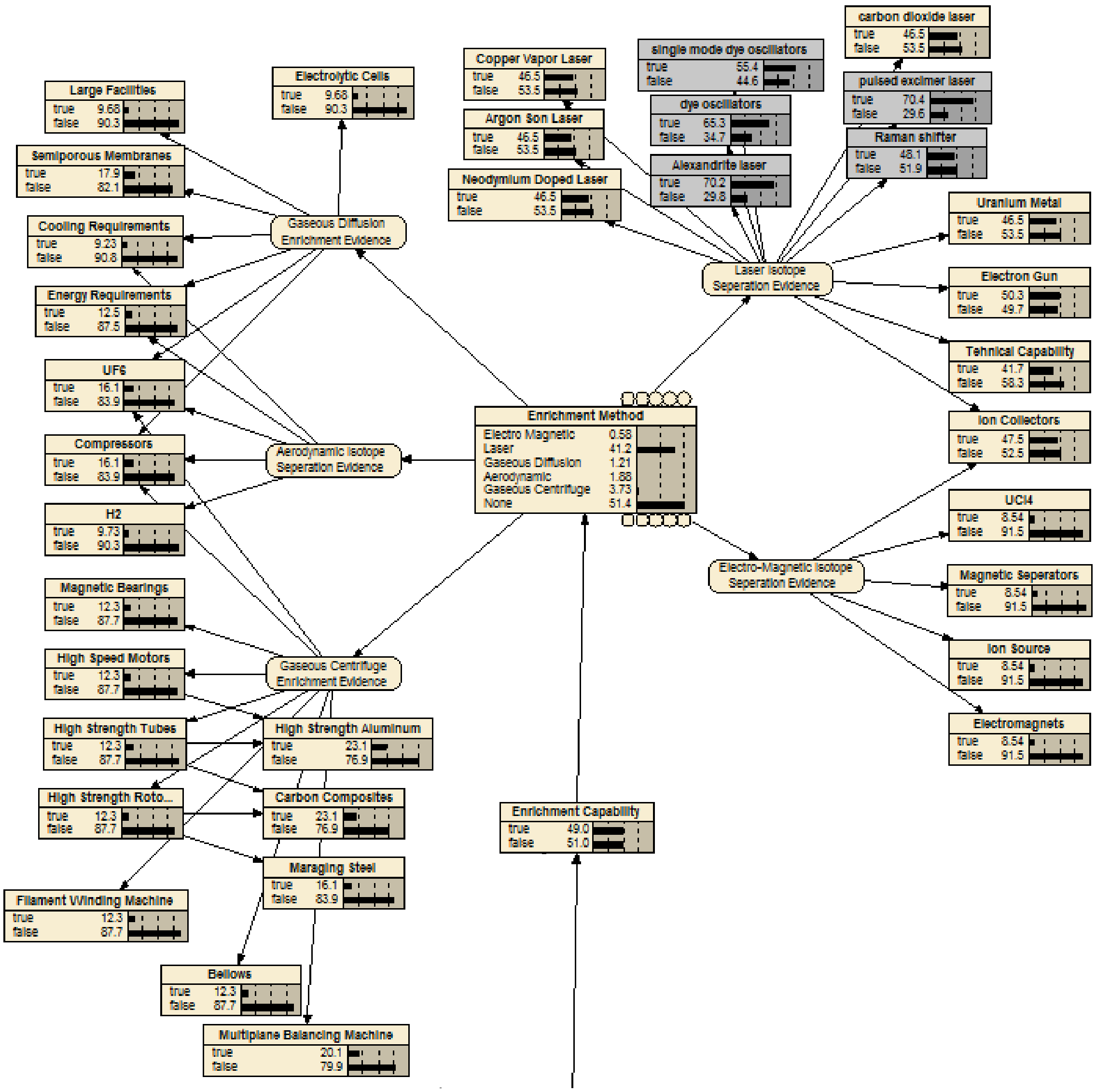


Figure 4-4. BANE uranium enrichment network entropy and mutual information overlap

With Figure 3-7 the proliferator is in the initial nuclear weapon program stage and favors gas centrifuge uranium enrichment. The first section in Table 4-1 is for the Figure 3-7 situation where the agent seeks a latent deterrent uranium enrichment program. The technical nodes having the highest mutual information for the Figure 3-7 scenario are weighted towards gas centrifuges, as shown in Table 4-I. The second section of Table 4-1 contains the mutual information for the Figure 4-4 laser enrichment latent deterrent case. The highest mutual information technical nodes in the second section of Table 4-1 are heavily slanted towards those further sustaining laser enrichment.

Capturing real world variations amongst and between individuals, corporations, NGOs, and governments to the greatest possible extent improves BANE fidelity. Increasingly accurate data connections lead to improved BANE mutual information ties. If a proliferator and a defensive agent were exactly matched across all areas a stalemate would occur with the proliferation frozen in place. However, “exact” equality occurring across proliferation affecting resources, forecasting or executing indigenous research, international connections, and counter proliferation skills is virtually impossible.

Areas such as agent internal and external uncertainty on awareness and capabilities meld well with mutual information decision making. Coupling mutual information and uncertainty randomization, for instance, can create incorrect agent perceptions causing sub-optimal choices. The problem of incorrect data linkages plagues both individuals and powerful government agencies. When the stakes are nuclear proliferation with the associated military, economic, and political costs, the wrong information assessments have profound regime and national security implications.

Table 4-I. Proliferation network entropy change following affinity technology transfer

Number	Netica Proliferation Node	Proliferation Base Case Mutual Information	Netica Proliferation Node	Post-Laser Enrichment Transfers Mutual Information
1	UF6	0.25081	Laser Isotope Separation	0.66664
2	Compressors	0.25081	Tehnical Capability	0.63161
3	Gaseous Centrifuge Enrichment	0.20622	Ion Collectors	0.48285
4	Aerodynamic Isotope Seperations	0.09774	Argon Son Laser	0.47764
5	High Speed Motors	0.09206	carbon dioxide laser	0.47764
6	High Strength Tubes	0.09206	Uranium Metal	0.47764
7	Bellows	0.09206	Copper Vapor Laser	0.47764
8	Filament Winding Machine	0.09206	Neodymium Doped Laser	0.47764
9	Magnetic Bearings	0.09206	Raman shifter	0.44375
10	High Strength Rotors	0.09206	single mode dye oscillator	0.32392
11	Maraging Steel	0.06722	dye oscillators	0.21283
12	Energy Requirements	0.06432	Alexandrite laser	0.17011
13	Gaseous Diffusion Enrichment	0.06147	pulsed excimer laser	0.16844
14	Cooling Requirements	0.05644	Electron Gun	0.05783
15	Carbon Composites	0.04838	Gaseous Centrifuge Enrichment	0.03944
16	High Strength Aluminum	0.04838	UF6	0.02128
17	Multiplane Balancing Machine	0.0364	Compressors	0.02128
18	H2	0.03166	Aerodynamic Isotope Seperations	0.01964
19	Electro-Magnetic Isotope	0.02901	Gaseous Diffusion Enrichment	0.01254
20	Large Facilities	0.01425	High Speed Motors	0.00809
21	Laser Isotope Separation	0.00461	High Strength Tubes	0.00809
22	Ion Collectors	0.00451	Magnetic Bearings	0.00809
23	Magnetic Seperators	0.00411	Bellows	0.00809
24	Electromagnets	0.00411	Filament Winding Machine	0.00809
25	UCl4	0.00411	High Strength Rotors	0.00809

IV.A.2. Netica Cases for Agent Information

A powerful Netica GUI and API feature for agent decision making involves Netica "Cases". With Netica Cases, agents can assess the associations between technical components along nuclear proliferation pathways. For clarity purposes, the definition of a proliferation pathway is all the knowledge, technology, and equipment needed to achieve a nuclear weapons program goal. Depending upon the proliferation pathway branch, its pursuit can alleviate the need to acquire specific capabilities unique to another proliferation pathway branch. Branches on proliferation pathways may each require several common nuclear or non-nuclear technologies. A simplified uranium enrichment network is illustrated in Figure 4-5 using Boolean logic in a fault tree diagram.

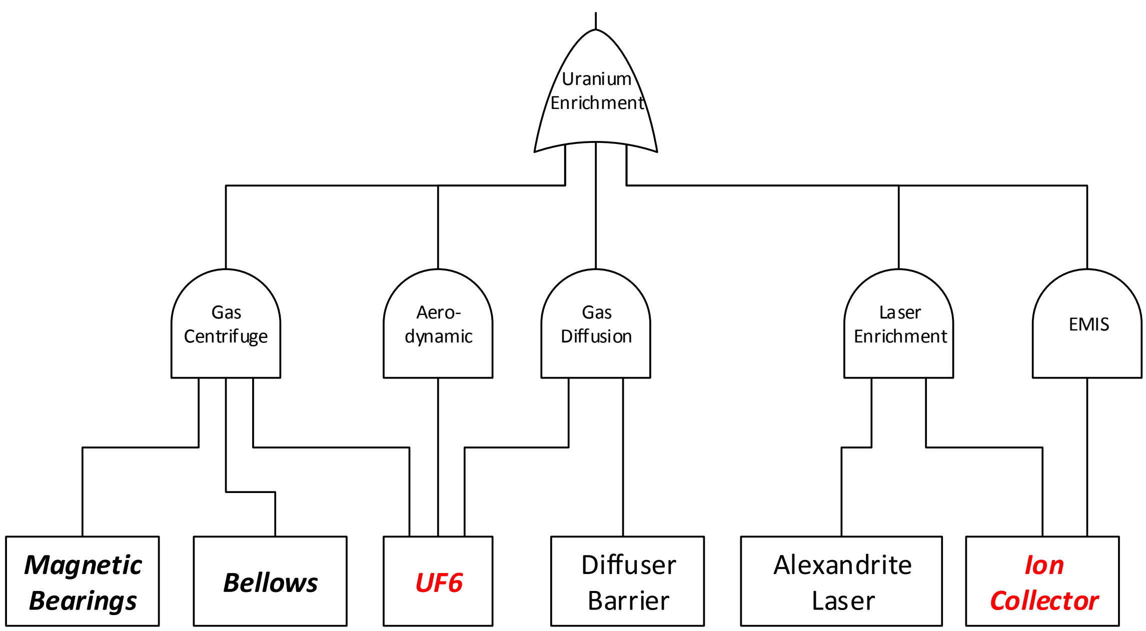


Figure 4-5. Boolean logic fault tree simplification for Netica proliferation network

Figure 4-5 demonstrates the nature of key nuclear proliferation knowledge, technology, and equipment elements. At the top of Figure 4-5 is the uranium enrichment parent gate with 5 children representing possible enrichment methods. Uranium enrichment is an OR gate because a proliferator only needs to possess any one capability to succeed. If a particular aspect of one proliferation pathway is too challenging, then another route might let the agent entirely bypass that hurdle.

Each of the 5 uranium enrichment methods are configured as AND gates. At least two different proliferation aspects are needed for the different uranium enrichment methods to be successful. In actuality, the 5 uranium enrichment methods in Figure 4-5 should be a mixture of AND and OR gates for full Netica network accuracy. Gas centrifuge rotors and tubes can be fabricated using a variety of material feedstock. A number of lasers might be modified and tuned to succeed in creating a selective uranium atom ionization mechanism. However, the children nodes for uranium enrichment depicted in Figure 4-5 are all needed for the particular parent method. This justifies AND gates being appropriate for descriptive purposes.

Some of the Figure 4-5 uranium enrichment bottom level nodes are specific to one uranium enrichment method. These include Magnetic Bearings and centrifuge rotor Bellows which are bolded and italicized. Other nodes that represent proliferation aspects shared between uranium enrichment methods are bolded and italicized, but also noted in red. The shared nodes in Figure 4-5, and especially in the BANE proliferation network, have major proliferation implications by enabling hedging.

When running Cases, Netica relies on the current network equations indicated in section II.B, Figure 2-3. Every possible set of node state arrangements is first defined in Netica based on Netica GUI user or agent Netica API choices. For a Netica Case, the number of possible states, n, for a set with i nodes where each node has m states is governed by:

$$n = \prod_{i=1} m_i \qquad 4\text{-}21$$

Netica then uses the node governing equations to convert the node state probabilities into deterministic node state outcome distributions. The run distributions are tabulated, and if using 100 runs the result is a node state outcome occurrence probability. The occurrence probability for different state arrangements of the bolded and italicized nodes in Figure 4-5 using Netica Cases are shown in Table 4-II.

The Table 4-II example only uses nodes with true or false outcomes; but, Netica Cases work with nodes having more than two states to understand proliferation network technical linkages. For the starting proliferator in Figure 3-7, the most likely outcome is that almost 60% of the time the proliferator fails to master any nodes. A more capable proliferator with an advanced uranium enrichment program or greater resource and technical base would have a lower all false occurrence probability.

Table 4-II. Proliferation forecasting using Netica Cases

Probability (%)	UF6	Ion Collectors	Magnetic Bearings	Bellows
0.633	TRUE	TRUE	TRUE	TRUE
0.121	TRUE	TRUE	TRUE	FALSE
0.121	TRUE	TRUE	FALSE	TRUE
1.235	TRUE	TRUE	FALSE	FALSE
5.791	TRUE	FALSE	TRUE	TRUE
1.025	TRUE	FALSE	TRUE	FALSE
1.025	TRUE	FALSE	FALSE	TRUE
10.436	TRUE	FALSE	FALSE	FALSE
0.069	FALSE	TRUE	TRUE	TRUE
0.711	FALSE	TRUE	TRUE	FALSE
0.711	FALSE	TRUE	FALSE	TRUE
7.277	FALSE	TRUE	FALSE	FALSE
0.557	FALSE	FALSE	TRUE	TRUE
5.747	FALSE	FALSE	TRUE	FALSE
5.747	FALSE	FALSE	FALSE	TRUE
58.794	FALSE	FALSE	FALSE	FALSE

Consideration should be given for a serious nuclear proliferator having no uranium enrichment capability. The proliferator could elect to pursue the plutonium proliferation pathway with natural uranium fuel. Above the Figure 4-5 top level uranium enrichment OR gate would be another OR gate for obtaining SNM. With BANE network expansion, other proliferation routes besides uranium-235 enrichment and aqueous plutonium reprocessing could be added. An example is thorium-232 based generation of U-233 and its subsequent reprocessing.

Returning to Table 4-II, the next most probable occurrence is that only UF_6 mastery is true. Quick inspection of Figure 3-7 or Figure 4-5 shows how UF_6 is used in 3 out of the 5 uranium enrichment methods. A proliferator seeking to hedge proliferation bets can pursue a shared node allowing a quick jump into which ever pathway becomes most enticing. The situational changes that facilitate an eventual pathway selection after hedging include new affinity connections or changes in available indigenous resources or technology. With latent deterrence the hedging option plays a role when comparing technical success to other factors like non-detection. Often the shared technology is foundational to more advanced proliferation research and operation. The basic nature of shared technology can in turn make it harder to associate with treaty or dual usage violations supporting a nuclear weapons program.

After UF_6, the second most likely single outcome from the Table 4-II Case is that only Ion Collectors are present amongst the nodes. As with UF_6, Ion Collectors are important for 2 of the 5 uranium enrichment methods. A proliferator could again hedge by pursuing ion collectors and at a later stage decide whether to go for laser enrichment or EMIS.

The chances of the Magnetic Bearings or Bellows used in gas centrifuges occurring separately is actually slightly less likely than them occurring together with UF_6. For a proliferator pursuing gas centrifuge enrichment the AND gate nature has an impact. Obtaining any of the Magnetic Bearings, Bellows, or UF_6 components alone has far less utility than possessing them all for a gas centrifuge. If the proliferator invests resources in one of the necessary AND nodes not benefitting another pathway, they are "pot committing" to a particular proliferation route. The Magnetic Bearings or Bellows are less likely to appear alone than the UF_6 or Ion Collectors, since they are only applicable to the gas centrifuge proliferation pathway.

The chance of the UF_6 and Ion Collectors showing up together represent a proliferator uranium enrichment hedging at a low level. The occurrence of UF_6 with just Magnetic Bearings or Bellows is the next most possible situation. However, it represents a proliferator committing to obtaining a unique gas centrifuge component but not sufficiently to obtain the other requisite components to master the technology.

For a defensive agent, Netica Cases are also valuable for ascertaining proliferating agent future pathway options. A defensive agent benefits from knowing the Boolean logic fault tree layout for proliferator pathway technical requirements. The key AND gate component bottlenecks represent opportunities for establishing difficult to overcome proliferation hurdles.

Figure 4-5 and Table 4-II indicate how Magnetic Bearings and Bellows are both necessary gas centrifuge constituents. An intelligent defensive agent recognizing this fact could focus on denying the proliferator mastery of a particular technology. Without an AND gate technology the proliferator could not achieve mastery of that proliferation pathway. Focusing on fewer technology, knowledge, or equipment denials is easier for a resource constrained defensive agent to undertake for several reasons. First, a defensive agent might not have the resources or connections to stop a concentrated proliferating agent across all proliferation pathways. By denying a few crucial capabilities, the defensive agent can have an oversized proliferation impact.

Second, in reality a counter proliferation entity cannot declare all areas of global trade banned due to proliferation concerns. Business and economic interests in the country would lobby and use their influence to weaken and circumvent trade restrictions if they became overly restrictive. In addition, there would be a threshold where businesses located in other countries would step in to make sales. At some point the national interests of economic growth and preventing unemployment would override poorly substantiated restraints. National security and alliance preservation can also affect the willingness of states to curtail certain types of trade depending upon the intended recipient. Like a real counter proliferation entity, a defensive agent will have greater success in building counter proliferation coalitions if the banned trade area is tightly focused.

Third, recognizing proliferator investments in hedging technologies can help a defensive agent shift a proliferating agent towards another nuclear weapons program pathway. The shifting can force the proliferating agent to spend more resources or ease the detection on potential partner defensive agent. With BANE tying the demand and supply side proliferation drivers, making the supply side costs greater could shift the demand push. Section I.B discussed how the South Koreans and Taiwanese pulled back from nuclear proliferation under pressure from the United States as a powerful security and economic patron.

IV.B. Optimization for Constrained Agents

Technical success along any step of a proliferation pathway requires economic investments and detection risks over a period of time. Proliferating agents seek optimal solutions balancing these concerns based on their capabilities. Defensive agents use the technical success, resource, detection probability, and time considerations differently in pursuing their defined optimal counter proliferation posture.

Unless acted upon by an outside agent, once technical progress has occurred for a proliferation step it remains available. Along a pathway step, resource allocation, E_i, and detection probability, D_i, attributes are partially cumulative. Resource recovery and memory retention and fading rates vary based on the agent for adjusting resource placement and detection risk accumulation. Allocating resources alters agent proliferation and counter proliferation pursuits based on information loss according to:

$$E_{tot} = \sum_{i=1}^{i=t_{\max}} E_i * w_{E,i} \begin{cases} if \quad i \le C_E, \; w_{E,i} = 1 - y_E * \log_{10}(i) \\ if \quad i > C_E, \; w_{E,i} = 0 \end{cases} \qquad 4\text{-}22$$

In Equation 4-22, i is time increment, t_{max} is maximum time for summation function, $w_{(E,i)}$ is a resource weighting factor, y_E is an agent specific resource factor, and C_E is an associated resource time constant before recovery occurs.

An updated detection probability for contemporary BANE agents takes the proliferation step aggregation and introduces memory loss. The decline in proliferation memory mirrors real world institutional information losses. Proliferation and counter proliferation expert knowledge of past proliferation actions atrophies. Updated detection probability memory retention changes agent proliferation and counter proliferation perceptions based on:

$$D_{tot} = \sum_{i=1}^{i=t_{\max}} D_i * w_{D,i} \begin{cases} if \quad i \le C_D, \; w_{D,i} = 1 - y_D * \log_{10}(i) \\ if \quad i > C_D, \; w_{D,i} = 0 \end{cases} \qquad 4\text{-}23$$

In Equation 4-23, i is time increment, t_{max} is maximum time for summation function, $w_{(D,i)}$ is a detection probability weighting factor, y_D is an agent specific detection probability factor, and C_{D} is an associated detection probability time constant before memory fading occurs.

The time based limitations in Equations 4-22 and 4-23 cover some of the BANE agent specific nuclear proliferation attributes. Several of the real world limitations applicable to proliferating agents are indicated in Table 4-III.

Table 4-III. Proliferating agent challenges and associated implications

Limitations	**Implications**	
	Resource	**Detection**
Proliferation research	Proliferation budget allocation	Produce proliferation signatures
	Money unavailable for other security or economic purposes	Introduce government and private sector fiscal irregularities
Entity economic growth	Proliferation budget trajectory	Proliferation budget indicators are changed
International connections	Alter proliferation expenditures	Corporate and key individual trades and deals emerge
Compulsion and coercion for global assistance	Reduce indignenous proliferation program scope	Hostility and frustration amongst forced entities
	Increase proliferation program financial efficiency	Grudging support

Table 4-III contains factors modifying proliferating agent parameters expressed as variables for Equation 4-22 and 4-23. A major proliferation challenge is that research takes time to yield nuclear and non-nuclear components for a weapons program. The technical success is a function of the different nuclear proliferation resources an agent can call upon. Resources can be allocated to faster proliferation technical success with an associated detection penalty. Simply adding more proliferation resources suffers diminishing returns. More rapid progress may lead to greater proliferation detection

probabilities triggering defensive agent interventions. Still, increasing proliferation budgets can pay proliferation dividends when the proliferating agent economic situation is improving.

Hiding proliferation amongst large volumes of global trade and domestic corporation transactions is easier for a well-connected proliferator. From a probabilistic standpoint, a global pariah has a higher detection chance since fewer interactions must be monitored. A powerful proliferator can also engage in international compulsion on nuclear proliferation. However, there may arise future resource or detection costs that can backfire. The jaded support might have lax communications security and be unconcerned about the proliferation leaking out.

BANE defensive agents using Equations 4-22 and 4-23 will bring unique counter proliferation variable parameter values. Table 4-IV describes several major counter proliferation areas that defensive entities face.

Table 4-IV. Defensive agent challenges and associated implications

Limitations	Implications	
	Resource	Detection
Available budget	Counter proliferation budget allocation	Alters capabilities for assessing different proliferation activities
	Resources focusing on analysis, for instance, cannot be spent on taking action against proliferation	Expending resources is not the same for all defensive acros every counter proliferation area
Entity economic situation	Less bueracratic fighting in budget expansion versus contraction	Fluctuations in different aspects of counter proliferation
Domestic relationships	Funding redundancy and repeating prior research	Counter proliferation methods, technologies, and awareness fails to match funding expectations
International connections	Areas of responsibility allows for lower individual costs	Complementary counter proliferation skill sets are more effective when interests align

A number of defensive agent challenges considered in BANE are described in Table 4-IV. From a defensive agent standpoint counter proliferation research pays dividends in improving abilities to detect, assess, hinder, rollback, and collapse proliferation networks. Better technology may lead to more accurate proliferation information; but, blind faith in the technology can exacerbate incorrect information beliefs. A defensive economic situation can affect whether resources reach critical counter proliferation programs. If the entity the defensive agent belongs to is undergoing economic ascendancy, then even inefficient funding plans can still create counter proliferation gains.

Domestic and international cooperation between defensive agents is not always smooth. Within states, government bureaucracies can expend almost as much effort in turf battles as achieving their missions. Acrimonious relations can degrade the effectiveness of even high levels of counter proliferation funding. International contacts matter for defensive agents because of unique access, skill sets, and capabilities. Alignment can be a challenge for international defensive agent cooperation. Nonetheless, diverse counter proliferation partnerships can extend across more proliferation territory making such programs riskier.

Equations 4-22 and 4-23 are important for understanding how BANE agents optimize multiple proliferation considerations in Tables 4-III and 4-IV simultaneously. Temporal linkages force agents to confront their past choices. This prevents short term risk taking from turning into unrealistic long term BANE simulation benefits. Accurately modeling aspects of the proliferation process aids in drawing appropriate conclusions from BANE.

IV.C. Internal Agent Uncertainties

The BANE uncertainty modules introduce ambiguity in several nuclear proliferation areas. Proliferation and counter proliferation R&D does not proceed at a uniform pace. For a particular agent, the uncertainty modules create fluctuations in progress at any time step. Figure 4-6 demonstrates agent R&D uncertainty impacts by overlaying BANE uncertainty runs at several time steps on a proliferating agent simulation. The uncertainty distribution in Figure 4-6 is Gaussian with BANE operating in deterministic mode.

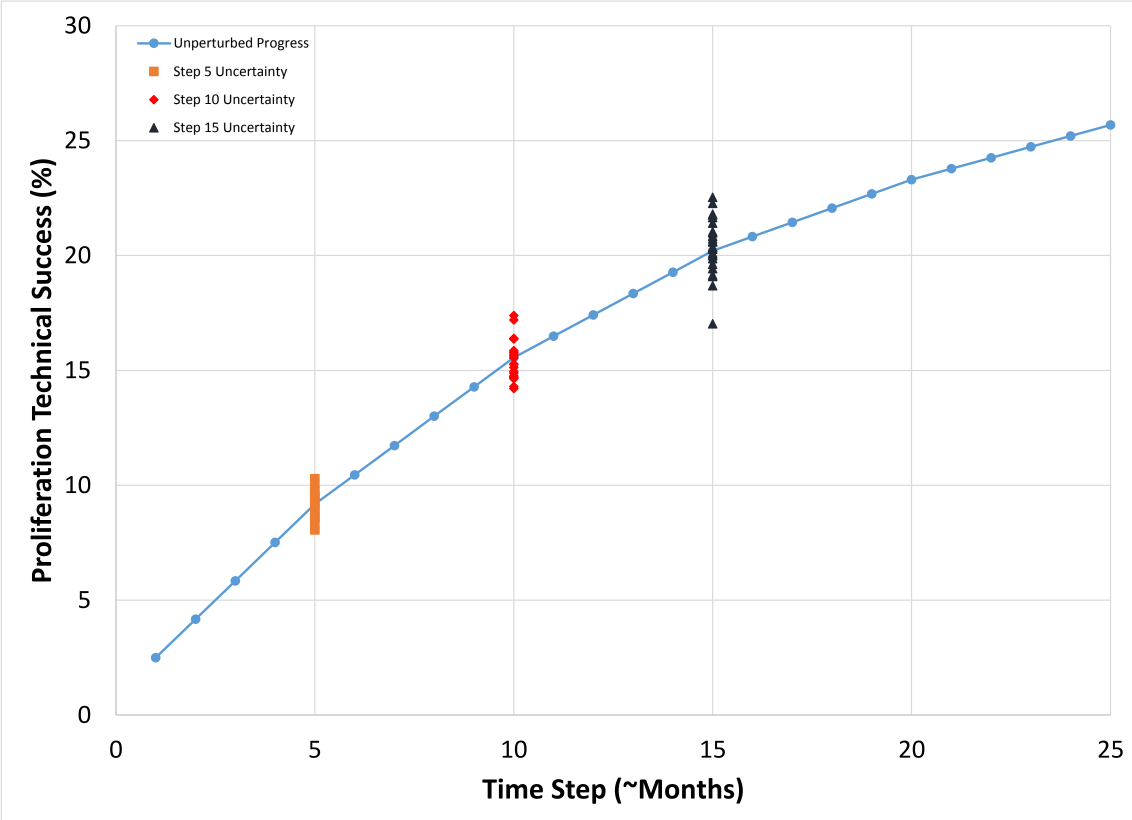


Figure 4-6. Uncertainty distributions at regular BANE simulation intervals

The deterministic BANE simulation in Figure 4-6 indicates the proliferating agent technical success without perturbations. Technical success with uncertainties only taken at the time steps for 5, 10, and 15 is included in Figure 4-6 to show uncertainty aggregation. At each time step the uncertainty effects build, leading to greater fluctuation in technical success.

Time step 5, in general, will have smaller uncertainties for several reasons. First, the variations in technical success are solely due to R&D perturbations associated with that time step. Later time steps have their variations plus prior time step uncertainties.

Second, the base proliferation R&D performed includes research that is less technologically advanced with greater certainty of success. Third, there are more hedging opportunities early in proliferation pathways. Slow progress when hedging does not remove multiple pathways from being available. This makes recovery from small research setbacks less damaging than when pursuing more focused proliferation activities.

At time step 10, there is the potential for slow or fast progress from time step 5 to be cancelled out by the opposite occurrence. The randomness of R&D means that a progress slow down might precede a major breakthrough. This cancelling relationship with a Gaussian, or even R&D range, distribution keeps the technical success progress centered somewhat on the deterministic technical success. Of course, with increasing uncertainties the deviation from the deterministic technical success grows.

The BANE simulations at time step 15 display even greater differences due to the uncertainty aggregation. Part of the justification for larger BANE simulations further along a proliferation pathway is that specialized R&D can cause bigger technical success swings. Higher level R&D usually entails more resources and detection considerations. A major technical success can enable greater resource or chancier detection in a previously unavailable area. Suffering a research setback with advanced R&D can cause significant follow-on repercussions that slow-down the nuclear weapons program in unexpected ways.

A very important fact about BANE internal agent uncertainty implications is buried in the Figure 4-6 data. Proliferation technical success considers an agent's ability to achieve its goal. How the objective is achieved in BANE is left for the agent to decide based on dynamic feedback. If an agent makes a technical breakthrough they can pick the appropriate proliferation pathway for advancement subject to constraints like resource and detection probability. Similarly, a challenge might require additional R&D effort to overcome; thereby, making another proliferation pathway more attractive.

Early in the proliferation decision making, a proliferator might chose HEU or plutonium for a weapons pathway based on available infrastructure and expertise. The influence of an unexpected affinity proliferation connection could make the other route more appealing. The appearance of Abdul Qadeer (A.Q.) Khan held major sway for the Pakistani program going down the HEU nuclear weapons pathway. In a negative sense, enhanced proliferation scrutiny from a defensive agent could negate an expected proliferation pathway. Technically the proliferation hurdles might be less of an issue than the economic and security isolation during and after the nuclear weapons program.

IV.D. Temporal Affinity and Influence Evolution Modules

The affinity framework precursor to BANE was developed and tested using the open source Repast Simphony software. Attractive Repast Simphony aspects include support for complex system modeling and High Performance Computing (HPC) features.[97] Several programming options for Repast Simphony ABM are JAVA for its visualization optimized package and C++ for HPC. An initial Repast Simphony advantage was autonomous, modular verification testing of dynamic ABM proliferation pathway evolutions.

The BANE affinities modules benefitted from Repast Simphony verification efforts. An example used for calibrating later BANE affinity modules was a series of independent proliferators with desires to establish proliferation networks. The proliferating agents seek supplies and technology to overcome proliferation technical barriers. Each neutral supplier agent has a certain resistance to serving as a proliferator, but that resistance can eventually be overcome by repeated proliferator approaches. Wearing down of suspicion, i.e. removing negative influence, is associated with continued business and personal relationships between the proliferator and its target neutral supplier.

Once a proliferator has established a proliferation connection, the new proliferator proceeds to support the original proliferator by making additional network connections. In the ABM case shown in Figure 4-7, there are several hundred neutral suppliers, depicted as blue stars. The neutral suppliers have at least relatively beneficial nuclear proliferation capabilities. There are only a few initial proliferators, displayed as orange triangles. The proliferation network growth is tracked and indicated via red lines with arrows depicting affinity relationships. Figure 4-7 shows the affinity model for one run of the nuclear technology acquisition network.

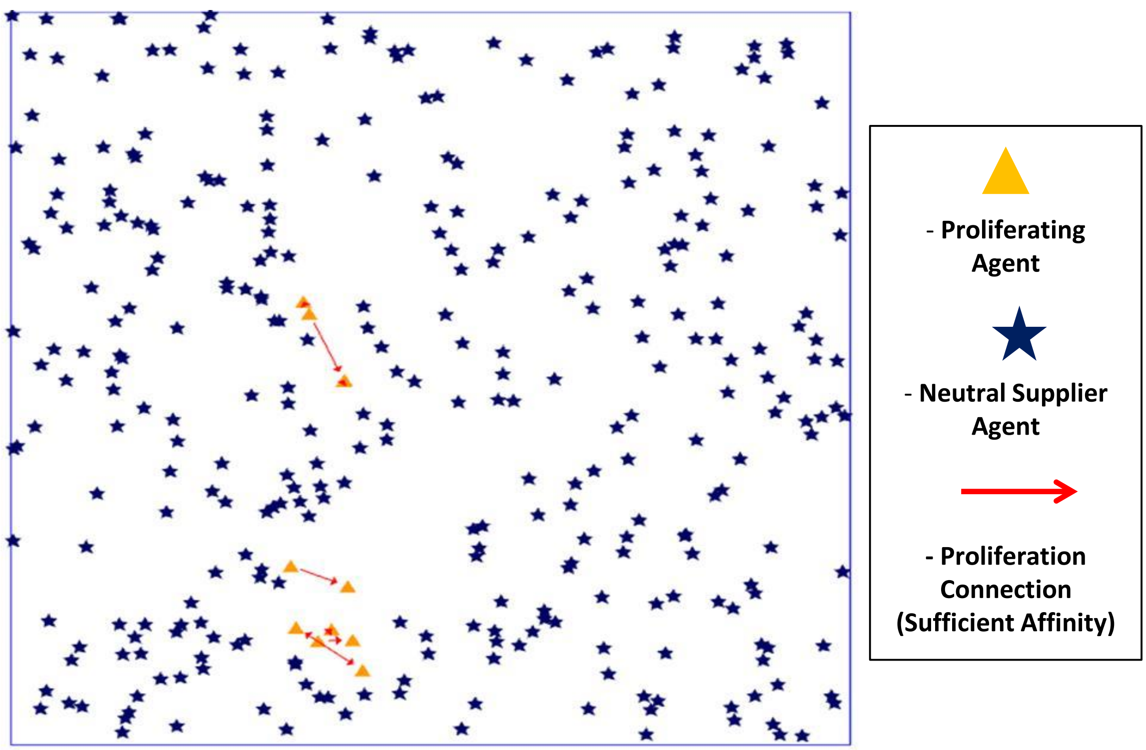


Figure 4-7. Repast Simphony inspired affinity based nuclear proliferation network

With each Repast Simphony affinity model run, the code stochastically creates an iteration with different initial starting affinity proximities between the proliferator and potential supplier agents. In addition, each neutral supplier agent resistance to serving as a proliferator varies depending upon the run. The dynamic neutral supplier and proliferator engagement alters the proliferator's estimation of its ability to achieve its nuclear weapon goal. The first generation model allowed the user to determine ranges for proliferating agent perceptions regarding indigenous knowledge, technology, skills, and experience. International proliferation networking influence levels via clandestine or dual-use routes are also user adjustable. The proliferation example raised questions later addressed in BANE about permitting corrupted supplier agents to break free from a proliferating agent's network. The introduction of corrective actions, such as increased export controls or neutral supplier government intervention, were explored as cooperation ending events.

The number of illicit nuclear proliferation sales and exchanges happens far more regularly than the number of states that successfully developed nuclear weapons. From an ABM perspective, that makes ML using pattern recognition and testing / tuning analysis much easier. Realistic individual, company, and country data from different sources could enable statistically significant nuclear export control and dual use testing for validation purposes. Furthermore, individual Nuclear Suppliers Group (NSG) and Zangger Committer violations might have similarity to other internationally regulated weapon regimes.[98] The missile technology control regime (MTCR) or the Organization for the Prohibition of Chemical Weapons (OPCW) are two prime candidates for exploring respective proliferation violations. Depending on the additional data, weighting the MTCR and OPCW transgressions less than the NSG and Zangger violations could prove statistically beneficial.

The affinity and influence adjustments for BANE agents occur on a time step basis. Two agents, A and B, might be considering an affinity relationship on category x. The agent affinities are therefore, A_X and Bx. The governing constraints for insufficient BANE affinity are:

$$2 < A_x \parallel B_x < 8 \quad \text{4-24}$$

The agent affinities can be governed by Equation 4-24 leading to a cooperation failure for a wide range of reasons. A primary justification underlying the lack of interaction might be lack of proximity. The absence of trust, mutual commitment, or deep common interest is detrimental to proliferation engagement. The sufficient BANE affinity regimes are governed by:

$$\left(A_x \,\&\, B_x\right) \leq 2 \quad \text{4-25}$$

$$8 \leq \left(A_x \,\&\, B_x\right) \quad \text{4-26}$$

Equations 4-25 encompasses situations such as collaboration due to mutual opposition to a particular state or set of beliefs. While Equation 4-26 represents positive cooperation affinity for reasons such as shared history or alliance. The BANE affinity modules treat affinity as a snapshot in time, so updates are needed to coincide with changing global power and relationship dynamics.

Time based affinities in BANE draw upon the influence modules to represent agent opportunities and challenges for proliferation related exchanges. The BANE agent influence variations are handled in intervals across multiple categories. The basis of affinity stems from the distinctive agent initial affinity and influence changes:

$$A_{x,i} = A_{x,0} + F_x t \quad \text{4-27}$$

t is time, $A_{(x,i)}$ is agent affinity at a particular time, $A_{(x,0)}$ is initial agent affinity level, F_x is agent specific influence change rate.

BANE affinities are constrained between 0 and 10 for Equation 4-27. Influence adjustments can be positive or negative; and, the agent influence is broken up using affinity bin levels. Affinity categories realistically do exhibit interdependence. Economic growth can correspond with more security resources being available or an increasingly attractive political system. Other influence adjustments equations are possible including logarithmic, polynomial, etc. However, exploring more advanced influence equations in BANE is beyond the scope of this work.

IV.E. Omniscience and Monitoring Agent Implications

The BANE omniscience and monitoring modules build upon several optimization and other module features. However the omniscience and monitoring modules approach proliferation from a defensive agent oriented perspective. Defensive agents seek to locate anomalous behavior that indicate the presence of nuclear proliferation. Detecting proliferation relies upon pattern analysis and recognition.

No entity can ever be entirely omniscient about itself, let alone others. Incomplete information can lead to incorrect judgments causing improper actions. The reciprocating spiral of failure occurs in real life. Allowing false feedback to send defensive agents down the wrong monitoring paths benefits BANE realism. Proliferator resource tracking and detection analysis are broad categories with implications for defensive agents. Resource and detection arenas offer subtle nuances which different defensive agent type's parser better.

The resource recovery rate incorporates the budget cycles for an agent. The default BANE approach is a funding cycle aligned with larger state bureaucracies and corporations. Approximately one year budgets are the expected norm. Major deviations by an agent from the anticipated resource recovery rate could suggest a proliferation operation. Figure 4-8 shows the resource recovery rate for a proliferating agent using a budget roughly corresponding to an annual funding cycle.

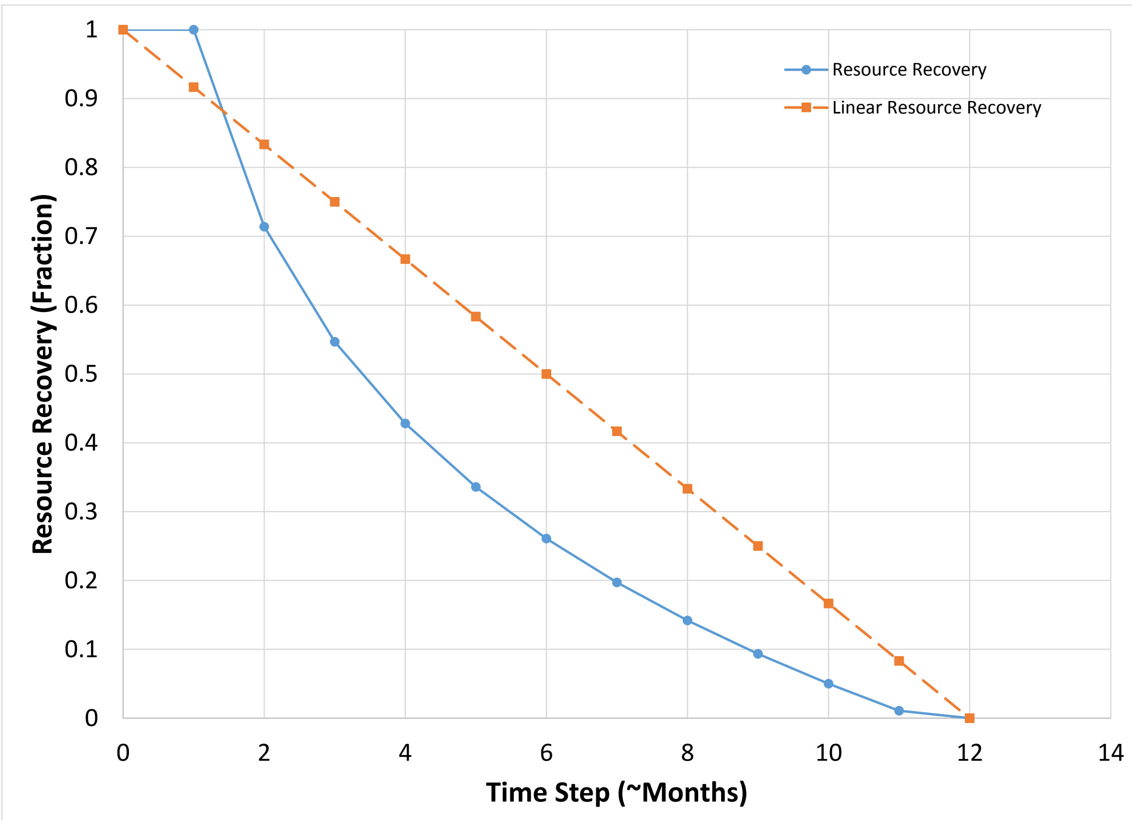


Figure 4-8. Expected agent resource recovery rate

A linear resource recovery rate is included in Figure 4-8 for contrast with the logarithm based Equation 4-22. Near the end of a project fiscal cycle Equation 4-22 handles an increased chance the agent can expend funds again without looking as suspect. The additional resources could appear buried as natural organizational budget growth or year-end fiscal tweaking. The linear resource equation is more restrictive on resource surges further from initial allocation.

A defensive agent monitoring and then finding nuclear weapon program R&D is not omnipotent. Therefore, counter proliferation is also constrained by the resource recovery Equation 4-22. There is a finite supply of resources for defensive agent corrective action. This means defensive agents must be careful about how they approach setting back proliferation.

Proliferation detection in BANE accounts for time based information changes similarly to resources. Proliferators can have perceptions on their tolerated detection level. Depending upon the proliferation progress and the monitoring detection agent the detection threshold is insufficient to avoid raising suspicion. If the proliferator just undertook a R&D proliferation step with heightened signatures, for instance, then less capable defensive agents may be alerted. Figure 4-9 shows the detection memory losses associated with a defensive agent monitoring suspected proliferation.

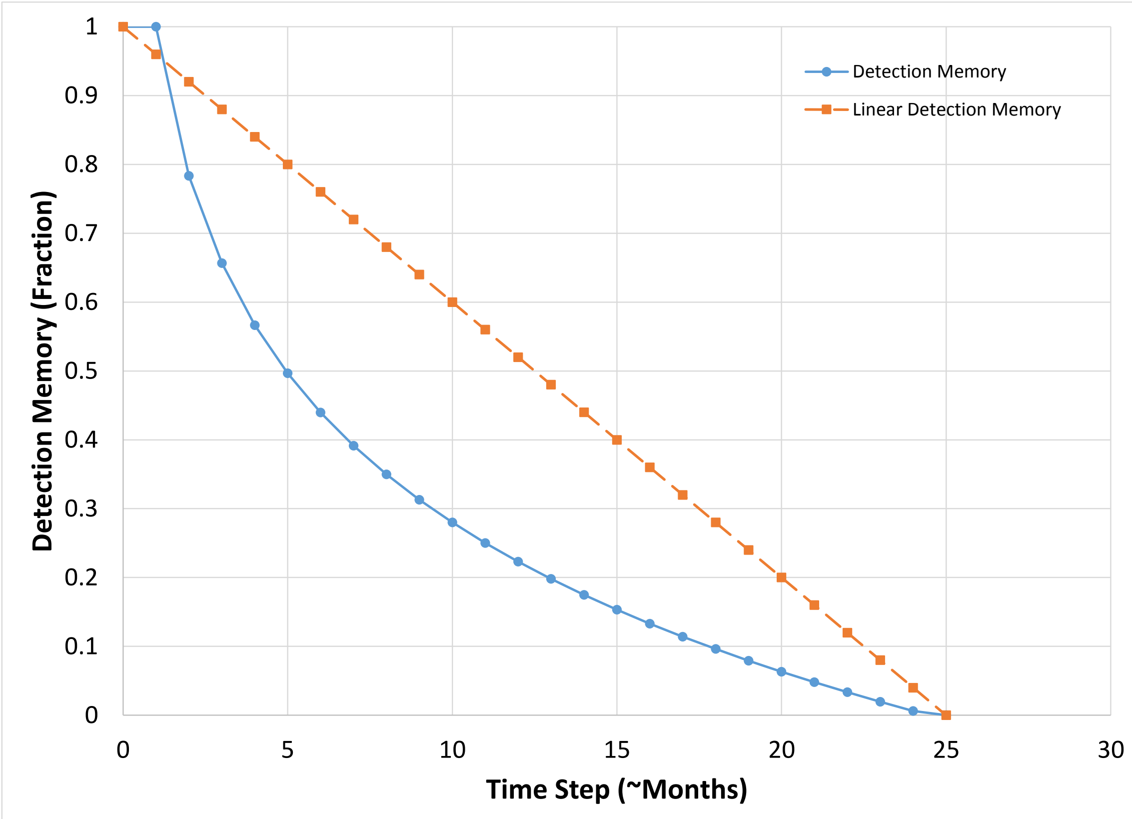


Figure 4-9. Expected defensive agent memory loss

Proliferation awareness falters over intervals as illustrated in Figure 4-9. Defensive agents lose the ability to correlate linked proliferation activities over time. The logarithmic based Equation 4-23 addresses the rapid decline in memory the longer between event occurrence and needed recollection. A proposed linear detection memory loss is overlaid on Figure 4-9. The memory loss response with Equation 4-23 better approximates the difficulty for defensive agents to draw proliferation conclusion. This is particularly true for seemingly disparate events separated by substantial time periods.

Wrapped up in proliferation detection are numerous physical, environmental, electronic, human capital, and other signature types. Investments in uncovering environmental signatures might lead to detection weaknesses against electronic proliferation trails. A more nuanced set of detection equations would increase defensive agent granularity. Exploring missing proliferation detection chances due to poor defensive agent cooperation could be informative for decision makers. However, unwrapping the BANE detection equation into many signature constituents exceeds the thesis boundaries.

Another area of note is including uncertainties on defensive agent monitoring. Ambiguity in defensive agent detection makes errors possible when searching for proliferation. Behavior that seems like erratic resource expenditures might not indicate proliferation. Failing to correlate rapid proliferation activities can cause nuclear weapon programs to be missed for long periods. When the proliferation is noticed again, the task of the defensive agent might be far more challenging.

The memory loss response representing Equation 4-23 in Figure 4-9 does not address the actual "detection probability threshold" for defensive agents. Different defensive agent detection capabilities may more effectively penetrate proliferation networks. Proliferating agents can miscalculate or take risks in pursuing proliferation. If the defensive agent detection probability threshold is sufficient it can take advantage of the oversight. The memory loss function in Figure 4-9 then factors in for recognizing proliferation. Once the proliferation is detected, the defensive agent may begin taking counter measures.

IV.F. Agent Empowerment Synopsis

BANE has an array of modules to facilitate intelligent agent actions. The modules use entropy and mutual information for proliferation pathway determinations based on technical success. Optimization modules incorporate resource and detection criteria that modifies the preferred agent choices. Lacking omnipotence, BANE agents can experience proliferation setbacks. However, they can sometime make major breakthroughs ahead of schedule.

Affinity proliferation connections open up opportunities for major pathway jumps. Defensive agents can also use affinities to increase their range of coverage to counter proliferation. Absent omniscience, BANE defensive agents must continually monitor and seek out proliferation in order to hinder or roll back nuclear weapons programs.

CHAPTER V

MODULE VERIFICATION WITHIN BANE

Nuclear nonproliferation verification of BANE is emphasized at the modular level. Several of the BANE modules can be tested alone, or a few modules. Within a complex ABM or MAS, testing individual agent and small group actions in narrow fields builds confidence in complex simulation results. Expected agent behavior can then be more robustly checked.

The BANE module verification testing allows for exploring historical impacts on nuclear proliferation activities. The French, South African, Iraqi, and Swedish nuclear weapons programs were analyzed. Case study verification and limited validation testing of the case studies centered on the BANE Netica GUI and API Parser modules. Prior Bayesian analysis work at Texas A&M University was crucial in developing verification and limited validation BANE benchmarking.[99,100]

Verifying agent empowerment applications of several BANE modules bounds their capabilities for intricately connected proliferation scenarios. Understanding how agents handle limitations when balancing multiple constraints can aids tuning BANE towards more real world simulation. In a social science context creating environments where a few relationships can alter proliferation opportunities is important. Uncertainties plague proliferating and defensive agent progress through information overloading and misdirection. Each case considered helps with realizing BANE operating capabilities.

V.A. BANE Bayesian Results in ABM Context

Historical case studies were used for assessing the BANE Bayesian methodology cogency. The French and South African nuclear weapon programs are evaluated using BANE to test the Netica GUI network. Time based evidence assertions for historical cases are incorporated inside BANE modules for the Netica API Parser and Affinities. Iraq and Sweden provide another two historical cases for BANE analysis. However, the Iraq and Sweden cases use BANE to gauge states not reaching nuclear weapon acquisition. Substantiating BANE across multiple proliferation cases prevents preferential tuning of the overarching Netica GUI proliferation network to provide correct results for just one small sub-set of proliferation scenarios.

V.A.1. France Nuclear Weapons Program

Elements within France explored a nuclear weapon program, but official government attentiveness following World War II accelerated the effort.[101] In 1948 indigenous French uranium mines in the Autun, Limousin, and La Crouzille regions were located.[102] Triggering a domestic French capability for the uranium mine acquisition in BANE leads to the uranium enrichment gas centrifuge probability increasing. Figure 5-1 shows a 25.8% gas centrifuge true probability as the favored enrichment pathway.

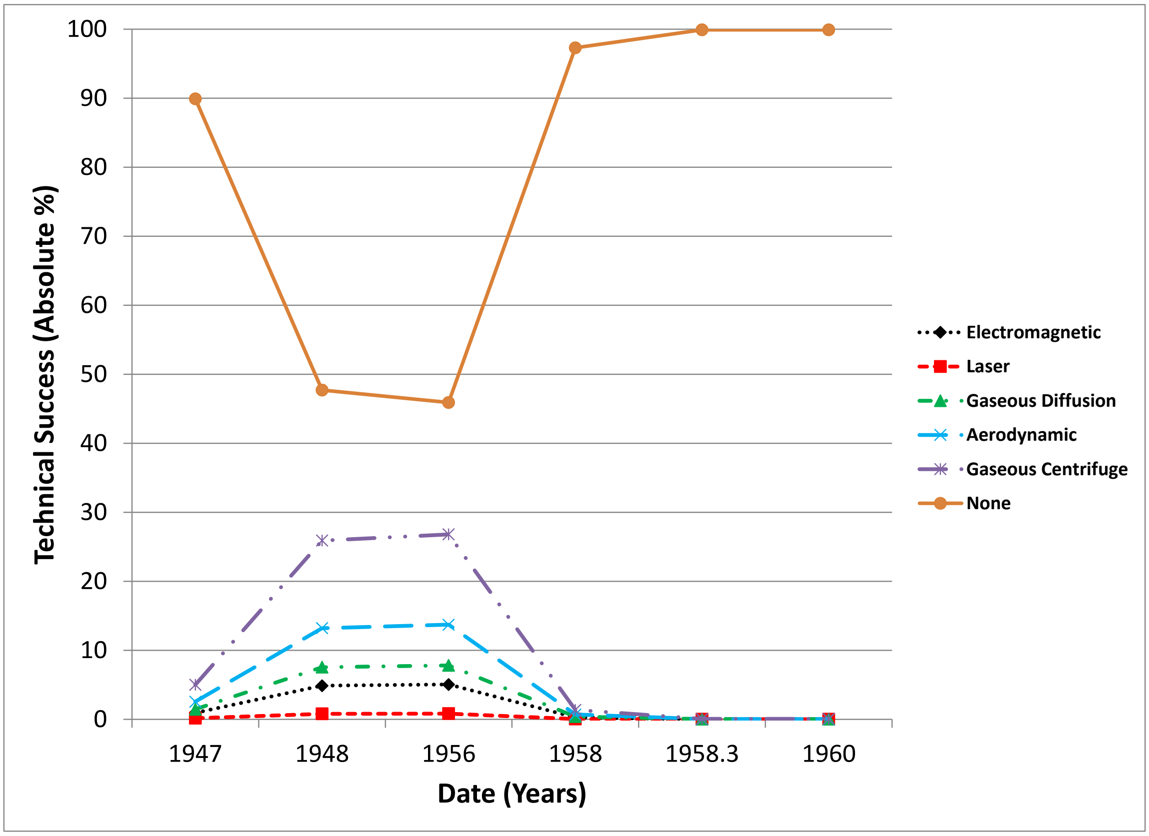


Figure 5-1. Netica GUI analysis of early French nuclear weapon program uranium enrichment pathway

In 1956 the French G-1 production reactor for plutonium became operational.[103] Using BANE the domestic reactor node is set to "true" through French research efforts. The G-1 reactor addition causes the BANE plutonium implosion pathway technical success to rise in Figure 5-2 to 8.51%. BANE correctly maintains some French uranium enrichment pathways pathway options through 1956. At 8.72% the HEU gun type pathway is marginally higher than the plutonium implosion route. The HEU implosion device pathway looks most promising in 1956 with 10.20% true probability.

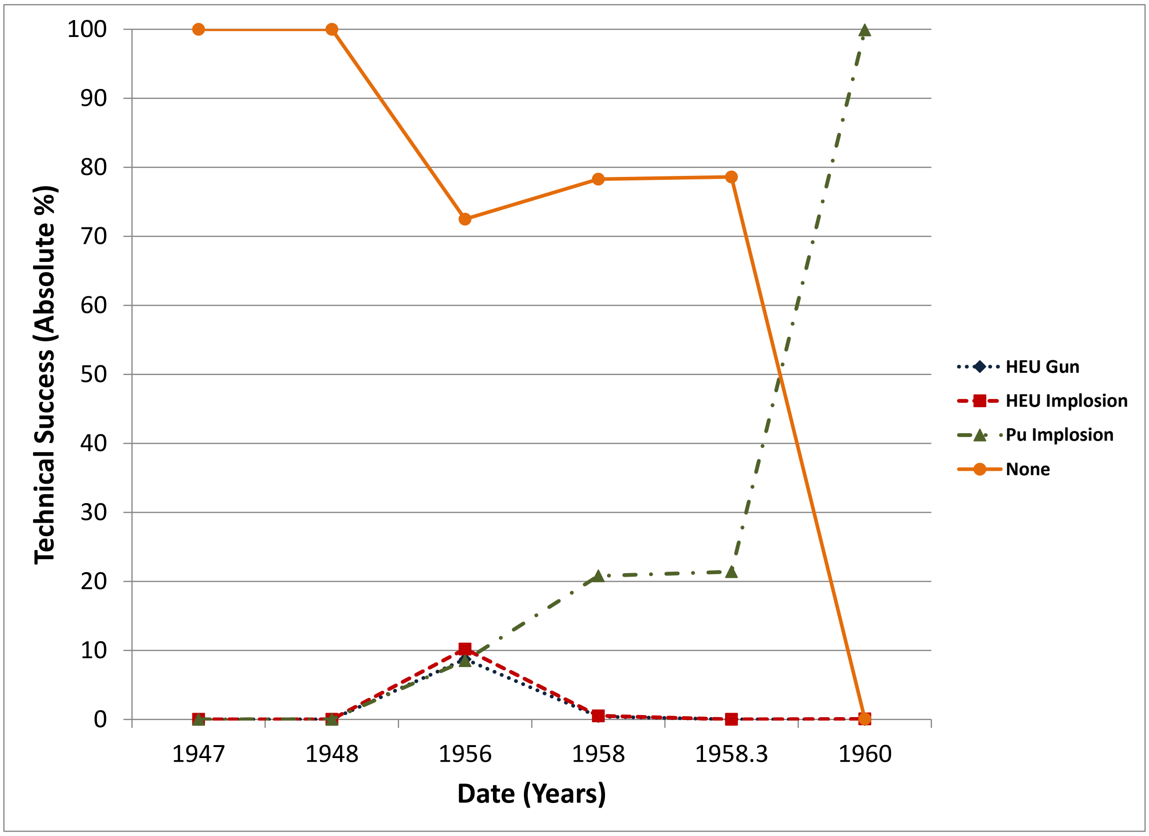


Figure 5-2. Netica GUI analysis of early French nuclear weapon acquisition pathway

The French desire for enhanced prestige, not only within the North Atlantic Treaty Organization (NATO) but also on the global stage, coincided with General de Gaulle's June 1958 rise to power. The French Chemical Separations Plant (CSP) at Marcoule started operations in July 1958 using the plutonium uranium exchange (PUREX) process. By the end of 1958, CSP produced 0.67 lbs/day of plutonium.[104] Within BANE, the French agent obtaining reprocessing and plutonium capabilities basically zeroes out all the Figure 5-2 HEU weapon pathways.

From a weapon perspective, BANE indicated a 21.6% true probability for the French agent pursuing a plutonium weapon. Activating the BANE testing stage to indicate awareness of French agent nuclear weapon site preparation agent increases the plutonium implosion weapon true probability to 100%. On February 13th, 1960 the French conduct their inaugural weapon test with a 70 kiloton plutonium implosion device.[105] Hence, BANE truthfully identifies the first French nuclear weapon conclusion.

In the BANE French verification case, only major proliferation technologies were triggered by the French agent. Smaller nuclear weapons constituents were activated as needed, such as specific reprocessing methods or test equipment. Prior to the French agent committing to nuclear weapon testing, 20% true probability for the plutonium implosion route was the highest indicated by BANE. Results from the French case show the limitations of a few large proliferation signatures purely depicting nuclear weapon programs. Instead BANE suggests that the culmination of a larger array of smaller events form a mosaic specifying proliferation progress.

The role of identifying single large proliferation facilities for highlighting nuclear weapon procurement must be put into proper context. The French case suggests the extent large facilities aid particular weapons path selection. Entering intelligence collection or other data on significant proliferation technologies does effectively bound nuclear weapon acquisition pathways. Absent linkable proof of multiple constituent nuclear weapons equipment, a high likelihood of determining the final device success type and time is limited. The French BANE scenario results demonstrate the network behaves properly.

V.A.2. South Africa Nuclear Weapons Program

South Africa began its nuclear program in the early 1950s, and by 1952 the West Rand Consolidated Mine and uranium plant were operational as Figure 5-3 shows.[106] The BANE HEU and plutonium weapon pathways indicated in Figure 5-4 for the South African agent hover near 7%. Returning to South African uranium enrichment in Figure 5-3, the 36% gas centrifuge true probability is the highest. Aerodynamic isotope separation has the next largest true probability at 17% in 1952.

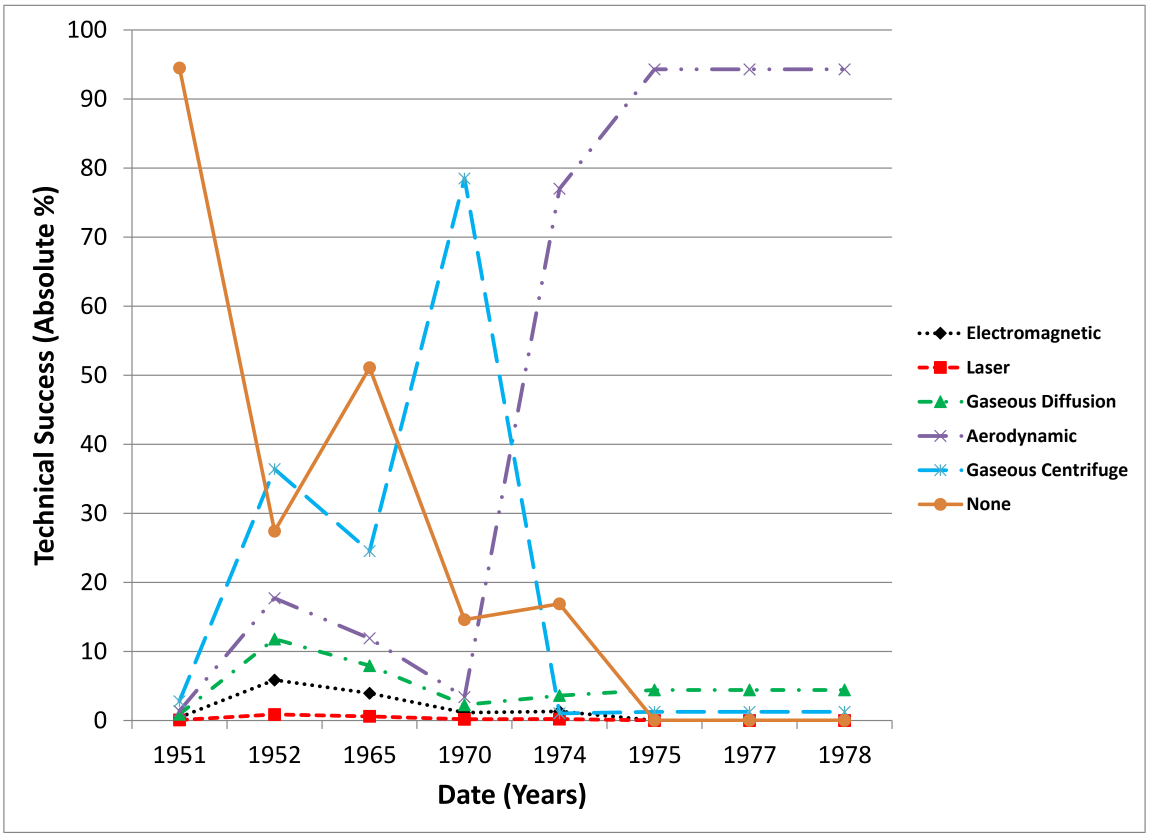


Figure 5-3. Netica GUI analysis of South African nuclear weapon program uranium enrichment pathway

In 1965 the United States origin Safari-I South Africa reactor initiation occurred. A United States agent used a BANE affinity induced transfer to account for the Safari-1 reactor availability to the South African agent. Obtaining the domestic reactor lowers the South African agent gas centrifuge and aerodynamic separation true probabilities to 24.5% and 11.9%, respectively.

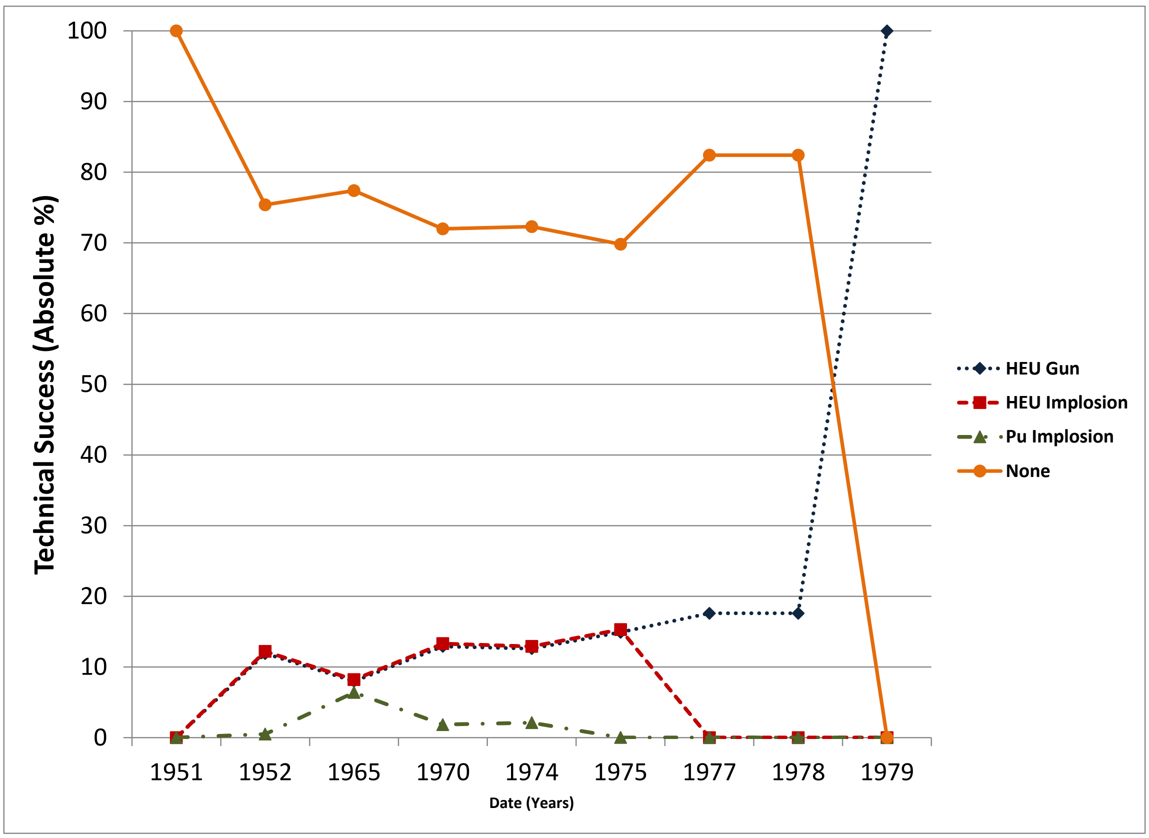


Figure 5-4. Netica GUI analysis of South African nuclear weapon acquisition pathway

The South Africans pursued ultracentrifuge research for uranium enrichment, which was assessed to take place in the early 1970s.[107] Research and acquisition of high speed motors in BANE through indigenous South African agent research is granted as a technological progress surrogate. With high speed motors the South African agent reaches a 78.5% likelihood for its gas centrifuge pathway as shown in Figure 5-3. The seeming gas centrifuge preference shifted the HEU gun and implosion weapon true probabilities to a little above 10%. In contrast, the 1970 plutonium implosion weapon true probability plummeted to just under 2%.

A BANE affinity interaction takes place to address the 1974 interaction between a West German agent providing SNA on uranium enrichment to the South African agent. Steinkohlen Elektrizitaia AG (STEAG) was a West German firm whose Becker jet nozzle technology was provided to South Africa.[108] The STEAG knowledge transfer is emulated in BANE by giving the South African agent mastery of aerodynamic technology children nodes. In response the aerodynamic uranium enrichment true probability reaches 77%, while Figure 5-3 indicates the remaining enrichment options become negligible. The Figure 5-4 weapon preferences are mostly unchanged, and the inclination towards HEU weapons remains.

The 1975 start of operation at the South African Pelindaba enrichment facility is covered in BANE by activating the UF_6 node.[109] As a result the aerodynamic enrichment true probability reaches 94.3%. The HEU gun type and implosion weapon likelihoods each move up to approximately 15%. The South African nuclear weapons program sourced tungsten from several African countries, such as allied Rhodesia, in 1977.

Experience with propellants, internal ballistics, and advanced explosive igniters led to a 1977 gun type test absent an HEU core.[110] In BANE the gun type weapon test node is switched to true based on the South African agent affinity material transfer and indigenous high explosive research. The South African agent HEU gun type pathway success moved up to 99.4%. By 1977 the South African inclination towards a gun type device was apparent; and, the BANE derived proliferation network factually highlights the preference by dropping the South African agent HEU implosion weapon pursuit to zero.[111]

BANE module verification studies on South Africa indicate the role knowledge, technology, and equipment assistance play in nuclear proliferation pathway selection. Obtaining German origin aerodynamic knowledge and expertise incentivized the South Africans to pursue an aerodynamic uranium enrichment option. The BANE network responded appropriately with the aerodynamic pathway dominating the other uranium enrichment pathways. With increasing information, the normalized arrangement of BANE networks designates the impact of evolving proliferation decisions on available pathways. The importance of a few key affinity support efforts were demonstrated for South Africa's nuclear weapons program.[112]

V.A.3. Iraq Nuclear Weapons Program

The Soviet Union provided nuclear assistance to Iraq through a 2 (Megawatt) MW research reactor, which achieved criticality in 1967. A Soviet agent affinity transfer to the Iraqi agent is initiated in BANE for possessing a reactor. With only a reactor the BANE pathways for both weapon and enrichment remain low. Obtaining an indigenous uranium mine near the Syria-Iraq border in 1974 aided the Iraqi nuclear program.[113] Figure 5-5 shows that in 1974 gaseous centrifuges are the most likely uranium enrichment route, with a BANE “true” probability of 22%.

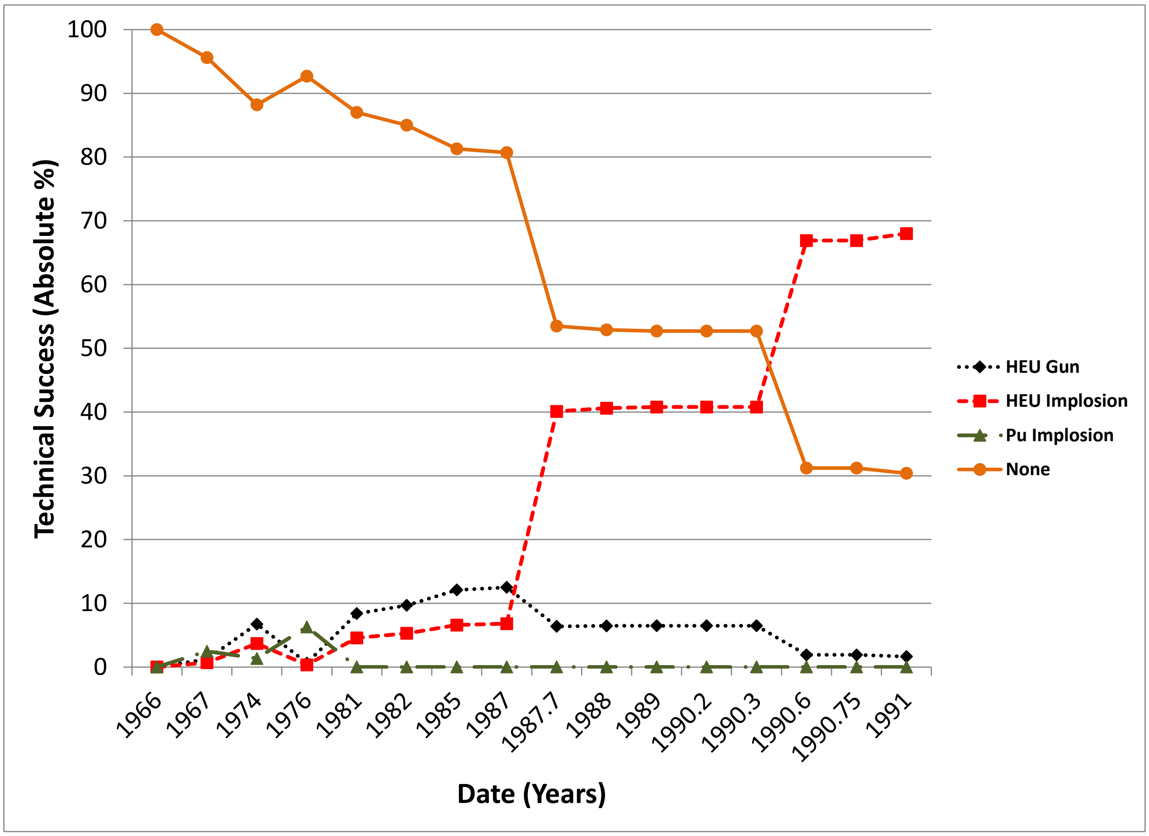


Figure 5-5. Netica GUI analysis of Iraq nuclear weapon acquisition pathway

An Iraqi radiochemistry pilot laboratory was constructed in 1976 with Italian assistance.[114] The radiochemistry lab could reprocess plutonium using three radiation shielded hot cells. The Italian agent technology transfer facilitates the BANE reprocessing capability node activation, causing the Iraqi agent enrichment paths to decrease to miniscule values. The plutonium implosion nuclear weapon pathway was the only credible option with a 6.31% true probability shown in Figure 5-6.

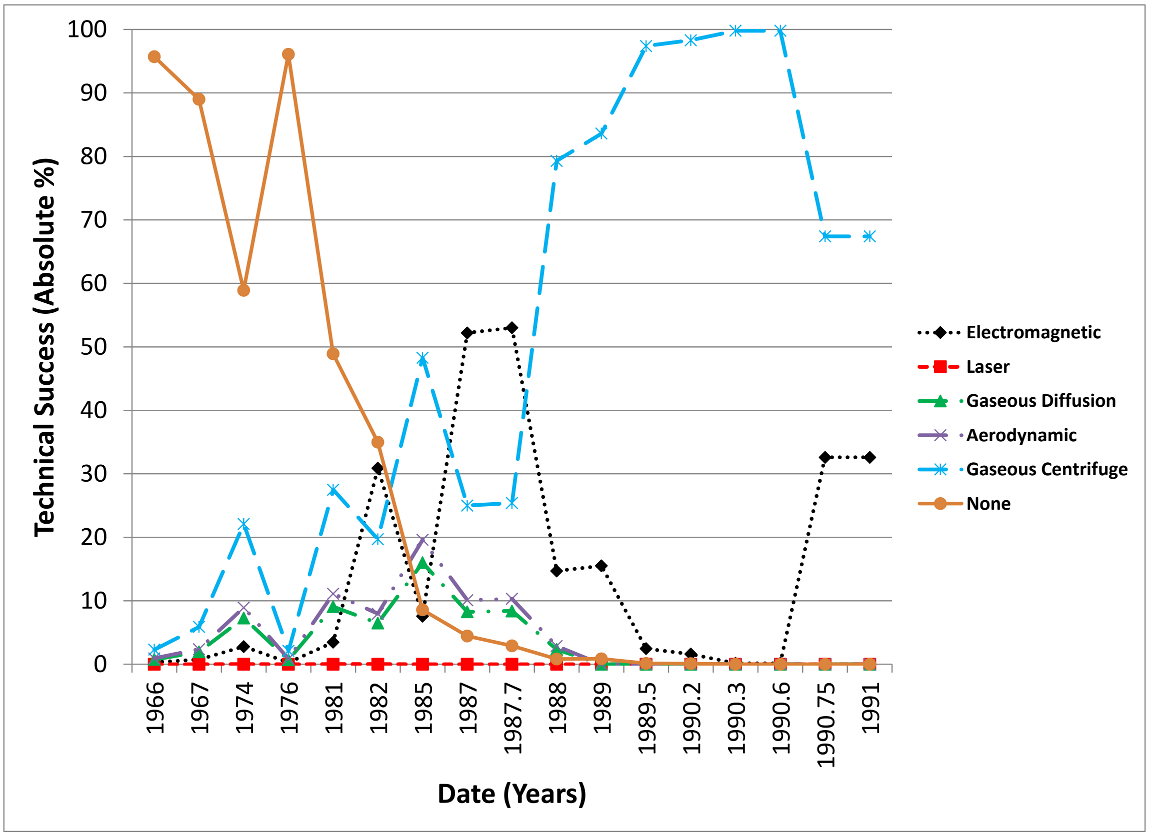


Figure 5-6. Netica GUI analysis of Iraq nuclear weapon program uranium enrichment pathway

A France-Iraq contract for the 70 MW Osirak nuclear reactor was crafted in 1976. However, shortly before the planned Osirak startup, Israel Defense Forces (IDF) aircraft bombed the facility to prevent its operatio.[115] The BANE reactor node for the Iraqi proliferator is set to “false” to match with the IDF defensive agent strike. The Iraqi agent plutonium implosion pathway becomes negligible based on the physical destruction of the Osirak complex.

Iraqi R&D on a UCl_4 facility started in 1984, with the corresponding BANE UCl_4 node activation. The Iraqi proliferation network adjustment depicted EMIS in Figure 5-6 having a 30.9% true probability. The 1980s was a period of Iraqi interest in multiple uranium enrichment pathways, including gas diffusion.[116] By 1985 R&D focuses became the diffuser and compressor systems, industrial scale heat exchangers, and particularly gas barriers. In BANE the Iraqi agent was credited with the needed compressor and energy requirements for gas diffusion. The 1985 proliferation information updates shifted the EMIS pathway likelihood to less than 8%, while the gas diffusion true probability rose almost 10% to 16%.

While trouble arose with Iraqi gas diffusion barrier designs, plans were developed for 70 R120 and 20 RR60 separators to reach 20% and 93% HEU levels. Iraqi agent R&D in BANE reached the level were separators were made available. In Figure 5-5 the EMIS pathway increased significantly to 52.2%. This represented the Iraqi's taking EMIS into the early production stages.

The Iraqi nuclear weapon program scientist Khidhir Hamza completed $120 million worth of contracts for technology supporting nuclear weapons development.[117] Individuals such as Khidhir Hamza are modeled in BANE as supporting proliferating agents to the primary Iraqi proliferating agent. The supporting proliferating agents can more easily engage with German neutral suppliers without triggering the same Iraqi proliferating agent scrutiny. The contracts with Germany were part of Hamza's August

1987 trip; and, included a flash camera using x-rays with the design specification allowing imaging through high explosive gas products.[118] Assistance from a proliferating individual in BANE led to the x-ray flash camera being credited to the Iraqi proliferating agent. The HEU implosion pathway likelihood jumped to over 40% in Figure 5-6, but had not impact on the Figure 5-5 pathways for uranium enrichment.

In 1988, indigenous Iraqi R&D successfully manufactured a UF_6 resistant tube with applications for gas centrifuges. In BANE this corresponded to achieving high strength tube access, and the gas centrifuge true probability rose to almost 80% with a substantial drop in EMIS likelihood. Difficulties with gas diffusion barrier production led Iraq to shift R&D from it in 1989.[119] The Iraqi agent in BANE shut down the gas diffusion paths by turning them to completely false. The BANE Iraqi proliferation network responds with the gas centrifuge true probability reaching 83.6%. Within BANE indigenous technical limitations can hinder a proliferating agent attaining mastery of a nuclear technology. As expected in the real world, proliferating agents in BANE can move backwards along a pathway while leveraging existing resource, knowledge, and technical investments. When practical a BANE proliferating agent selects a new pathway where it considers its indigenous capabilities sufficient to achieve its desired proliferation objective.

In the late 1980s Iraq received 25 maraging steel sets suitable for gas centrifuge production. Previously the Iraqis had been restricted to less capable aluminum centrifuge tubes. Out of the 25 sets, 19 maraging steel kits were employed in gas centrifuge related testing and analysis. The Iraqi centrifuge program sourced 20 carbon fiber rotors in

1990. Through BANE affinity technology transfers, the Iraqi agent first was attributed the right to use maraging steel and then carbon fiber rotor nodes. At this point, Figure 5-5 shows the gas centrifuge pathway is at 98.3%. Months later UF_6 was introduced in the centrifuges; and the UF_6 node activation via BANE credits Iraqi domestic research advancements. The Iraqi proliferating agent yields a 99.8% likelihood of obtaining gaseous centrifuge capability.

It should be noted that the Iraqi proliferation teams worked under, and made progress despite, extreme personal risk. The Iraqi nuclear weapon technical leader Hussein al-Majid meted out death sentences if he deemed the technical progress insufficient.[120] Thus, the nuclear weapon team was willing to risk higher detection levels in order to obtain outside SNA. Iraqi organizational and bureaucratic leadership thereby decisively influenced the proliferation program, generally in a negative manner.

By 1990, Iraq was seeking an HEU implosion weapon concurrently with its uranium enrichment program. Through external connections Iraq obtained neutron initiator design specifics associated with nuclear devices using centrally located beryllium-polonium. The Iraqi nuclear weapon schematics employed a combination natural uranium reflect and tamper. Accordingly in BANE, affinity technology transfers are considered the sources of the Iraqi agent HEU implosion design data. Triggering the appropriate initiator, reflector, and tamper nodes in BANE leads to a 66.9% HEU implosion pathway likelihood.

1990 was a busy Iraqi proliferation year because 8 EMIS separators started functioning. The maximum enrichment the Iraqi's achieved was 7.2%, out of the few hundred grams of enriched uranium produced. Consequently, crediting the Iraqi proliferating agent with acquiring the remaining electromagnetic nodes increased the BANE network probability to 32.6% in Figure 5-5. BANE showed the network oscillations for the Iraqi agent between two competing enrichment technologies.

Iraq defined the high explosive lens dimensions in January 1991. In BANE the explosive lens node was turned on, which led to a 68% likelihood for the HEU implosion weapon. The First Gulf War began in mid-January 1991, leading to the International Atomic Energy Agency (IAEA) eventual dismantlement of major nuclear program aspects.

V.A.4. Sweden Nuclear Weapons Program

Sweden is an interesting nuclear proliferation case, since it actively pursued a nuclear weapon but abandoned the program for political and not technical reason. The first stages of the Cold War witnessed Swedish exploration of a nuclear weapons program.[121] The Soviet Union threat provoked Sweden by the late 1940s to assess the necessary nuclear and non-nuclear knowledge and infrastructure. At the beginning of the 1950s, several Swedish military officials publicly stated a desire to possess nuclear weapons.

In 1957 Sweden took steps towards a nascent nuclear program by acquiring a small, United Kingdom origin plutonium quantity.[122] In that context BANE modeled the Swedish proliferating agent as receiving an affinity based transfer from a cooperative United Kingdom proliferating agent. The Swedish agent triggers the plutonium node without setting the reactor node to true despite it being the expected plutonium acquisition route. The BANE plutonium weapon probability grew to 7.78% as indicated in Figure 5-7; and, the HEU weapon pathways expectedly were unchanged from zero. Swedish weapon designers by the late 1950s had mastered advanced high explosive implosion methods needed for nuclear weapons.[123] BANE granting as "true" the implosion knowledge node jumps the Swedish proliferating agent plutonium weapon pathway to 29.8%.

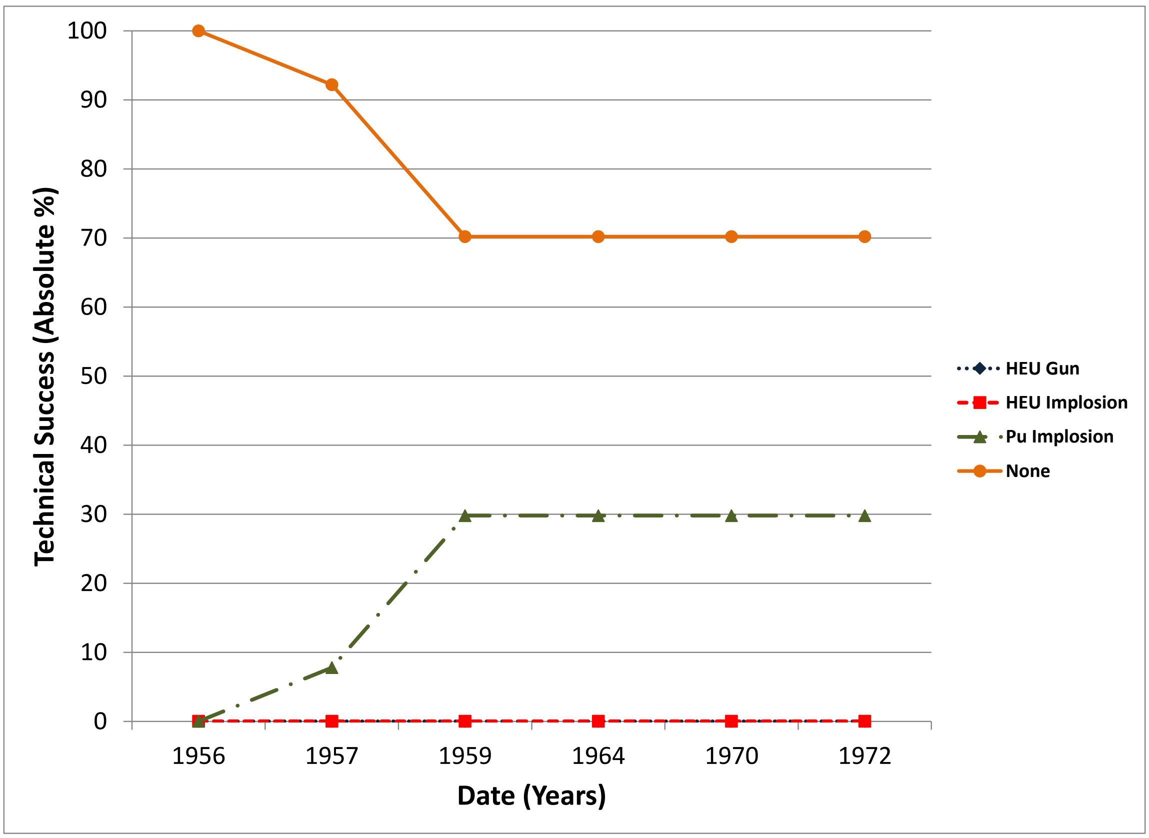


Figure 5-7. Netica GUI analysis of Sweden nuclear weapon acquisition pathway

Sweden developed plans for building a research reactor and explored establishing a reprocessing plant. However, in 1964 nuclear officials abandoned the reprocessing plant idea due to the cost.[124] In BANE, an agent representing Swedish leadership can actually take a defensive agent posture in opposition to the Swedish proliferating agent. The Swedish leadership defensive agent thereby compels the shutdown of the Swedish proliferating agent reprocessing capability node.

In 1970 the Swedish political leadership cancelled the planned reactor for economic and technical intricacy reasons.[125] Again, the Swedish leadership defensive agent intervenes leading to the reactor node being switched to false for the Swedish proliferating agent. The Swedish proliferating agent weapon pathway remains since the plutonium node is still present. Figure 5-8 shows the negligible enrichment pathways throughout the BANE simulation. At effectively zero, the uranium enrichment values demonstrate how the BANE network handles situations where a nuclear weapon was sought, but the decision to cease proliferation efforts occurred. In 1971, when Sweden signed the NPT, policy and not technical choices precluded nuclear weapon production.[126] The Swedish plutonium weapon true probability never breaches the 30% threshold. Nevertheless, the plutonium implosion pathway being credibly significant truthfully reflects the most promising route available to Sweden for obtaining a nuclear weapon.[127]

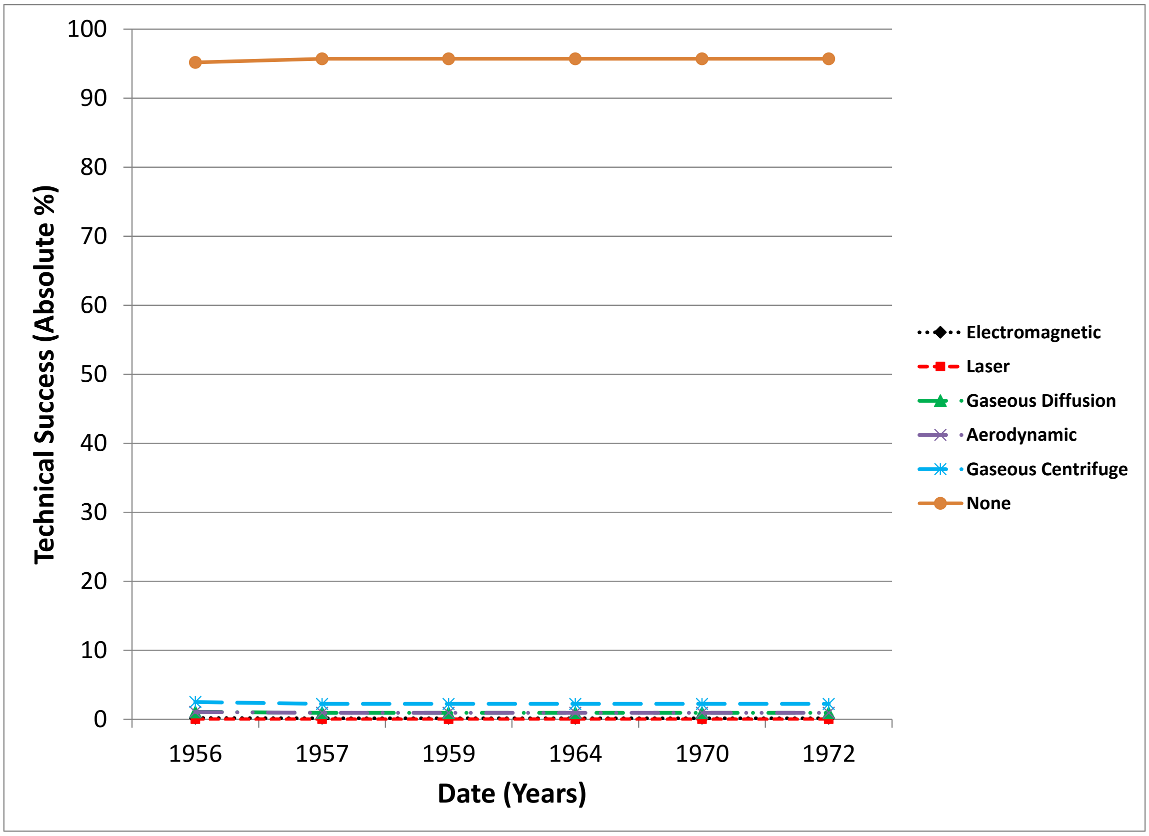


Figure 5-8. Netica GUI analysis of Sweden nuclear weapon program uranium enrichment

V.A.5. Netica GUI and API Historical Weapons Analysis Results

Due to an insufficient number of historical cases, the BANE Bayesian Netica GUI network presented in this work cannot ever truly be validated. There simply is not enough historical data to obtain sufficient statistics. However, the above four cases demonstrate that the Bayesian network aspect of BANE has been verified to a sufficient degree. The behavior of BANE is in accordance with what is expected in such situations, and ultimately gives the same outcome as the historical cases. The Bayesian proliferation network component of BANE, while never being able to be completely validated, can provide useful insights for understanding proliferation. Extension of the hypothetical cases with the broader BANE tool, however, definitely improves the Netica proliferation network as a learning tool. Inclusion of the Netica proliferation network enhances the overall BANE utility in the future as a predictive proliferation analysis tool.

V.B. Empowering Module Verification Testing

BANE modules are designed to empower intelligent agent decision making. A series of BANE verification tests were performed on single and small groups of modules. The first area of analysis focused on agent handling of different resource and detection concerns. A second BANE aspect of interest is the handling of just a single affinity technology transfer without other factors. Third, several BANE modules aid in understanding the impact of defensive agent uncertainty on proliferating agent choices.

V.B.1. Demonstrate Agent Objective Trade-Offs

An entity contemplating reduced nuclear latency or nuclear weapon acquisition must envisage jeopardizing the status quo. Perceiving countervailing benefits from proliferation may swing the calculus depending on the objective. If a substantial decrease in nuclear latency is achievable without major economic dislocations or international backlash, leaders might embark on a proliferation program. Recognition of heavy global sanctions and military threats could retard or prevent some nuclear programs from starting.

A verification test for BANE addresses a proliferating agent facing different resource and detection constraints. Weak constraints on a proliferating agent might represent a robust economic and technical base. A sufficiently advanced state could conceivably undertake covert proliferation with minimized signatures. A developing state could seek a similar nuclear outcome, but with significantly higher dislocations. The challenges for a developing state include lower resource expenditure rates and a weaker technical base. Developing state limitations impede proliferation technical progress and raise concerns regarding counter proliferation intervention. BANE inferences from weak and strong constraints on proliferation support are depicted in Figure 5-9.

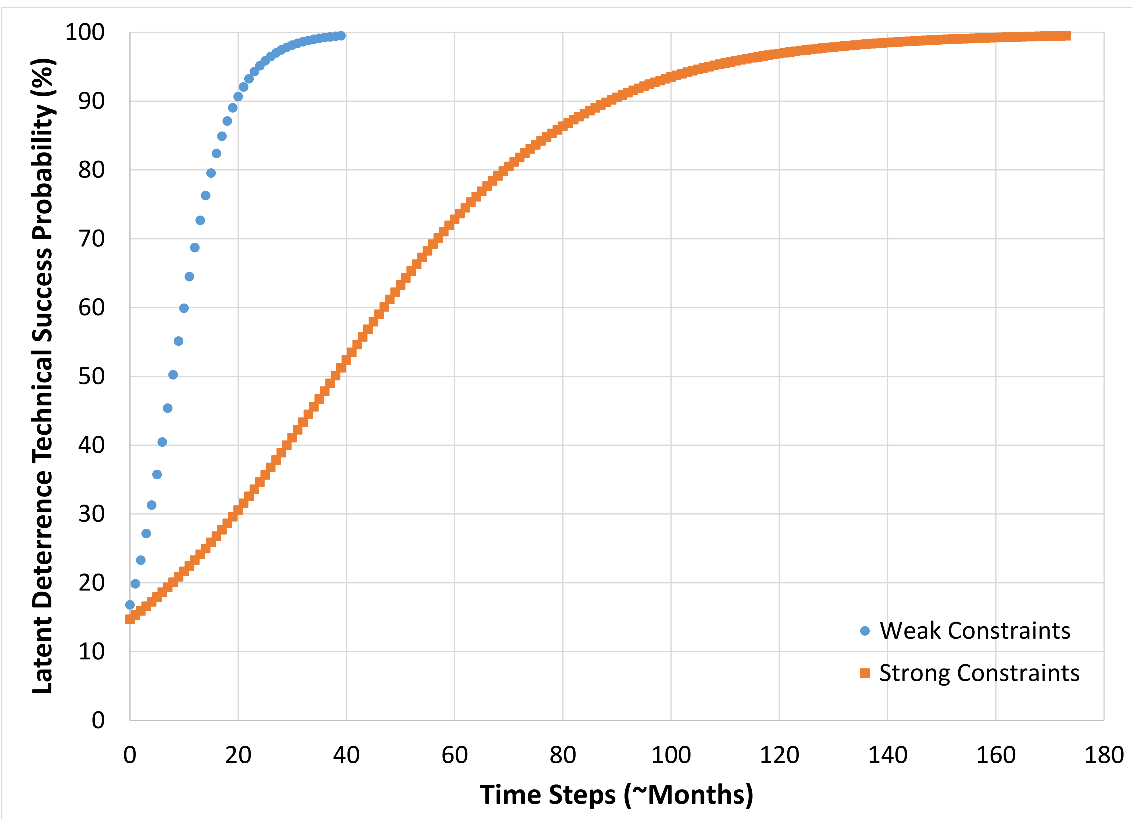


Figure 5-9. Proliferating agent resource and detection constraint variations

The proliferating agent with only weak constraints in Figure 5-9 achieves a latent nuclear deterrent posture much faster than one with strong constraints. From a BANE verification standpoint this agent conduct is expected. A weakly constrained agent can sustain a much higher proliferation resource application rate. An assumption is the weakly constrained proliferators knows its large high technology sector can justify its nuclear R&D. These major benefits combined to allow the weakly restricted proliferating agent to achieve, in just under 40 time steps, its nuclear latency goal.

The strongly constrained agent can only dedicate a small resource flow towards proliferation. A constrained agent might be proportionally allocating more proliferation effort than the weakly limited agent. The arrangement might occur for the constrained agent due to a less developed resource and technical base. Absent a growing industrial or even commercial sector, the constrained agent is assumed to be suspect for strongly advocating a domestic nuclear fuel cycle front end. Outside scrutiny, therefore, might necessitate greater demonstration of transparency efforts through IAEA agreements and inspections beyond requirements.

V.B.2. Agent Relationship Alterations

During the early stages of proliferation, an agent seeking latent deterrence might not have a strong uranium enrichment or plutonium reprocessing preference. Thus, the proliferating agent assesses its capabilities for producing SNM. If the agent has slightly greater plutonium reprocessing technical R&D and infrastructure that is its preferred proliferation pathway. Operating in isolation restricts the proliferating agent to only its indigenous R&D.

Realistically, no agent is entirely isolated. The proliferating agent can seek outside assistance for achieving its proliferation objective. A successful affinity transfer can trigger major proliferation pathway shifts. Comparing a proliferating agent absent and receiving outside affinity technology transfers is shown in Figure 5-10.

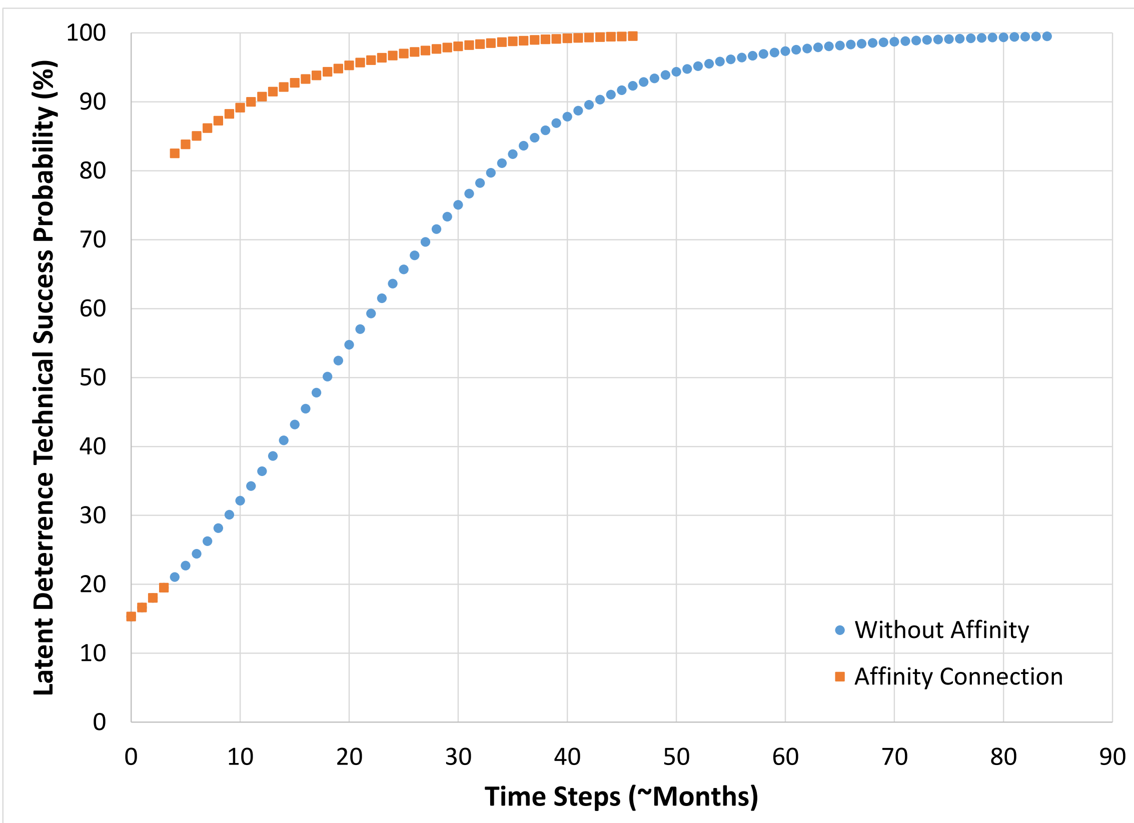


Figure 5-10. Proliferating agent without and with affinity transfer

In the first Figure 5-10 scenario, the proliferating agent operates without any possibility of affinity transfers aiding its latent deterrence. The proliferating agent begins making initial investments in its plutonium reprocessing program. Early in the proliferation program the agent is hedging on specifics such as cladding removal. As the proliferating agent selects particular pathways its R&D effectiveness picks up. The increased R&D value comes from more direct application to achieving a proliferation objective vis-à-vis hedging. However, committing to a proliferation pathway entails risks if defensive entity detection, technical hurdles, or economic costs at key steps are prohibitive.

The closer the proliferating agent gets to its objective the more difficult it becomes to achieve true mastery of the myriad component required. The physics and engineering integration challenge emulated in BANE is faced by real world actors undertaking complex technical projects. Eventually the indigenous R&D succeeds at time step 86 in providing the proliferator the desired latent deterrent reprocessing certainty.

Providing the proliferating agent with external assistance can cause significant pathway alteration. In Figure 5-10 an affinity connection is made early in the proliferating agent latent deterrent effort. To test proliferating agent flexibility, the affinity technology transfer was in gas centrifuge uranium equipment rotors and tubes. Several industries, such as the aerospace and high end sporting goods, use cutting edge carbon fiber composites. The affinity connection could be end user certification falsification, or a complicit provision with full knowledge of intended use.

Prior to the affinity transfer the proliferating agent was proceeding with plutonium reprocessing. The rapid addition of carbon fiber rotors and tubes led the proliferator to conclude uranium enrichment is the best latent deterrence option. However, the proliferating agent still needs to procure and / or perform internal R&D on other technologies to develop effective gas centrifuges. The proliferating agent rate of progress begins to plateau fast because as it approaches the technical integration phase. With the affinity transfer the proliferating agent reaches a latent deterrence posture with uranium enrichment in 46 time steps.

Relationships can dramatically speed up the success timeline for agents. Figure 5-10 indicates that two technology transfers can almost cut in half the latent deterrence time. The affinity case study demonstrated the importance of defensive agent with implications for several areas. Monitoring and proliferation rollback alone are insufficient actions for all defensive agents. Tracking and awareness of key neutral suppliers is important for preventing proliferators from making rapid increases in capability. Shortening windows for effective counter proliferation can force decision makers into poor negotiating and military positions.

V.B.3. Omniscience and Uncertainty Challenges

Lacking omniscience, defensive agents actively monitor for proliferation activities. Defensive agents vary in terms of discovering different proliferation aspects. As mentioned in Chapters 3 and 4, one defensive agent might excel at gathering human information on proliferation and another imagery processing. A third defensive agent might have the international credibility to obtain on-site access, but lack awareness about broader proliferation patterns.

Discerning proliferation activities also has a strong probabilistic element. There is no guarantee that a defensive agent will locate proliferation. Initiating searches may uncover proliferation, or they might cause a false positive that garners undue international attention. An illustration of the nuclear latency implications due to a defensive agent is shown in Figure 5-11.

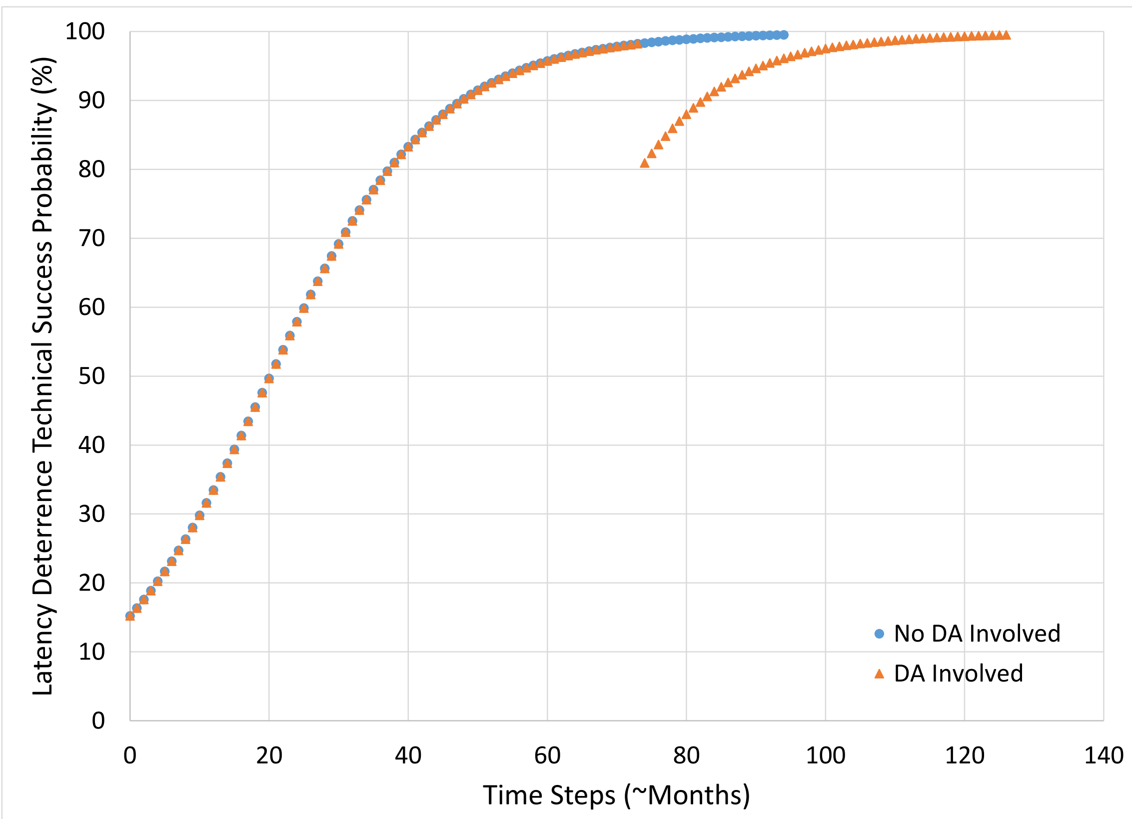


Figure 5-11. Impact of defensive agent intervention on proliferating agent

In Figure 5-11, the proliferating agent selects a plutonium reprocessing pathway. Pursuing nuclear latency through aqueous plutonium reprocessing dictates an agitation and separation system as a technical requirement. For the first situation, the defensive agent does not recognize some proliferating activities are circumventing normal export controls. Once the defensive agent is aware of the violations the proliferating agent has already attained plutonium reprocessing mastery. With BANE, failure is a distinct defensive agent outcome.

In the second situation, the defensive agent monitors for proliferation and notes export control discrepancies. Upon closer analysis the defensive agent realizes proliferation is occurring and prevents centrifugal contactor R&D progress. The defensive agent resource recovery, however, is insufficient to engage in further counter proliferation. The scenario is modeled as though the defensive agent can also not elicit other defensive agents to aid in the nuclear latency rollback. This situation might occur for a few reasons. Missing conclusive proliferation "proof" may fail to quickly generate wide spread global sanctions or strenuous IAEA inspections. Therefore, the proliferating agent can reconstitute its proliferation program around mixer settler systems as an alternative.

Stacking defensive agents assisting each other is a powerful counter proliferation strategy. When proliferation is found, different defensive agents within a government can cause compounding problems for the nuclear weapons program. Applying political pressure, scrutinizing and restricting exports, initiating focused hindrance, physically removing key components, and others options can be integrated simultaneously. For the

Figure 5-11 scenario only a single defensive agent was considered. Balancing the multiple defensive agent skills building on each other can be done in a general sense. Linked defensive agent proliferation program effects require carefully tailored and calibrated parameters to implement.

V.C. BANE Module Verification and Validation Limits

BANE verification testing of individual and small linked modules groups was performed for the historical cases of French, South African, Iraqi, and Swedish nuclear proliferation. The historical case study verification allowed for checking BANE performance focused on the Netica GUI and API modules. When developing the historical case testing, the BANE output results matched expectations. Specific BANE modules aspect verification was demonstrated for agent information handling, optimization with limitations, affinities, and defensive agent monitoring.

Analyzing the BANE historical case study results provided limited validation testing. Increasing the proliferation event range to states that pursued, but did not acquire, nuclear weapons improved the data pool. However, the small number of proliferation events renders statistically significant BANE testing for validation very difficult.

CHAPTER VI

INNOVATIVE CASE STUDY ANALYSIS WITH BANE

The limited number of historical nuclear proliferation incidents makes validation testing of BANE more difficult. Limited validation testing of multiple BANE modules is possible to see how the tool operates when assessing different proliferation scenarios. In this chapter, more in-depth studies of integrated proliferation case studies are examined.

VI.A. BANE Multi-Module Verification Testing

The BANE multi-module verification testing allows for more exploration of intricate scenario and historical factor impacts on past nuclear proliferation activities. A conceptual case study of export control violation impacts on proliferation is undertaken. The conceptual case study is somewhat loosely based on the Dr. A.Q. Khan gas centrifuge proliferation network experience. From a more historic perspective, the early Soviet Union and Pakistani nuclear weapons programs were analyzed.

VI.A.1. Case 1: Export Control Violation Impacts on Nuclear Proliferation

The first multi-mode verification scenario considers nuclear proliferation export control violations with multiple agent types and classes. The scenario focus is a “primary” proliferating agent seeking latent nuclear deterrence. A domestic enrichment program is preferred by the primary agent. Within the proliferation ecosystem are a number of neutral agents that might support the primary agent. However, several defensive agents are monitoring for proliferation activities; and, they can cooperate where mutual interest align.

A case study emphasizing several major aspects of proliferation together demonstrates the range of BANE capabilities. Multifaceted policy, economic, technical, and social science factors vie in BANE for dictating proliferation progress. In Figure 6-1 supportive and adversarial proliferation aspects are displayed for a particular interaction outcome.

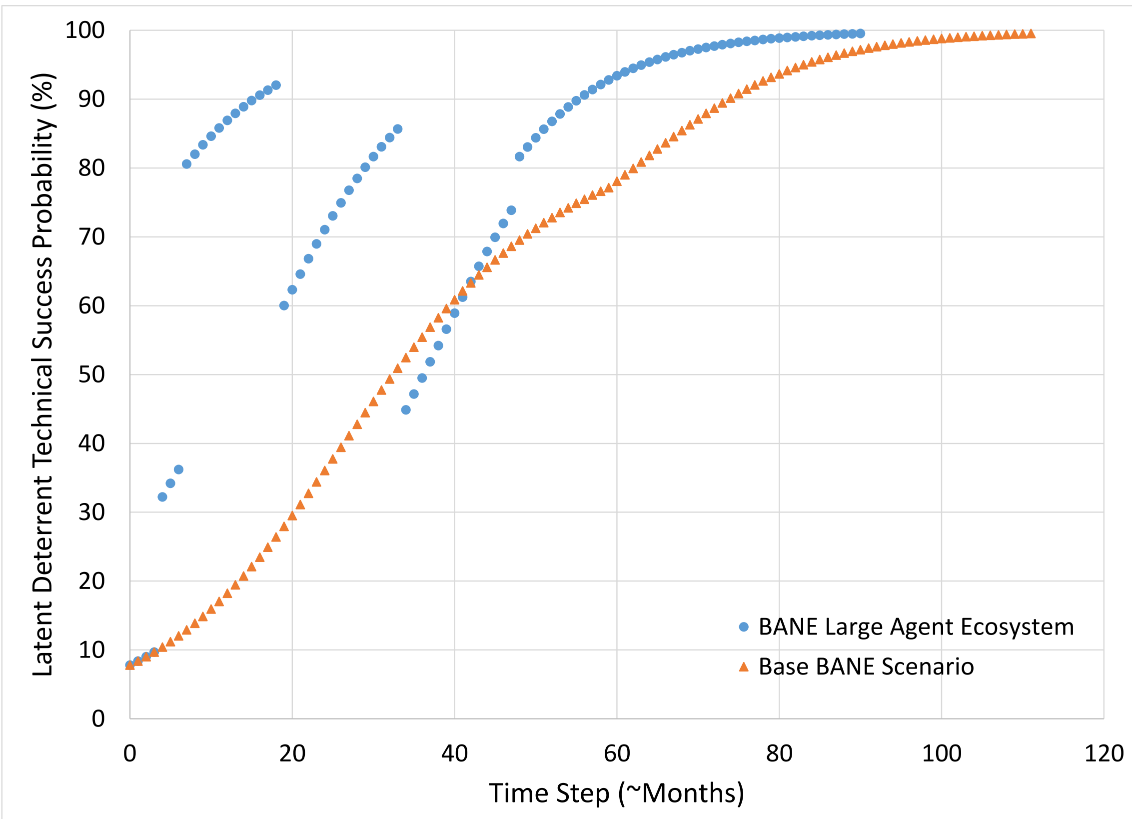


Figure 6-1. Impact of export control violations and responses on proliferation

The primary agent "fortuitously" makes a useful proliferation connection early. This is analogous to a proliferator obtaining access to an A.Q. Khan based gas centrifuge proliferation ring. The neutral supplier provides first generation aluminum tube centrifuge technology. Through the initial neutral supplier connection the primary agent quickly makes another supplier contact. The second neutral supplier uses the first for routing additional gas centrifuge related rotor technology. After the second neutral supplier, the primary agent has advanced rapidly and pursuing advanced composite gas centrifuge becomes feasible. Leveraging its indigenous composites industry is studied by the primary agent.

The quick succession of international contacts and hurried primary agent proliferation progress does raise flags. This is loosely analogous to the counter-proliferation detection experienced by the A.Q. Khan network and its clients.[128] A monitoring defensive agent notes the seemingly sudden nuclear acquisitions. Additional defensive agent scrutiny leads to an evolving awareness of the primary agent covert nuclear program. Reaching out to an allied defensive agent, an effort is initiated to roll back the primary agent proliferation. The primary agent domestic filament winding machine capability is setback by the defensive agent partnership.

The defensive agents relax their vigilance on the proliferating agent until they again note potentially significant proliferation. A coordinated defensive agent response marks magnetic bearing R&D for interruption. Losing the magnetic bearing access after the filament winding machine gas centrifuge stoppage temporarily cripples the primary agent nuclear program. The primary agent does benefit from gas centrifuges lessons learned. Returning to less advanced technology, the primary agent pursues maraging steel gas centrifuges. Eventually, through persistent effort the primary agent succeeds in obtaining its latent nuclear deterrence after 91 time steps.

A comparison base scenario is provided in Figure 6-1. The base scenario constrains the proliferator to purely internal R&D progress. For a less effective proliferator such as Libya, the base scenario is a better approximation of the weak internal technical and governmental organization structure underpinning nuclear proliferation. A justification for this posture might be an extreme paranoia of covert nuclear program detection. In reality, the last decades have ushered in a growing information and digital age. Therefore, a proliferating agent would never be completely cut off from potentially beneficial proliferation knowledge and technology. When coupled with applying newer technology to older methods of proliferation, a large increase in proliferation capability is possible.[129]

Absent international connections, the proliferating agent progression begins with the familiar hedging strategy. After committing to gas centrifuges, the proliferating agent undertakes to master the pathway R&D sections. Just prior to 60 time steps, the proliferating agent heavily invests in advanced centrifuge technology. The prompt over expenditure of large R&D resources matters for undertaking a succession of high technology proliferation pathway projects. Even with the additional R&D resource commitment, the proliferating entity still requires 112 time steps to succeed.

Contrasting the base scenario with the first situation underscores the value of affinity connections for nuclear proliferation technology transfers. In the first scenario the proliferating agent was successful at achieving latent deterrence over 20 time step sooner. This was despite the two defensive agent interventions. Without the burdens extracted by the defensive agent coalition, the proliferating agent success could easily present the global community with a latent deterrence fait accompli.

For a truly authentic proliferation assessment greater detail could be included for the proliferating, defensive, or neutral supplier agents. A proliferator wanting a nuclear weapon for immediate security concerns and with a stronger technical and government system would likely proliferate far more effectively using gas centrifuges.[130] Whether the defensive agents are more effective in stopping proliferation or international political pressure reduces proliferating agent demand for proliferation could be elaborated upon. Using BANE to explore those and other interlocking proliferation details could shed new light on more effective counter proliferation strategies.

VI.A.2. Case 2: Soviet Union Foreign Assistance and Espionage

In case 2, the nuclear weapon proliferation of Union of Soviet Socialist Republics (USSR) is considered. The USSR nuclear weapons program contains many proliferation aspects seen in later nuclear proliferation efforts. The major Soviet move came in October 1940 to initiate its nuclear weapons program. The governing Soviet Presidium funded the annual acquisition of 1500 kg of uranium bearing materials and the 300 kg of uranium salt from Soviet industries.[131] Soviet government proliferating agent actions were matched through activation of the uranium mining BANE node. Following Soviet domestic uranium mining the BANE network responded by increasing the HEU gun and implosion weapon pathways into the teens shown in Figure 6-2. The plutonium implosion route was unchanged with virtually no chance of occurrence. At this stage in

1940, the BANE network depicted in Figure 6-3 favors gas centrifuge uranium enrichment. Figure 6-3 then displays BANE favoring gas diffusion, with the remaining uranium enrichment routes being negligible.

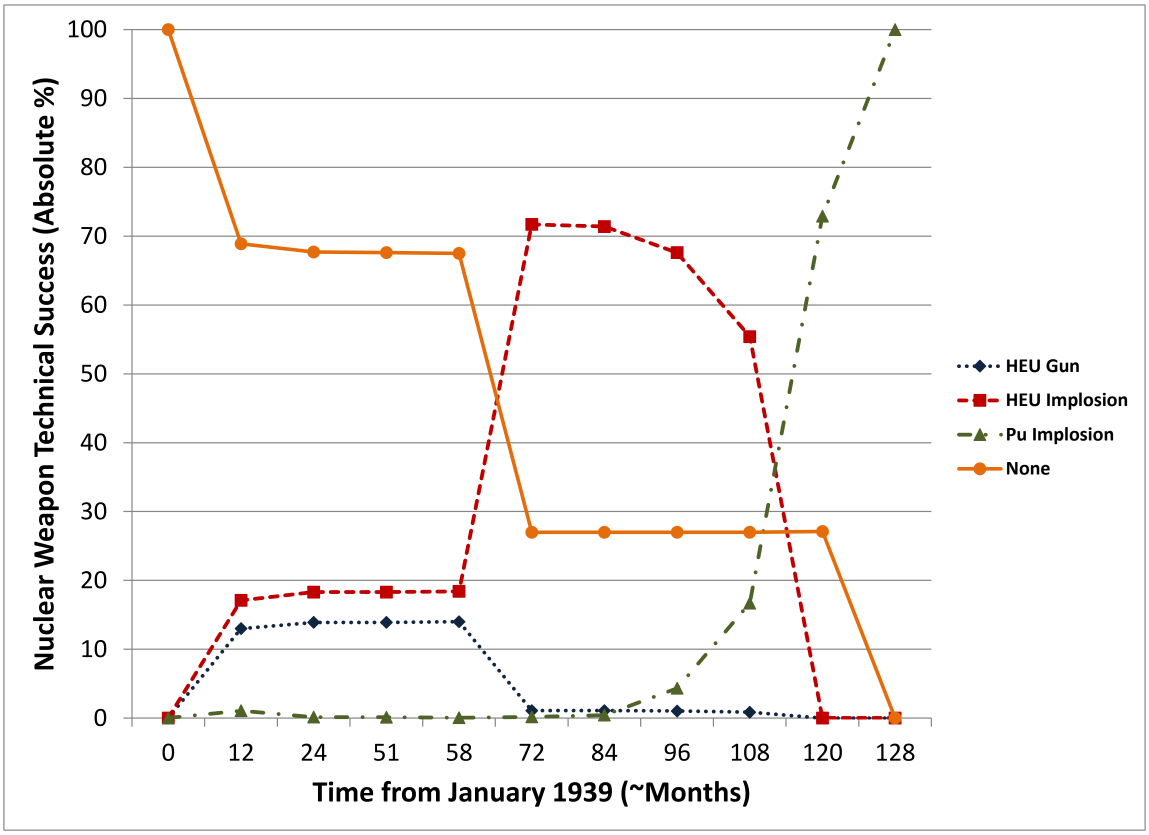


Figure 6-2. BANE Soviet Union nuclear weapon acquisition pathways

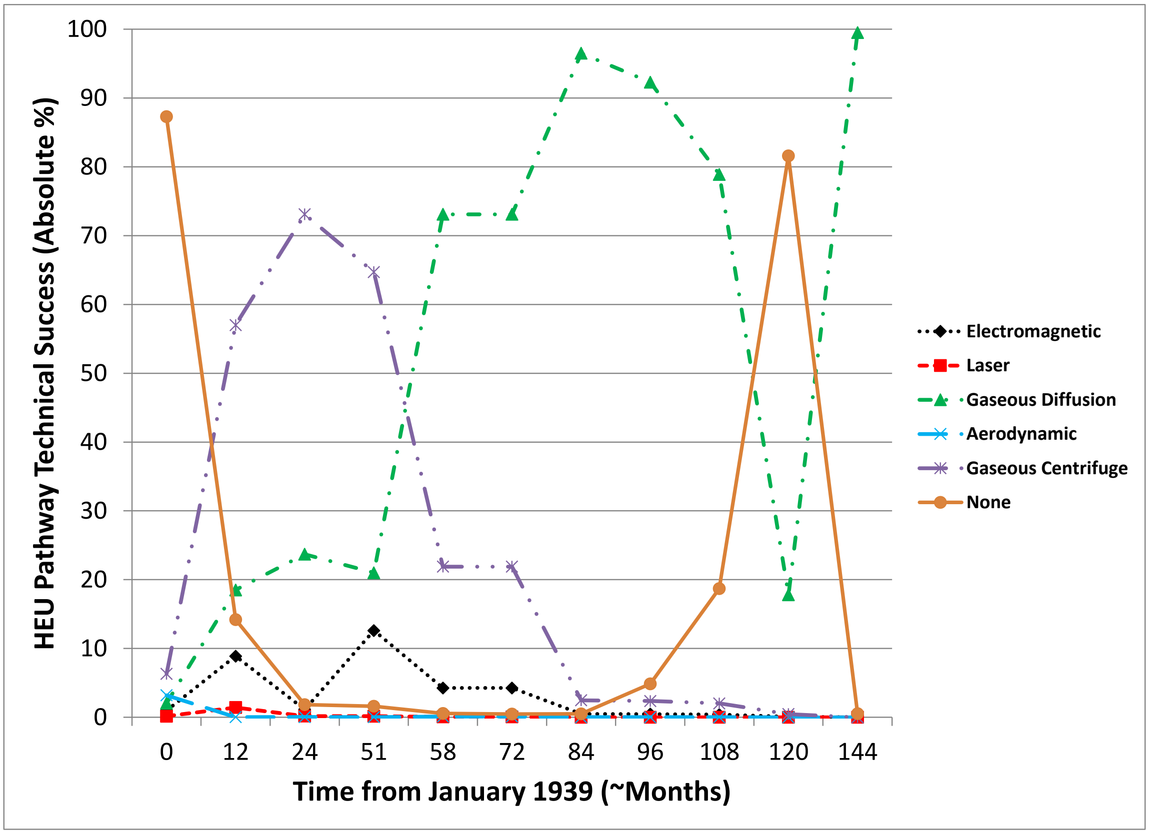


Figure 6-3. BANE Soviet Union uranium enrichment method pathways

Although Soviet UF_6 expertise escalates the gas centrifuge and diffusion pathway primacy, the relative weapon route preferences remain unchanged. The interest in UCl_4 suggests Soviet investigation of the EMIS HEU pathway in 1943. The EMIS UCl_4 constituent shifts the BANE Soviet proliferating agent EMIS route up at the expense of the gas centrifuge and diffusion pathways. However, by the end of 1943 Soviet attention fixates on gas diffusion uranium enrichment instead of other HEU producing technologies. The Soviets possess the necessary gas diffusion energy requirements. Once the Soviet proliferating agent meets the energy requirements the gas diffusion pathway increases significantly. The gas centrifuge pathways probability falls; and, the other enrichment routes practically decline to zero.

The United Kingdom contributed Klaus Fuchs to the Los Alamos Laboratory in 1944.[132] Fuchs was part of the "Tube Alloy" team assisting with the Manhattan Project. Additionally, Fuch was a Soviet spy who was able to transfer nuclear assistance, particularly on implosion methods for plutonium weapon initiation. The BANE network ancillaries for Fuch's plutonium implosion technology provided to the Soviets are the high explosive lends, plutonium initiator, and tamper designs.[133] With the neutral agent assistance from Fuch's, the Soviet HEU implosion pathway probability surges dramatically. The Soviets also are widely considered to have receive nuclear secrets from other Manhattan project penetrations. Nuclear benefits accrue from Soviet espionage diversity using other sources such as Julius and Ethel Rosenberg, David Greenglass, and Morton Sobell.[134]

In the centralized Soviet bureaucracy, its leader, Josef Stalin had significant influence on the nuclear weapons program. Choosing the plutonium implosion pathway for nuclear weapons was swayed from the upper Soviet echelons. By 1947 construction on nuclear reactor and a corresponding plutonium reprocessing plant began. The fundamental scientific R&D behind plutonium reprocessing was successfully completed. The BANE network responded by making the plutonium implosion pathway more likely. Construction finished on the reprocessing plant in 1948. Reflecting enhanced Soviet reprocessing expertise, the BANE network grew the plutonium implosion path vis-à-vis the HEU nuclear implosion route. When the Soviet Chelyabinsk-40 reactor complex became operational for plutonium production the Soviet proliferating agent decisively favored a plutonium implosion weapon. Once the Soviet agent mastered plutonium production, the BANE network demonstrates the HEU implosion device probability becomes miniscule. The plutonium implosion weapon became the dominant weapon pathway.

On August 29th, 1949 the USSR initiated its first complete nuclear weapon system test. The USSR RDS-1, Soviet code name "First Lightning," nuclear device provided a 20 kt nuclear yield.[135] The U.S. developed "Fat Man" plutonium implosion nuclear weapon was very similar to the later RDS-1. The Soviet test in 1949 confirmed the Soviet proliferation agent BANE Bayesian network indication of a plutonium weapon.

It is worth bringing attention to the pathway tradeoff nature of the BANE Bayesian network. Technical steps raising the plutonium weapon route probability were partially or entirely offset by lessening the enrichment pathway probabilities. Intuitively this is expected behavior. Acquiring expertise and production of HEU is not obligatory for a plutonium weapon. This matches the belief that plutonium pathway pursuit comes at the expense of uranium enrichment efforts. The Soviet gaseous diffusion pathway drops upon obtaining stable plutonium production. Still, BANE does respond with an increase in gas diffusion likelihood once the diffusion facility became available for enriching uranium.

Hans Bethe's 1945 prediction estimated the USSR obtains a successful nuclear weapons program by 1950.[136] That it took the Soviet's 4 years, suggests that the USSR espionage benefit was 1 year. Outside assistance undoubtedly provided the Soviet Union's nuclear weapons program with economic and technical benefits.

Later nuclear weapon R&D by the Soviets and captured Germans and Austrians led by Dr. Max Steenbeck and Dr. Gernot Zippe in areas such as gas centrifuges.[137,138] An exploratory scenario of the Soviet gas centrifuge progress considering expected outside assistance extent is important. The captured World War II former adversaries supported Soviet gas centrifuge development.[139] With gas centrifuges based on foreign assistance the Soviets developed a less energy intensive and more efficient means to produce HEU.[140]

The United States only learned about the Soviet progress on gas centrifuges following the Soviet release of Dr. Zippe during summer 1956.[141] By 1957, Dr. Zippe was in the United States being debriefed about the Soviet gas centrifuge program. With Dr. Houston Wood, Dr. Zippe at the University of Virginia helped the United States recreate his gas centrifuge research provided to the Soviet Union.[142] BANE results shown in Figure 6-4 suggest how captured German and Austrians benefited the Soviet gas centrifuge program.

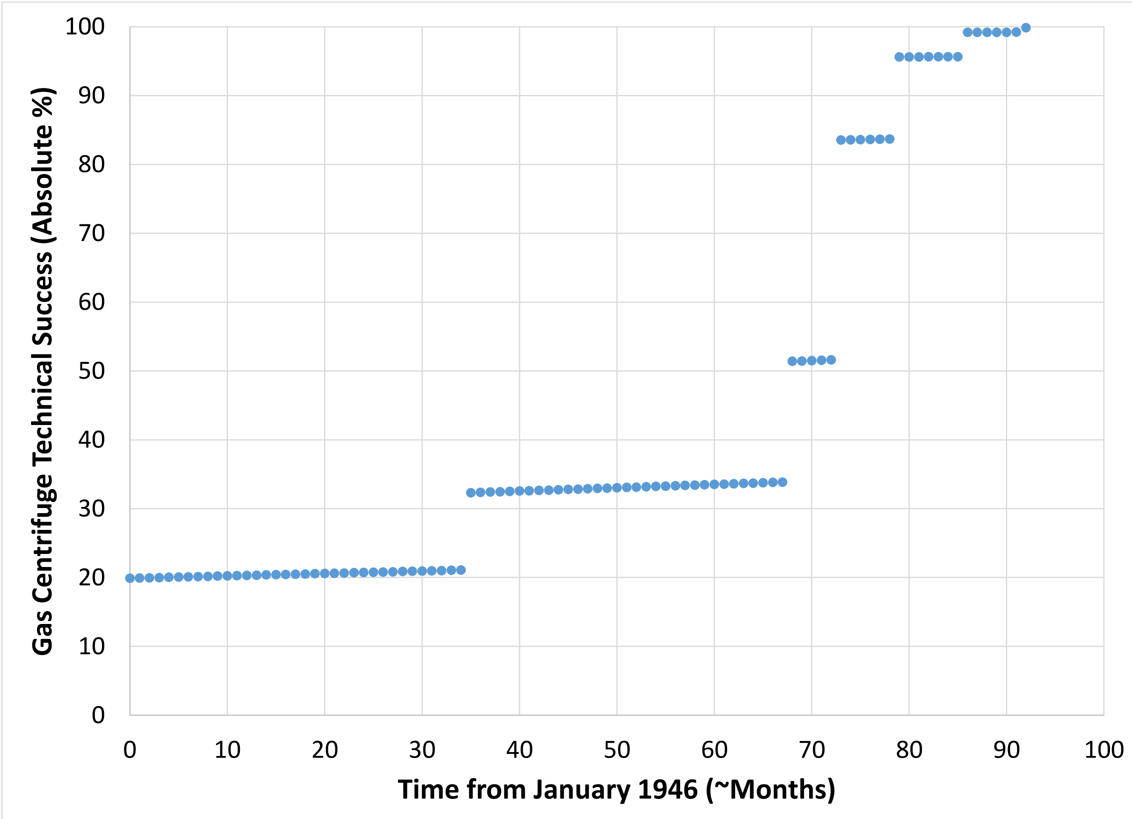


Figure 6-4. BANE scenario of Soviet gas centrifuge uranium enrichment progress

The Soviet Union first developed a viable uranium enrichment method using the gaseous diffusion process. Figure 6-4 shows a BANE scenario for the possible outside aid provided by non-Soviets to the Soviet Union gas centrifuge program. The starting point for Figure 6-4 is January 1946, following Dr. Steenbeck and Dr. Zippe forming their team from seized scientists.[143] Some initial gas centrifuge design interest was spawned from a German, Fritz Lange, who left Germany for the Soviet Union prior to World War II.[144]

Starting in 1949 four large Soviet gas diffusion sites were built at the Electrochemical Plant (EKhZ) in Zelenogorsk, the Anagrsk Electrolysis and Chemical Plant (AEKhK) in Angarsk, Irkutsk region, the Urals Electrochemical Combine (UEKhK) in Novouralsk, and the Siberian Chemical Combine (SKhK) in Seversk.[145] The spy Klaus Fuchs worked on gas diffusion separation barriers and his assistance helped encourage Soviet uranium enrichment planning and direction.[146] Significant Soviet resources, technical expertise, and industrial output went into developing the gas diffusion plants. From 1955 to 1957 the Soviets were bringing the last gas diffusion plant at UEKhK online. Thus, the gas diffusion and gas centrifuge uranium enrichment routes competed for limited Soviet technical and industrial output.[147] The resource limitation is readily apparent in the low progress rate for Soviet gas centrifuges Figure 6-4 depicts.

Progress on Soviet gas centrifuges included technical advancements, such as in metallurgy development, which would later prove useful. In Figure 6-4 innovations in those outside areas are shown with BANE to provide key gas centrifuge capability jumps. The focus of the BANE study was the time to creation of the first successful Soviet gas centrifuge prototypes. The Soviet gas centrifuge study showcases the ability of BANE to assess major nuclear program component technical success. It should be noted that the Figure 6-4 timeline extends beyond the much shorter timeframe for the really dedicated Soviet gas centrifuge program work.

The Soviet and German gas centrifuge teams exchanged information, but the flow was not always equal both ways. In early 1952, the Soviet researcher Dr. Evgeni

Kamenev had major contributions for a successful sub-critical gas centrifuges.[148] By keeping the rotor length beneath the height in which it would pass through critical flexing while spinning a stable centrifuge was created. Dr. Kamenev was part of Dr. Isaac Kikoin's Soviet gas centrifuge research team.

The Dr. Steenbeck and Dr. Zippe team successfully employed the bottom needle bearings and top magnetic bearings to gas centrifuges.[149] The needle bearings were important to allow the gas centrifuges to reach balanced, high rotational speeds without friction damage. The magnetic bearings at the rotor top allowed the stabilization of the remainder of the fragile rotor while preventing wear. The top and bottom bearing system created the means for a properly aligned rotor and substantially decreasing individual gas centrifuge stage power consumption. Another advantage of the magnetic bearings was it opened the way for electromagnetically induced centrifuge rotation.[150] Prior mechanical rotation systems introduced friction and degradation that impeded efficient centrifuge operation.

The Soviets under Dr. Kamenev also created the molecular pump system using an outer protective tube casing. The magnetic bearing system helped created a pressure gradient in the rotor which increased the UF_6 gas separation efficiency. A pressure evacuation system using a molecular pumping configuration could then remove the slightly built up protective tube pressure. The decreased power draw meant less pump work was needed per gas centrifuge stage.

Dr. Kikoin aided the gas centrifuge design effort by implementing a bottom stationary scoop within the rotor. The bottom scoop enhanced the countercurrent UF_6

gas flow and pressure differential. The improved UF_6 flow increased the concentration of heavier $U^{238}F_6$ near the scoop bottom exterior. With a baffles arrangement just beneath the top rotor scoop the countercurrent flow was maintained. The lighter $U^{235}F_6$ concentrated near the upper central portion of the rotor above the baffles for removal to the next stage.

The international approach to gas centrifuge development worked for the Soviet Union. In Figure 6-4 BANE indicates how major breakthroughs between the different gas centrifuge design teams boosted the overall program technical success. The advancements were made while the Soviet Union continued to bring online the proven gas diffusion plants. BANE properly showed relative R&D difficulties by one team could be countered either internally or with the assistance of the other researchers. By 1953 the Soviet Union had developed an effective sub-critical gas centrifuge.[151,152] However, it would not be until 1956 that the apprehended German and Austrian scientists would be allowed to leave the Soviet Union.

The gas centrifuge program gave the Soviet Union a large boost in uranium enrichment capability once the pilot plant design was proven.[153,154] Banks of interconnected sub-critical centrifuges could replace gas diffusion stages in the existing uranium enrichment facilities. The physical size of the uranium enrichment plants remained unchanged.[155] What benefited the Soviet Union was the replacement centrifuge banks produced much higher Separative Work Units with lower power consumption.[156] The centrifuge bank upgrade was therefore a severe external detection challenge. From an electro-optical satellite image standpoint the Soviet enrichment facility footprint remained the same.[157]

VI.A.3. Case 3: Pakistan External and Internal Nuclear Aid

Pakistan is the third nuclear weapon analytic case. In 1961 the Rawalpandi Pakistan Institute of Science and Technology (PINSTECH) was opened; and, in 1963 the 5 MW research light water reactor (LWR) was constructed.[158] Later, they built an associated reprocessing facility. BANE responded to these facilities becoming operational by growing the plutonium weapon path probability in Figure 6-5. Although small, the most plausible nuclear weapon likelihood was through gas centrifuges.

Canada and Pakistan signed a 1965 contract to build the 137 MW(e) Canadian Deuterium Uranium (CANDU) pressurized heavy water reactor (PHWR).[159] By 1972 the CANDU was completed as the Karachi Nuclear Power Plant (KANUPP). The BANE Pakistani proliferating agent activities were influenced in 1972 by Pakistani President Bhutto's three year nuclear weapon objective.[160,161]

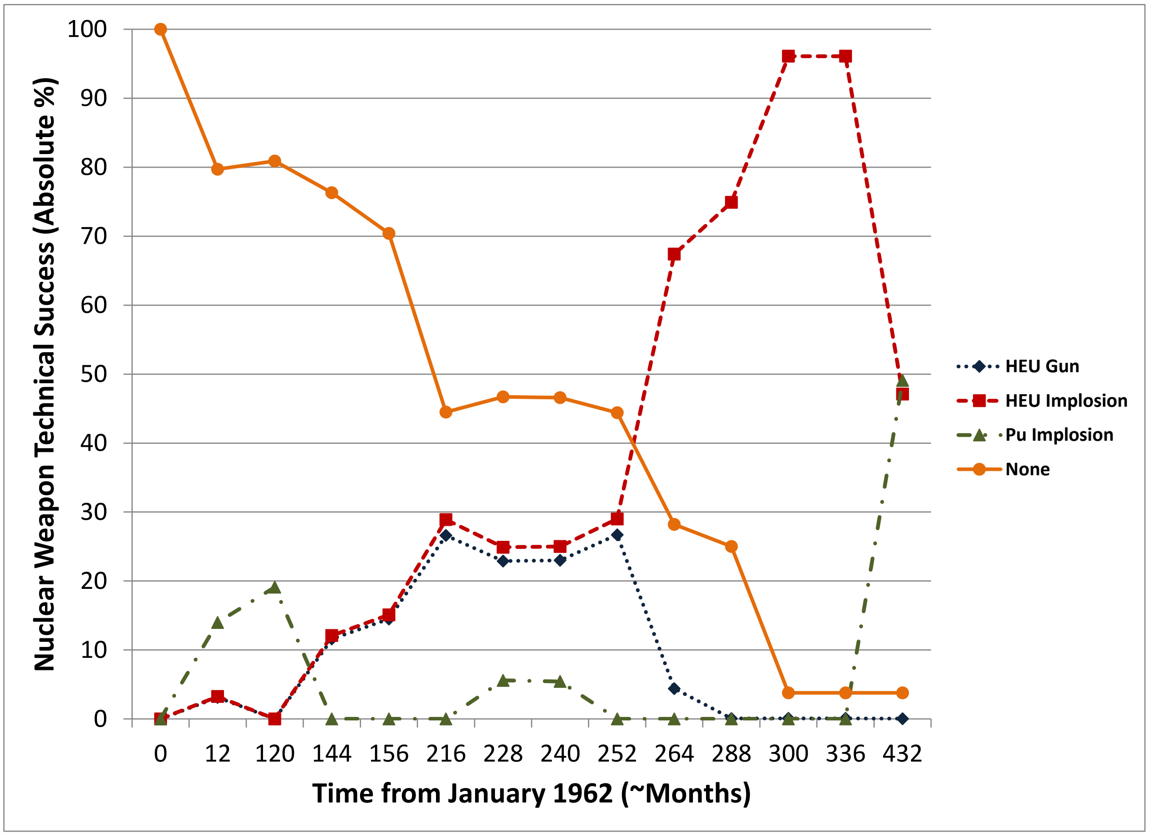


Figure 6-5. BANE Pakistan nuclear weapon acquisition pathways

Although in 1972 the plutonium pathway spiked, by 1974 it begins to recede for a few reasons. Following the establishment of KANUPP the Pakistani's reached an agreement for France to provide an industrial scale reprocessing plant.[162] Despite having an inked contract, the French later pulled out of the deal. The impetus for the cancellation was the 1974 Indian "Smiling Bhudda" nuclear device test. The 1974 Indian nuclear test led to enhanced international restrictions on export controls for nuclear and related technologies. The increased export controls in BANE greatly decreased non-

Pakistani affinity engagements, while heightening the Pakistani proliferating security concerns.

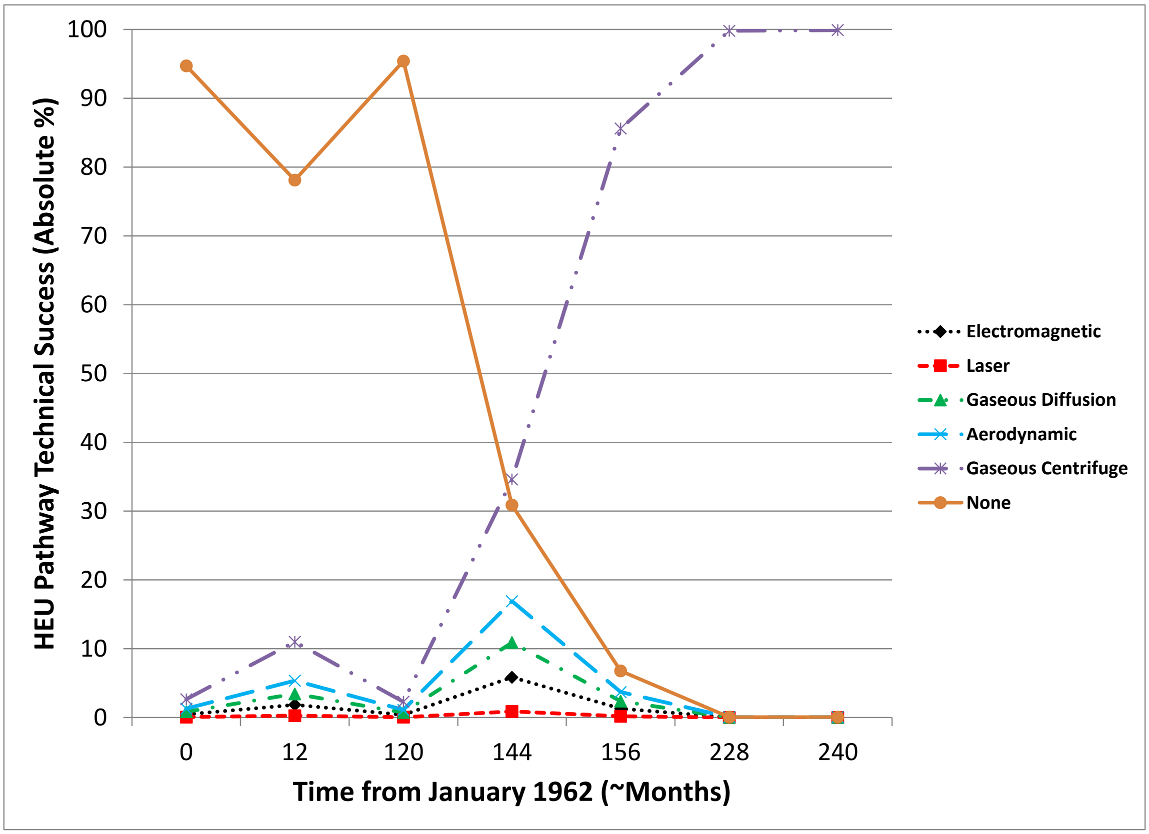


Figure 6-6. BANE Pakistan uranium enrichment method pathways

Inertia for the URENCO gas centrifuge expert A.Q. Khan's return to Pakistan came from the1974 Indian nuclear device explosion. Khan recommended that Pakistan pursue uranium enrichment using gas centrifuges. The Pakistani's began the gas centrifuged based Project 706, which was instituted and obtained priority as the primary SNM acquisition pathway.[163] In BANE the Pakistani proliferating agent choices increased the HEU weapon routes. Correspondingly, the plutonium implosion weapon route declined to a negligible level.

With A.Q. Khan's assistance in 1974 Pakistan's uranium enrichment options grew. Through the auspices of the Dr. A.Q. Khan proliferating agent gas centrifuge knowledge and supplier network, the Pakistani proliferating agent started receiving gas centrifuge constituents. The BANE network indicates the greatest proliferation pathway stems from gas centrifuge uranium enrichment as expected from the Project 706 program. Using his connections Dr. Khan, acquired 6000 Netherlands origin maraging steel tubes. The BANE network adjusts to the Dr. Khan agent supplied connections triggering the high strength tubes and maraging steel Pakistani proliferating agent capabilities. Furthermore, Dr. Khan secured material and equipment rerouting and other assistance through entities located in Germany, Switzerland, the United Kingdom, Canada, and Malaysia.[164,165] At this point the over 99.9% uranium enrichment likelihood uses the gas centrifuge pathway. The HEU gun and implosion weapon routes continued to grow at the expense of the plutonium implosion routing being zeroed out.

The overall benefit of the A.Q. Khan network is debated versus the indigenous Pakistani gas centrifuge program.[166] The URENCO Cultivated Nuclear Orbital Rotor (CNOR) was the first Dutch attempt at building a supercritical centrifuge. The plans and designs stolen by A. Q. Khan did not have the later Dutch fixes that eventually enabled their operation.[167] The Pakistani infrastructure base allocated to centrifuge designs might have been effective for supercritical machines, but required outside technical expertise to initially build the supercritical centrifuges. The effort to obtain critical gas centrifuges components internationally alerted global counter-proliferation attention to Pakistan. A. Q. Khan's lack of direct gas centrifuge building and operating expertise was also considered by some to hinder Pakistan's program.[168]

The early 1980s did witness a Pakistani renewal in plutonium reprocessing desires. Reportedly,Pakistan received some plutonium reprocessing technical support from a Swiss company.[169] The Pakistani's created pilot and small scale plutonium reprocessing facilities.[170] The plutonium facilities are included in BANE for the Pakistani proliferating agent. The evolving Pakistani proliferation capabilities altered the BANE network whereby the plutonium implosion weapon again grew to being non-negligible.

The Dr. Khan proliferating agent aided the Pakistani proliferating agent by standing up in the early 1980s an industrial scale UF_6 production facility. The UF_6 facility was constructed piecemeal from a West German origin supplier.[171] The indigenous UF_6 access benefits Pakistan's gas centrifuge SNM route. However, the centrifuge path was so high to begin with, the UF_6 provides only a minor HEU weapon benefit relative to the plutonium implosion pathway. Starting in 1982 Pakistan possessed sufficient gas centrifuges to annually build six HEU nuclear weapons. The BANE Pakistani proliferating agent HEU node was triggered. Again, the plutonium implosion weapon pathway declines to functionally zero, while the two HEU weapon pathways probabilities enlarged.

The HEU implosion path was bolstered by Pakistan's 1986 high explosive package cold test for an implosion system.[172] The associated BANE network change involved the Pakistani proliferating agent developing high explosive package proficiency. The presence of a HEU high explosives implosion system caused the HEU gun type likelihood to plummet relative to the HEU implosion nuclear weapon pathway. Later testing of a more comprehensive non-nuclear implosion system occurs. In response, the BANE weapons package is assessed to the Pakistani proliferating agent. The BANE network responds by further increasing the HEU implosion pathway. At this point the HEU gun type weapon likelihood becomes insignificant.

For nuclear weapon diagnostics, buying oscilloscopes in 1987 is beneficial to Pakistan.[173] With BANE, the oscilloscope acquisition causes the HEU implosion pathway to become incredibly probable for the Pakistani proliferating agent. Following US intelligence revelations about Pakistan uranium metal machining, HEU pit capability is assigned to Pakistan.[174] Figure 6-7 indicates the benefit of foreign assistance to Pakistan's secondary route for obtaining SNM for nuclear weapons.

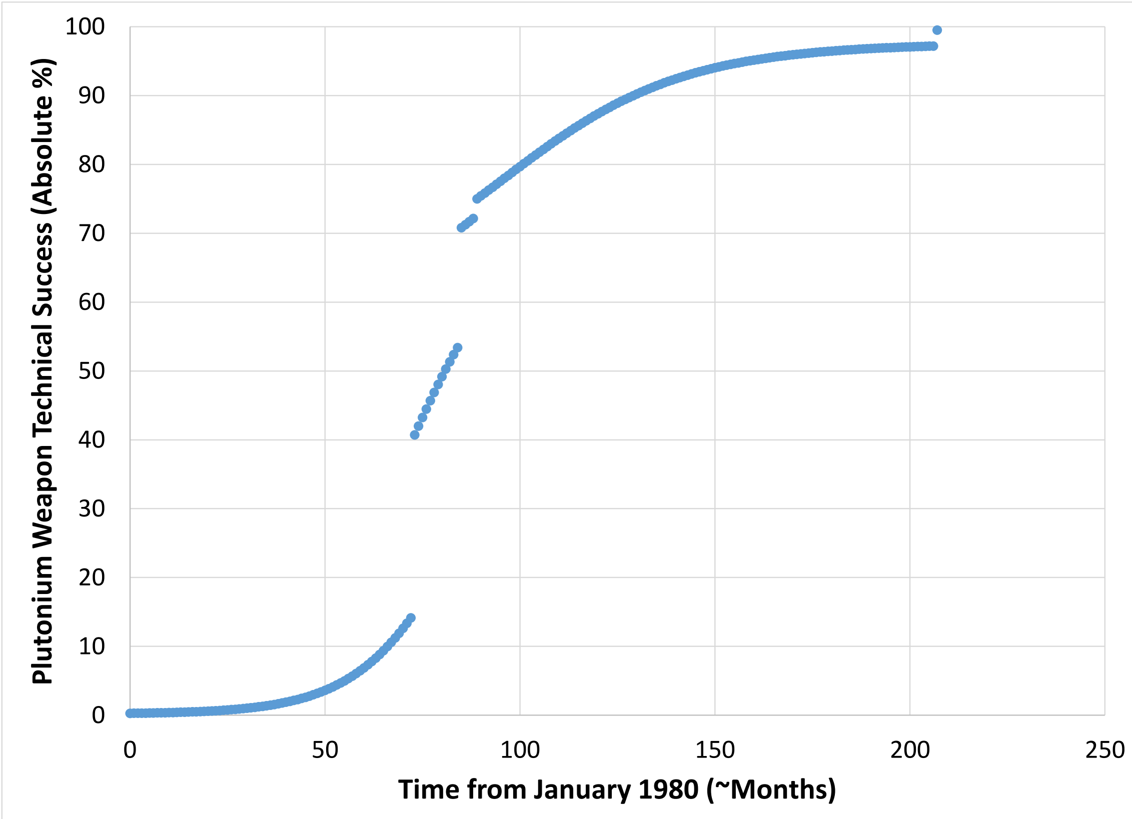


Figure 6-7. BANE Pakistan plutonium secondary SNM weapon route

In the 1990's China provided valuable assistance to Pakistan's nuclear program.[175,176] The BANE Bayesian network nuclear reactor was beneficial to the Pakistani proliferating agent based, and represented the work started indigenously at Khushab.[177] The addition of the domestic nuclear reactor effort represented several major technical pushes being undertaken by the Pakistan proliferating agent. In Figure 6-7 the jump in expected plutonium weapon success is demonstrated by BANE. Although not all achieved at once, the Pakistani proliferating agent was eventually better positioned to conduct R&D with additional resources.

Completion of the HEU nuclear implosion weapons provided some cross over expertise to the Pu implosion route. In Figure 6-7 the two smaller jumps arise from the nuclear weapon assistance between Pakistani proliferating agents. Towards the end of the BANE simulation several events converged. First, the availability of plutonium as an SNM option even if not allocated from safeguarded civilian usage to non-civilian purposes. Second, the expectation of additional nuclear weapon test data from the Pakistani nuclear tests. Eventually the Pakistani plutonium implosion device reached rough equilibrium with the HEU implosion weapon pathway. The HEU gun type or no nuclear weapon option likelihoods were trivial.

BANE demonstrates the centrality, for better or worse, of Dr. A.Q. Khan's technical knowledge and supplier network to Pakistan navigating the gaseous centrifuge pathway. Furthermore, Dr. Khan's presence was dictated heavily by the 1974 Indian nuclear test. As Pakistan's nuclear program evolves based on emerging proliferator abilities and connections, the BANE path selection probabilities adjust accordingly. This leads to BANE indicating alterations in different technologies and nuclear weapon stockpile opportunities.

VI.B. BANE Multi-Module Scenario Insights

Taking advantage of the full suite of BANE modules provides an advanced nuclear nonproliferation assessment framework. Each horizontal and vertical nuclear proliferation effort has domestic R&D and global knowledge or resource acquisition aspects. Proliferators constantly weigh the demand-side drivers of latent or actual nuclear weapon programs against the risk of international exposure. With BANE, the repercussion severity might be insufficient to deter an insecure state, or even non-state, entity. From a supply-side perspective, proliferators are considering the benefits of indigenous R&D versus external support in areas such as technology transfers. Variations in decision calculus are captured in BANE to study the impact of different resource, detection, and risk aversion postures on proliferation outcomes.

The export control violation case demonstrates the intertwined benefits and costs associated with foreign technology sources. Using the BANE network with entropy reduction, the proliferating agent recognized and updated its beliefs in the best nuclear weapon progress paths. The short term gains from external proliferation assistance are eventually challenged by the induced scrutiny from counter proliferation efforts. Chapter 6, case 1 defensive agents have the capabilities to levy strong penalties on the proliferating agent. However, for case 1 the defensive agents reach the limitation of their capabilities while the proliferation is ongoing. Without additional resource outlays, international partners, or other support, the defensive agents are forced to impotently watch as the proliferating agent reconstitutes its nuclear program. The defensive agent realism built into BANE simulations matches the trials of actual counter proliferation entities.

Moving into the historical realm, BANE displays its ability to account for a multitude of activities happening in rapid succession. The Soviet Union's nuclear proliferation program was dual track. The Soviets invested in internal nuclear weapons program R&D. Concurrently, the Soviets also exploited external espionage on the Manhattan Project with corresponding nuclear weapon gains conferred. BANE allowed for the multiple internal and external proliferation choices to dynamically influence the Soviet nuclear weapons program direction.

The Pakistani proliferation case presented a strong demand-side to a BANE proliferating agent. The eventual Pakistani President Bhutto declared, “Pakistan will eat grass or leaves, even go hungry in order to develop a [nuclear] program of its own.”[178] Pakistan’s conventional insecurity prompted a sizable fraction of its scientific community, including A.Q. Khan, to assist in developing the nuclear weapons program. Pakistan’s willingness to expend almost any means to overcome technical challenge is characterized in BANE by the level of internal support. The domestic support translated into Pakistan’s extensive tapping of international supply-side aid. Nuclear and non-nuclear knowledge, equipment, and material were all attained by Pakistan; and, these events are accounted for through the range of BANE modules.

CHAPTER VII

CONCLUSIONS

The BANE proliferation assessment tool balances intricate policy and technical factors simultaneously. The modular BANE arrangement facilitates including new proliferating, neutral, or defensive agent attributes in decision making. Verification and limited validation for BANE was performed using scenarios and historical case studies. As a newly developed tool, BANE has room for future contributions from computer science, engineering, and social scientists.

VII.A. Bayesian and ABM Justification for Nuclear Nonproliferation

The Bayesian and ABM methods are beneficial for BANE providing nonproliferation assessments. Bayesian inference has been employed in fields where information limits are ever present, such as intelligence. Correlating incomplete evidence for pattern recognition in BANE using Bayesian inference draws upon technical supply side proliferation linkages grounded in physics. Demand driven motivations for nuclear proliferation vary. Potential or current proliferator security, economic trajectory, or other factors modify the willingness to undertake proliferation steps. With Bayesian inference, the coupled demand and supply proliferation drivers are connected to create feedback interactions.

Nuclear proliferation does not occur in a vacuum. BANE's ABM capabilities address the interplay between entities pushing or pulling them towards undertaking nuclear weapons programs. The impact of a few key outside actors can cause major alterations in the robustness and effectiveness of proliferation. Understanding the multiplication factor of external support during critical proliferation phases is a BANE ABM derived advantage. The BANE ABM and MAS oriented ecosystem creates the framework for learning lessons about relative proliferation enabler, interference, and deterrent posture benefits.

A major drawback to contemporary nuclear proliferation tailored methodologies is their static nature. Barrier nuclear proliferation codes emphasize proliferation thresholds, often on the nuclear material side. For purely SNM characterization of a small subset of the proliferation supply problem, the Barrier methods are beneficial. Static Pathway methods are highly constrained for handling intelligent proliferators or restricted counter proliferation efforts. The Pathway code routes are generally setup before the simulation; and, to test system perturbations additional parameters must be adjusted prior to the next run.

From a technical perspective, dynamic nuclear engineering programs are more prevalent. The Cyclus code family forms a very dynamic nuclear fuel cycle simulator with well designed and implemented physics and engineering underpinnings. BANE is a dynamic Bayesian and ABM based code geared towards flexible nuclear proliferation assessments. The social science demand drivers and supply side enablers of nuclear proliferation are integral to BANE.

VII.B. BANE Modularity Benefits

The modular BANE nature offers multiple benefits for a nuclear nonproliferation enterprise. Nuclear proliferation is multi-disciplinary and multi-dimensional. Engineers from nuclear, chemical, electrical, and others along with physicist, business executives, senior military officers, political leaders and many other field are involved. Building BANE modules and sub-modules addresses the unique skillsets of the various fields associated with proliferation.

The Netica GUI and API Parser module categories are the broadest, and encompasses policy and technical sectors. A Netica GUI and API Parser delineation is overall the demand side areas of nuclear weapon arsenal type, size, and delivery are policy and military factors. Supply side Netica GUI and API Parser modules are technically oriented around determining the best nuclear weapon acquisition pathways. Boundary blurring is toughest for the Netica GUI and API Parser modules, as they are dominant in any BANE simulation.

The SQL data management system makes agent information accessible to other BANE modules. SQL database tables are agent searchable and manipulated to allow dynamic adjustment to proliferation preferences. Optimization within BANE includes additional fields associated with resources and proliferation detection. The preponderance of proliferation resource management decisions stem from politicians and military officers, with wide variations in business executive and senior technical researcher input. Detection capabilities are driven by a range of physics, engineering, and social science inputs that define counter proliferation prowess.

Maintaining BANE authenticity drove the uncertainty modules. No proliferation or counter proliferation entity can 100% predict proliferation progress. A major BANE motivation is handling the true nature of random proliferation advancements and setbacks. The BANE uncertainty modules can be included multiple ways to evaluate proliferation enterprises.

The affinity and influence modules are the bedrock of social science relationship development in BANE. Friendships, business connections, military liaisons, political confidence building all interact in proliferation decision making. Connections and affiliations in turn define technology transfers, dual use and export control cooperation, etc. BANE captures the social sciences contribution integral for a reliable proliferation assessment methodology.

Omniscience and monitoring modules incorporate challenges that appear unevenly along proliferation pathways. In BANE, the role of defensive entity power and competency can change proliferation political and technical calculus. Decision makers can be informed regarding the challenges of preventing and rolling back proliferation based on their actions. With a modular BANE framework, the omniscience and monitoring aspects can also be continually updated to match counter proliferation perspectives. Depending upon the user, the development of supplementary omniscience and monitoring modules added when pertinent for BANE upgrades is available.

VII.C. BANE Verification and Limited Validation Testing

Performing BANE verification testing on single and multiple module groupings built confidence in the code sections. The confidence in BANE module verifications forges trust when running the integrated code. Chapter 4 covers several single module, and some multi-module, BANE agent empowerment and subsequent verification testing. Shrewd agent technical success selection using entropy showcases BANE advanced information theory and ML employment. Generalized, multi-module empowerment exercises were demonstrated in Chapter 5. Agents were dynamically, and unexpectedly, confronted with proliferation challenges and opportunities requiring logical responses via multiple modules.

Historical proliferation case studies examined with BANE in Chapter 5 provide verification and limited validation. The French, South African, Iraqi, and Swedish cases explored successful and pursued nuclear weapons programs with different BANE modules involved. Running BANE calling modules as needed verified the agents were operating as expected. The limited validation stems from BANE matching historical proliferation trends when a large data quantity is available to inform agent choices. Realistically, the detailed information level with apparent connections is normally absent for ongoing proliferation activities.

There are only a handful of successful proliferation cases. Maybe another dozen to two dozen exist depending upon the definition of significant proliferation attempts. As noted in Chapters 5 and 6, genuine BANE validation would require tens of case studies across different proliferation sectors. In some areas, such as export control and dual use violations, getting enough cases for validation is feasible. However, for most proliferation sectors deference to comments by Alexander Montgomery and Scott Sagan regarding proliferation prediction fidelity limitations ring true.[179]

VII.D. BANE Case Study Proliferation Indicators

There are an array of policy, economic, technical and other limitations and constraints that prevent proliferators from achieving their nuclear program goals. The

Chapter 6 BANE case studies provide proliferation indicators that can suggest key points for decision making. With BANE, the proliferating agents can use Bayesian analysis to adaptively make intelligent choices to overcome pathway barriers. Learning behavior and the ability to backtrack on proliferation pathways are signs of successful agent emulation of actual human behavior.

The proliferation indicators from overconfident proliferating agents are part of BANE. Consciously introducing the potential for proliferating agent imperfections in BANE strengthens the nonproliferation enterprise realism. Social science specifies that individual and collective human choices are affected by “perceptions” of their surroundings. If the perceptions are erroneous then the choices made can be less than optimal. Therefore, BANE assessments are better by accounting for flawed agent decisions.

BANE highlights the effects of different types of proliferation activities on successful nuclear weapon acquisition. From an information denial standpoint, defensive agents operate without omniscience. Imperfect data prevents tailored nonproliferation responses in areas such as export controls or counter intelligence. Policy makers directing counter proliferation programs can witness how their funding selection or operational postures differentially hinder a variety of proliferation routes.

VII.E. Future Work

The structure of BANE was built with nuclear proliferation analysis at the center. As a new tool there is a wide array of opportunities for BANE expansion. Breaking the agent parameters down into more sections to increase agent diversity is one avenue for future work. Computationally, including parallel HPC to BANE would open up new areas for proliferation network relationships from policy, technical, and agent interaction standpoints. The data management system using SQL could undergo shifting to another data storage paradigm. Taking BANE beyond just nuclear proliferation could reveal proliferation pathway selection considering multiple weapons of mass effect and conventional weapon routes.

VII.E.1. Optimization and Agent Attribute Improvements

BANE facilitates agents optimizing technical choices for proliferation while factoring in resource and detection probabilities over time. There are several areas that could be examined and expanded to improve intelligent agent decision making. The resource category could be broken up into economic, industrial, technological, human capital, and possibly other sectors. The detection probability could be decomposed into specific aspects of environmental, electronic / cyber, and imagery proliferation information collection for instance.

Increasing the granularity on agent parameters will aid BANE simulation scenario accuracy. Tailoring agent factors better approximate real world nuclear proliferation situations of interest. Previous nonproliferation work considered databases and correlations that suggested proliferation.[180] With BANE existing information sources on entity characteristics both inside and outside traditional nonproliferation literature would be ideal. Table 7-I indicates a fraction of the sources potentially useful for upgrading BANE agent resource attributes.

Table 7-I. Subset of potential data sources for updating BANE agent parameters

Economic	Industrial	Trade	Technology	Social / Treaties
United States Patent and Trade Office	United Nations (UN) Industrial Development Scoreboard	Foreign Direct Investment	World Economic Forum Technology Index	Nuclear Weapon Treaties
European Patent Office	Electricity Production	Nuclear Cooperation Agreements	UN Development Programme Techology Achievement Index	Military Security Agreements
Gross Domestic Product	Steel Production		RAND Science and Technology Capacity Index	
Uranium Mine Production	Industrial Growth Potential		Power Reactor Capacity	
			Research Reactor Capacity	

Some of the databases in Table 7-I are widely distributed and accessible. If possible the other data sets could be obtained, otherwise substitute information resources could be employed. Enhancing BANE agent fidelity in the detection areas could come from a variety of input venues. For instance, outlines for IAEA open source analysis strategies and objectives are available.[181]

Several of the databases in Table 7-I hold potential for improving BANE agent affinity modules. Incorporating broader trade records might enable improved analysis of neutral supplier interactions with potential proliferators. Furthermore, technology and corporate acquisitions can serve as proliferation front and shell companies. Understanding the nature of dispersed, targeted intellectual property and equipment supporting proliferation is easier with BANE. The Bayesian inference and entropy relationship assessment in BANE is useful pattern recognition foundation.

VII.E.2. BANE Parallel and High Performance Computing

Growing the number of BANE agents in simulations has considerable proliferation assessment value. In BANE, each agent performs a number of complexly integrated calculations to determine future choices. Decomposing the resource and detection probability categories in BANE will intensify optimization calculations. Upgrading BANE parallel and HPC architecture will decrease the computational cost of agents requiring extra decision making.

Forecasting proliferation will need to recognize the increasing global interdependence and technology diffusion. There are significant number of government, corporate, and individuals involved in international and domestic commerce. Entities with proliferation technical expertise comprise a tiny subset of those conducting appropriate business and relationships. Taking advantage of multi-core processing will enable BANE to handle scaling agent sizes. The neutral supplier agents involved in BANE simulations could be expanded with greater computer resources to manage them.

A BANE version with parallel HPC architecture could readily undertake fully stochastic uncertainty simulations. Propagating uncertainty aggregation with large numbers of agents making thousands of decisions over hundreds of time steps is computationally challenging. Repeating the same BANE simulation stochastically hundreds or thousands of times could uncover policy and technical configurations favoring proliferation.

BANE is designed for computers with Windows operating systems. Taking BANE even partially into the open source arena may require a rethinking of Windows only compatibility. Locating open source programming library replacements, such as Boost C++, is worth exploring for BANE. A hybrid open system might be possible with BANE. The Netica API-C library works for UNIX. For BANE demonstration purposes in open source environments, providing a key for running Netica might be an option.

VII.E.3. Consider HDF5 for Supplementing SQL Data Management

SQL is the cornerstone of BANE data management. Each BANE agent possesses unique parameters that must be cataloged. Currently, SQL database operation in BANE is an appropriate mechanism for cataloging agent and proliferation figures. There are no information processing barriers with SQL databases running BANE on multiple Windows machines.

In the future, Hierarchical Data Format (HDF) might be a data storage method to consider. HDF version 5 (HDF5) is becoming more widely used in the scientific computing community for large scale data management. The HDF5 structure basis is hierarchical data objects versus the relational nature of SQL database tables.[182] As the complexity of SQL databases table information grows HDF5 will potentially offer faster accessibility and data manipulation.

Another advantage of HDF5 is the ease of exchanging data object datasets. Developers working on BANE with HDF5 would not need an intermediary program for moving SQL tables. The HDF5 datasets can easily handle user defined variable types. Combining data types has advantage for information placed in data storage.

From a cautionary standpoint, HDF5 is designed for open source software usage. There are ways to use pre-compiled HDF5 files with Visual Studio. The pre-compiled

HDF5 might not offer the same level of benefit for transitioning BANE from SQL. Redesigning the manner that BANE uses data storage from SQL databases to HDF5 datasets might shift the future implementation of HDF5.

VII.E.4. BANE Evolution into Weapons of Mass Effect Simulator

States balance pursuing Weapons of Mass Effect (WME) against conventional weapon acquisitions to further their national interests. WME includes the traditional biological, chemical, and nuclear weapons along with newer, advanced cyber weapons. Conventional weapons are generally easier to obtain than WME. Incremental adjustments in conventional air, land, or sea based weapons might not redress conventional weapon asymmetries. However, for a state the deterrence value of deployable WME relative to conventional weapons can justify the WME resource commitment.

Economic, technical, and outside non-detection constraints force states to prefer different WME pathways. Pursuing WME requires significant resource allocations away from other economic and security sectors. Knowledge and infrastructure thresholds in key areas must be reached depending upon the specific WME for successful proliferation. Counter WME defensive organizations dynamically attempt to thwart WME outside assistance and indigenous development.

Realistically, no two WME proliferators or defensive entities are exactly identical; and, ABM is a computational methodology addressing the uniqueness of those facilitating or preventing WME spread. Coupling ABM with Bayesian analysis is powerful from an omniscience limitation perspective. Bayesian analysis supports linking crucial knowledge and technology requirements into relationship networks for each WME sector. With a Bayesian network gaining information on proliferator actions in one WME field informs counter WME agents where to expend limited WME impeding capabilities.

Exploring BANE's modularity for expansion to analyze WME proliferation beyond just nuclear threats, and relative to conventional weapon selection, is a future work avenue. Expanding BANE to consider WME and conventional weapon options will increase policy maker understandings about the trade-offs states make in securing their national interests. Figure 7-1 describes a possible arrangement for a WME proliferation framework.

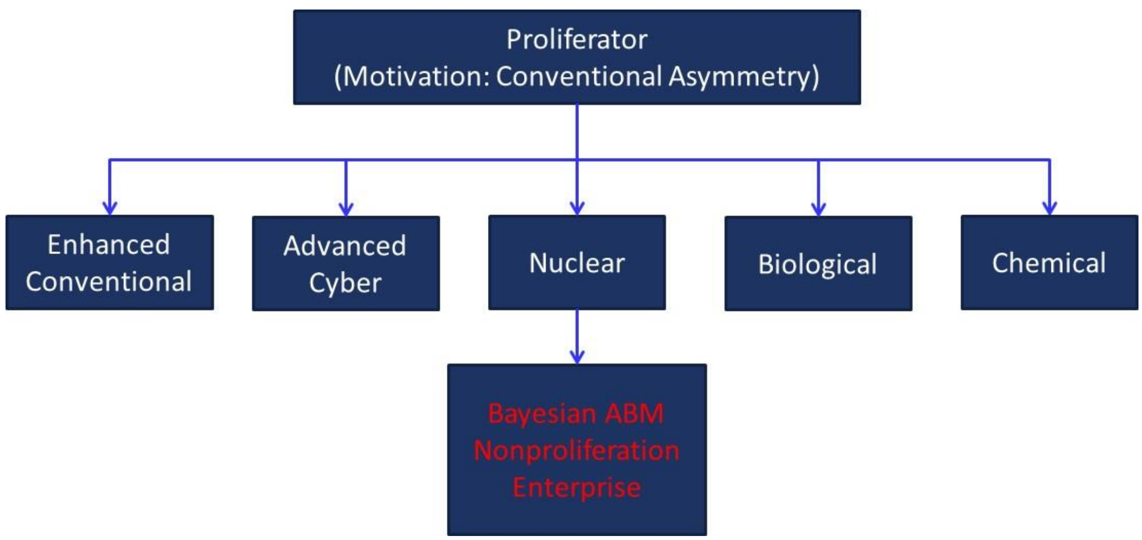


Figure 7-1. BANE arrangement for weapons of mass effect

An important facet of Figure 7-1 is the Enhanced Conventional sector. The Enhanced Conventional arena encompasses major evolutionary upgrades along with incremental increases in conventional weapons approaches. Evolutionary upgrades are new classes of weapons such as the historical introduction of wide spread precision guided munitions (PGMs). A small aerial force equipped with PGMs can devastate an entire armored division or industrial complex. Prior to PGMs the destruction assurance would require an entire air wing of hundreds of planes.

Incremental conventional weapons would allow analysis of qualitative and quantitative trade-offs for military forces. Assessing the cost, and risk of failure, for new weapon system types versus adding more slightly updated current generation weapons. Non-state agents could incrementally increase the capabilities and deployment rates of their improvised explosive devices (IEDs). A limited financial resource and technical base typically will push non-state actors toward conventional weapon preferences.

Following the BANE paradigm, failure to obtain a pursued weapon category precludes its utilization. However, acquiring the desired weapon does not indicate it will immediately be deployed. The presence of a WME may bring a valuable deterrent or prestige benefit. Improved conventional weapons can be stockpiled until a political or security situation justifies their usage.

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