PATHWAYS ANALYSIS FOR STATE PROLIFERATORS

A Thesis

by

MICHAEL REECE MELLA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2011

Major Subject: Nuclear Engineering

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Approved by:

Chair of Committee,	William S. Charlton
Committee Members,	David Boyle
	Christopher Layne
Head of Department,	Raymond Juzaitis

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ABSTRACT

Pathways Analysis for State Proliferators.

(May 2011)

Michael Reece Mella, B.S., Ohio State University

Chair of Advisory Committee: Dr. William S. Charlton

A computational tool to assess the most likely path a state proliferator would take in making a nuclear weapon was created in a Bayesian network. The purpose of this work was to create a tool to facilitate analysts and policymakers in learning about state proliferation. In carrying out this work, a previous Bayesian network based on nuclear weapon proliferation was expanded to include dual-use export controlled technologies. The constant nodes in the network quantifying technical capability, international networking, and available infrastructure were developed to be based on pertinent characteristics that were appropriately weighted. To verify the network, nine historical cases of state proliferation were tested over time, and the enrichment and weapon pathways were graphed. The network sufficiently modeled the cases, so it was concluded that, while one can never truly being able to sufficiently validate a network of this type, sufficient verification was achieved. The tool was used to gain knowledge and insight concerning technology transfers with four countries in hypothetical cases. This exercise proved that the network can in fact be used to learn about state proliferation under different policies and conditions.

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always

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TABLE OF CONTENTS

LIST OF FIGURES

Page

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

I.A. Objectives and Motivations

With the vast spread of technology globally, the threat of nuclear weapon proliferation is more real today than ever before. More countries than ever possess the latent capabilities to construct these ultimate weapons of mass destruction. The strategic and security implications of nuclear weapons make it a priority to attempt to prevent their proliferation. From the vantage point of the United States, in order to choose the correct postures and enact the right policies it is necessary to be able to assess a given nation's nuclear aspirations. This means examining the determining forces that push a nation towards the creation of one of these weapons, the skills and facilities they possess to carry out such a task, and the resources required in making the weapon.

It is becoming more important from an intelligence analyst and policymaker standpoint to accurately assess the paths a state may take to make a nuclear weapon, how far along the various paths the state is, and the time frame to reach points in that path. A computational tool that would assist an intelligence analyst or policymaker to determine the most likely path a state would take in making a nuclear weapon would be beneficial. Such a tool would facilitate the best policies at the best times. It can suggest policies that may increase the time necessary for a given state to complete its weapons program and provide time for further diplomatic efforts to take place.[1]

This thesis follows the style of *Nuclear Technology*.

The objectives are as follows:

1. Develop a network with the capability to predict the most likely path a state might take in proliferation, while incorporating evidence and motivations as a means to adjust these pathways.
2. Assess the relative impact of indigenous knowledge development and access to technology on the choice to proliferate.
3. Explore the impact of loose export control rules on the likelihood of proliferation.

The ability to learn from this computational tool is an important contribution to the future of the nonproliferation regime. It will provide quantitative analysis to support timely decisions to halt the spread of these weapons.

I.B. Proliferation Theories

Given the destructive nature of nuclear weapons and the immense strategic and political weight they bear, it has long been a topic of interest as to why nations decide to create them in the first place.[2-6] Examining the motivations for creating such weapons is a complex process. These motivations are the driving force behind the decision to make such a weapon as well as several of the specific pathway choices made.[7] The area of study that seeks to answer the question as to why states seek nuclear weapons is called proliferation determinism.

Realist

The two primary schools of thought on why nations decide to go nuclear in the first place are broken into the realist and the idealist philosophies. The realists view a nation's acquiring nuclear technical capabilities to be the key variable that ultimately determines the incidence of proliferation.[2] The idealists on the other hand believe there are other forces acting, and states are ultimately driven towards making a nuclear weapon by the idea that it is beneficial or necessary.[2] Ultimately the realist viewpoint sees technical ability as the only limitation to a world run rampant with nuclear weapons. Despite numerous examples to the contrary throughout twentieth century history, realists contend that eventually events will cause every nation to seek such a weapon. As a result of this line of thinking, realists view the supply-side technology controls as a necessary virtue for the nonproliferation regime.[2]

Idealist

The idealist viewpoint looks at proliferation pressures on the international, individual, and domestic levels. Idealists see nations as generally wanting to follow international norms and be perceived as good denizens of the earth.[2] Idealists perceive open societies as better followers of nonproliferation practices. On an individual level, proliferation is viewed as an emotional decision made by a top leader.[2] The domestic level may be plagued by numerous concoctions by national elites that push for the creation of such a device. Some of the concoctions include emphasizing a country's insecurity or its poor international standing, portraying the bomb as the best solution to these problems, articulating the political, economic, and technical feasibility of acquiring nuclear weapons, and successfully associating these arguments with cultural norms and political priorities.[3] The idealist worldview errs when framing proliferators as outside the norm. The idealist worldview tends to bolster stereotypes and paints an image of nations who choose the nuclear route as rogues, which clearly does not describe countries like India. Unlike the realists, however, the idealists stress that nuclear proliferation occurs specifically and not generally.[8] This concept is in accord with what has historically occurred and has allowed more insight into the timing of proliferation decisions.[2]

What is gleaned from the comparison of the realist and idealist theories is that a useful computational tool designed to assess the paths a nation could take in making a nuclear weapon should incorporate individual country data, including raw national statistics and current geopolitical forces pushing that nation towards the bomb decision. The tool should assess the required resources for making the bomb including technologies that are under export control regulations. Including export control rules will allow an analyst or policymaker to see how the path a nation is taking might be altered if such rules are enforced. A tool incorporating the driving forces from both proliferation philosophies would more accurately describe the most likely path as opposed to one that only focused on elements from one philosophy.

I.C. Making a Nuclear Weapon

Once the decision to go nuclear is made, there are many possible paths a nation can take to reach their end goals. The paths being considered in the following work can be broken into two routes, a uranium path and a plutonium path. The uranium path involves enrichment pathways and leads to either a gun type weapon or implosion type weapon. The plutonium path involves reactors and reprocessing facilities and leads to an implosion weapon. The following is brief descriptions of the paths stating the general steps that need to be taken to make a nuclear weapon.[9]

Uranium Path

In order to make a uranium weapon the following steps need to be taken. First the uranium needs to be obtained through mining. The mining step requires geologists, mining engineers, and mining equipment.[10] Next, the uranium, which is in the form of U_3O_8, has to be purified to rid the material of impurities such as boron, cadmium, chlorine, and rare earth elements. This can be done by solvent extraction processes. The next step is for the purified U_3O_8 to be converted into uranium hexafluoride, UF_6. This process is performed at a uranium conversion facility. The two chemical processes commonly used in conversion are the dry hydrofluor process and the wet solvent extraction process.

Within the dry hydrofluor process, the U_3O_8 is ground to a fine powder. Next, the ground material enters a fluidized bed reactor where it is kept at a temperature of 1000 to 1200 degrees Fahrenheit. This step converts the U_3O_8 to UO_2 The crude uranium dioxide UO_2 is passed to two successive hydrofluorination fluidized bed reactors, where interaction occurs with anhydrous hydrogen fluoride at a temperature of 900 to 1000 degree Fahrenheit. Uranium tetrafluoride is produced and treated at high temperatures with fluorine gas to form UF_6.[11]

The wet solvent extraction process uses a similar method to achieve UF_6. The difference is that the solvent extraction is performed prior to the reduction, hydrofluorination, and fluorination steps to remove impurities.[11] Both of these processes require the skills and abilities of chemical engineers.

The next step in making a nuclear weapon is for the uranium to be enriched in the isotope ^{235}U. Uranium with enrichment greater than 20% is known as highly enriched uranium (HEU). For a nuclear weapon, an enrichment of 90% or more, which is known as weapons grade, is desirable. The possible methods for enriching uranium include gaseous diffusion, gaseous centrifuge, aerodynamic, electromagnetic separation, and laser enrichment. All of these methods are large scale projects that use an abundance of resources and manpower from a variety of technical fields.

Gaseous diffusion is a process based on the physical principle that average energies of molecules with differing masses are the same in a gas. The principle implies that the lighter molecules will on average move faster. The UF_6 gas hits a barrier with pores on the order of 25 nanometers. The lighter ^{235}U molecules hit the barrier more frequently due to their greater velocity and hence pass through more often. The separation factor, that is, the amount of ^{235}U molecules that pass through as compared to ^{238}U is very small because the velocities of the two are not very different. Therefore, numerous stages and cascades are needed to continue passing the gas through until the desired enrichment is achieved. Blowing the gas through the semiporous membrane takes tremendous energy. This necessitates large facilities and cooling requirements for the gaseous diffusion process.[10,11]

Gaseous centrifuge enrichment utilizes the centrifugal force and the diffusive nature of gas to manipulate ^{235}U and ^{238}U in their gaseous UF_6 form. Essentially, a hollow cylindrical tube is filled with gas and accelerated by an electric motor to large velocities. The gas settles into dynamic equilibrium as a result of the centrifugal force pushing outward and the diffusive nature of the gas seeking to redistribute the gas equally in the volume.[12] A countercurrent flow is established in the separation chamber and the convective flow carries the lighter ^{235}U molecules to the top of the centrifuge and the heavier ^{238}U molecule to the bottom.[12] As with the gaseous diffusion method, the small separation factor requires numerous cascades of centrifuges to achieve the desired enrichment.[12] There are a large number of components necessary for gaseous centrifuge. The main ones include, high strength rotors (made of either aluminum, maraging steel, or carbon fibers), high strength tubes, high speed motors, baffles, and balancing machines. Gaseous diffusion and gaseous centrifuge are the most common forms of enrichment in the world today.

Electromagnetic isotope separation is an enrichment method that takes advantage of the physical principle that ions of different masses in motion will bend at different radii under the influence of a magnetic field. The radius of the path traversed by an atom under the influence of a magnetic field is proportional to the momentum of the particle and inversely proportional to the magnetic field strength. Current carrying coils and electric power are needed to produce the magnetic fields. Ionizing the uranium is most easily done when it is in the molecular form of uranium tetrachloride, UCl_4. The UCl_4 is heated to a gaseous state and then ionized by bombarding it with electrons. The resulting UCl_4 ions are accelerated through an electric potential. These ions then pass through a vacuum chamber under the influence of a magnetic field. Finally, the ions are bent into separation bins called ion collectors. The devices used for this process are called calutrons. Since a given calutron separates miniscule amounts of ^{235}U atoms, a large number is needed to reach an amount of ^{235}U necessary to make a nuclear weapon.[10]

Aerodynamic enrichment technology is another method which uses centrifugal forces to separate the ^{235}U and ^{238}U. A jet nozzle with a throat width of about 0.03mm is made whereby UF_6 diluted in H_2 can flow through it. The nozzle curves and releases the gas into two pathways, one for the lighter stream and one for the heavier stream. The centrifugal forces cause the separation of the light and heavy isotopes into the two paths. Like the other enrichment technologies, a large number of jet nozzle stages are required to achieve the desired enrichment level.[6]

The newest enrichment technology is laser enrichment. This process takes advantage of the sharp but slightly displaced absorption lines between ^{238}U and ^{235}U. It is possible with a fine tuned laser to preferentially ionize the ^{235}U atoms and then electrostatically separate them from the ^{238}U.[11] The ionization can be done with a variety of lasers including copper vapor lasers, neodymium-doped lasers, and Alexandrite lasers. The technology is still in its developmental stage so a nation that would choose this path would be technically advanced.

Once the uranium is enriched to weapons grade, a state has two different weapon paths to choose from: the HEU gun-type or the HEU implosion type. The HEU gun type is a crude design involving the collision of two subcritical pieces of HEU that together form a supercritical state. Gun-type weapons are the easiest to make as they require conventional chemical explosives to propel the one piece into the other and a tamper usually made of tungsten carbide that helps keep the pieces together long enough for the weapon to produce its intended yield. The gun design is the lowest technology nuclear weapon and the least efficient with respect to the use of HEU.[13]

The more sophisticated HEU weapon is the implosion-type. Implosion weapons are more efficient than gun-type weapons; however, this efficiency comes at increased complexity.[13] An HEU implosion weapon requires the careful machining of a pit of subcritical HEU that has a hollow center where a neutron initiator is placed. The physics behind an implosion weapon involve the pit of subcritical uranium or plutonium being compressed by the explosive force of conventional explosives until its density increases sufficiently to make the mass supercritical. At the point of peak compression, a burst of neutrons is released by the neutron initiator at the very center of the pit. In order to keep the weapon together long enough to obtain sufficient yield, a tamper is used. If the tamper does not also double as a reflector, a separate material, usually made of beryllium, is used to reflect neutrons back into the core of the weapon. Some designs also include a pusher made of high strength material like aluminum or beryllium. The complexity of the implosion weapon makes this a high efficiency weapon that requires an advanced level of technology.

Plutonium Path

The steps and technologies needed for a state to develop a plutonium weapon differ from that of the uranium weapons. The first significantly different step is the acquisition of a nuclear reactor. Plutonium production reactors use uranium metal as the fuel and if the reactor in use is a heavy water reactor (HWR) or graphite moderated reactor, natural uranium can be used for the metal. This however, requires the acquisition of heavy water, D_2O, which is composed of deuterium, a hydrogen atom with a neutron in the nucleus, and oxygen. Heavy water can be made at a heavy water production plant. The heavy water plant provides importance to a state proliferator because it gives the state another weapon path that completely avoids the enrichment paths.[14] Heavy water plants necessitate a technical infrastructure that is on par with ammonia production and alcohol distillation. Practical ways of making heavy water include distilling liquid hydrogen and chemical exchange processes that take advantage of the affinities of deuterium and hydrogen for various compounds.[14]

The fuel is burned in the reactor creating plutonium. When the spent fuel is taken out of the reactor, roughly 1% is plutonium. For an implosion weapon, it is desirable for the plutonium to consist of approximately 93% ^{239}Pu. This is known as weapons grade plutonium. Plutonium coming from a typical power reactor is between 50-60% enriched in ^{239}Pu, which is known as reactor-grade plutonium.[15] In order to obtain higher ^{239}Pu fractions, the fuel must be kept in the reactor for shorter periods of time. Due to the short time frame, power reactors are not good candidates for producing weapons grade plutonium because of the frequency of shutdowns. Plutonium production reactors may be able to refuel while operating to avoid delays in production. Due to the high spontaneous fission rate of plutonium, it is not able to be used for the gun-type design.[10]

Once the spent nuclear fuel is obtained from the reactor, the fuel must undergo reprocessing in order to extract the useful plutonium. The first step is to chop the spent fuel into pieces. Next, the pieces are dissolved in nitric acid. Solvent extraction is then used to separate the uranium and plutonium from the waste products. The most common method is the PUREX process which uses tri-n-butyl phosphate (TBP) and liquid-liquid extraction principals, combined with oxidation-reduction chemical reactions.[11] The plutonium is recovered as the nitrate $Pu(NO_3)_4$ and then converted to plutonium oxide. The plutonium oxide is then converted to a metal with the help of high purity calcium or magnesium. The plutonium is reacted with either the calcium or magnesium with a fluoride salt at a high temperature in a sealed vessel.[15] The metal is then washed in HNO_3 to remove residue, washed with water, and melted again in a furnace.

The remainder of the materials and steps in making the plutonium weapon are identical to those of the uranium implosion weapon.

I.D. Previous Work

The previous literature on this topic focuses mainly on proliferation determination and tapers off when it comes to computational methods for assessing pathways. There are a few recently created computational networks that can be built upon to gain further insight.

In previous related work, support is found to bolster both the realist and idealist views of proliferation. Another aspect of proliferation that has also been under study is the impact of technology transfers of sensitive nuclear assistance. A computational tool that assesses the most likely path a nation would pursue must take into account the numerous characteristics, both tangible and intangible, that push a state towards developing a nuclear weapon and assisting them along that chosen path.

Meyer (1984)

Research conducted by Meyer provided the first statistical model that attempted to explain why countries proliferate.[4] This study was an overview of the many proliferation determinants applied to historical cases. For several countries, nuclear propensity, which was defined as the extent of a nation's explicit predisposition toward initiating the manufacture of nuclear weapons, was plotted as a function of time. The conclusions argued against the realist theory of nuclear weapon proliferation in saying that the decisions to go nuclear were not solely driven by technological means but were largely impacted by political and military decisions.

Singh and Way (2004)

Another study performed a quantitative test of the correlates of nuclear proliferation.[5] A hazard and multinomial logit model were used to test theories of nuclear proliferation. In this research, the path to nuclear weaponry was broken into three stages that included exploring, pursuing, and acquiring nuclear weapons. The researchers concluded that nuclear weapons proliferation was strongly correlated to the level of economic development, the external threat environment, the lack of great-power security guarantees, and a low level of integration into the world economy.

PNNL (2005)

Pacific Northwest National Laboratory (PNNL) conducted a study of past proliferation events to gain insight on future proliferation.[9] The report describes how conclusions regarding the time necessary for completion of technologies and nuclear material production in addition to the approaches taken for acquiring the technology can be drawn from evaluating historical trends in nuclear technology development. The work shows numerous historical cases and the time required by states to develop certain technologies.

Hymans (2006)

Hymans did a qualitative study which compared the realist and idealist theories on nuclear weapon proliferation.[2] The work revealed insight behind what some theorize to be the driving force behind the decision to pursue nuclear weapons. Realists contend that access to technology is the limiting factor on whether states pursue a nuclear weapon and idealists believe that there are numerous other factors that push a nation towards the weapon.

Jo and Gartzke (2007)

A study that looked at the determinants of nuclear proliferation quantitatively was performed by Jo and Gartzke.[6] The work performed a statistical analysis of nuclear proliferation that incorporated numerous independent variables. It was found that security concerns and technological capabilities and important determinants of whether states decide form nuclear weapons programs and security concerns, economic capabilities, and domestic politics help explain the possession of nuclear weapons.

Ford (2008)

A network that displayed the pathways necessary for a terrorist group or rogue state to acquire special nuclear material (SNM) was developed by Ford.[16] SNM is defined as plutonium, U-233, or uranium enriched in U-235 or U-233. The network focused on three different types of nodes including skills, facilities, and materials. A number of input characteristics were created for each of the categories. Using the available resources an organization has and the nodes they already have access to, the most likely path towards acquiring SNM were assessed. The work showed the structure of proliferation pathways but did not show the most likely path. The network also did not reveal which parts of the pathways hold greater importance over others.

Freeman (2008)

The most pertinent source to the current work was the Bayesian network established by Freeman.[7] In this work, a Bayesian network for nuclear proliferation was established that tested the hypothesis that motivations, lead to intentions, which in turn lead to pathways. The network was structured off the idealist view which seeks to explain the other reasons why states decide to go nuclear besides having just the technical capability to do so. The Bayesian network tried to establish the relative threat that organizations and states pose. The network, however, did not include most export controlled dual-use technologies and it loosely quantified a nation's available infrastructure, technical capability, and international networking. In addition, the work did not test historical cases to verify the network.

Kroenig (2009)

Kroenig has studied the impact of sensitive nuclear assistance to nuclear weapon proliferation.[17] A hazard model was used to see determine the impact assistance had on proliferation in addition to the impact had by other characteristics such as GDP, industrial capacity, and regime type. The study determined that the sensitive assistance had the greatest impact of all the characteristics. The conclusions drawn from the research were that states that are better able to produce nuclear weapons, due to either international assistance or domestic capacity are more likely to do so, hence aligning with a realist proliferation view.

Potter (2010)

In a two volume book, Potter provided an extensive qualitative and quantitative study of nuclear proliferation.[18] The work considered theoretical perspectives regarding the reasons proliferation occurs. Potter elaborated upon a state's propensity for a nuclear weapon, the reasons that decisions to pursue the bomb are made, and the impact of proliferation on other states' attitude toward proliferation. The study delivered proliferation projections over the next decade in addition to effective policy measures to prevent proliferation in the future.

I.E. Overview

After considering the previous work done on topics related to the problem of finding the most likely path a nation would take in making a nuclear weapon, it was decided that Bayesian analysis would best model the likelihood. Bayesian analysis is used in many cases where courses of action are chosen that involve tradeoffs between multiple objectives.[19] Bayesian analysis is able to give a viable assessment of the belief one has in a given outcome, making it useful in this situation when reporting to an intelligence analyst or policymaker about the perceived likelihood of a given path based on numerous characteristics and evidence.

The existing Bayesian network created by Freeman provided a useful framework on which to expand. The motivations drive the system, automatically including aspects of proliferation determinism. The way the network is established, the constant nodes that include available infrastructure, international networking, and technical capability are integrated into key positions into the network. There is room to expand upon these nodes to incorporate numerous other characteristics that assess a nation's nuclear weapon potential.

In order to develop a computational tool that yields the most likely path a state would take in making a nuclear weapon the following steps will be taken. First, the existing Bayesian network will be expanded to include dual-use export controlled technologies. Second, the nodes in the network quantifying technical capability, international networking, and available infrastructure will be developed based on a list of weighted characteristics. Third, the network will be executed for nine historical cases of proliferation by states for verification and validation purposes. Finally, hypothetical cases will be used to learn from the network and the results will be assessed.

CHAPTER II

BAYESIAN NETWORK ANALYSIS

II.A. Bayes' Theorem

Bayesian networks are fundamentally based on Bayes' theorem. Bayes' theorem is derived from the conditional probability which states that if there are two statistically independent events, *A* and *B*, the probability of *A* occurring given that *B* has occurred, $P(A|B)$ is equal to the probability of both *A* and *B* occurring, $P(A \cap B)$ divided by the probability that B occurs:

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \quad (1)$$

Eq. (1) means that the chance of *A* happening because *B* occurred increases as the chance that they both happen together increases and it increases even more if the chance of *B* occurring at all decreases. So long as *A* and *B* are mutually exclusive, one can write the same equation with the *A* and *B* flipped:

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

Since the probability of the intersection of these events is the same, algebraic manipulation of the two equations will yield Bayes' equation: [20]

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (3)$$

To expand upon this form, one notes that the probability of B is equal to the probability of the intersection of *A* and *B* plus the probability of the complement of *A* (*Ac*) and *B*:

$$P(B) = P(A \cap B) + P(Ac \cap B) = P(B|A)P(A) + P(B|Ac)P(Ac)\ , \quad (4)$$

which, when substituted back into Eq. (3), yields

$$P(A|B) = \frac{P(B|A)P(A)}{P(B|A)P(A)+P(B|Ac)P(Ac)} \tag{5}$$

If state *A* has more than just two states it could be partitioned, then the probability of *B* is:

$$P(B) = \sum_i P(B \cap A_i) = \sum_i P(B|A_i)\, P(A_i) \tag{6}$$

Therefore Bayes' theorem for an event *A* with any number of states is:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_j P(B|A_j)P(A_j)} \tag{7}$$

The right hand side of Eq. (7) gives the posterior probability of event A while in the left hand side one inserts the prior probability of A not considering any other events. When applied to the proliferation network in this work, the prior probabilities, such as the belief of a state going down a certain path, will be used to calculate posterior probabilities, such as the likelihood of the state going down the path given that the fact that they have certain technologies.

Bayes' theorem provides the foundation for the network which will be expanded to quantify the most likely path a state might take in nuclear proliferation. Within the Bayesian network, different nodes will be mathematically computed by the Bayes' equation allowing flexibility in assigning the conditional probabilities of certain elements given the existence of other elements. The Bayesian network provides a means to test theories and hypothesis in a deductive manner by observing the outcome of the network. The testing of the deductive reasoning process was shown by Freeman when the network was used to test the hypothesis that motivations led to intentions, which in turn lead to pathways.[7] The network can also be used for inductive reasoning by observing what happens when it is applied to both historical and hypothetical cases and trying to see an insightful pattern by which to form a hypothesis. For example, the current work seeks to apply this inductive reasoning to cases of state proliferation to see the impact of loose export controls.

II.B. Bayesian Network

A Bayesian network is a graphical model for representing conditional independencies between a set of random variables.[21] Such a network is able to graphically show the joint probability distribution of a number of such variables. The variables are represented graphically by nodes and they are connected by arrows if a given node is conditioned upon another. The node that the arrow is coming from is the parent node and the node it is going to is the child node.

A good example of a Bayesian network is one used for medical diagnostics. When trying to determine what a patient has, there may be several nodes representing different illnesses. These nodes would be child nodes to several parent nodes, which represent evidence for the child node, including tests, genetic history, and health habits. A doctor may insert his initial beliefs about how such pieces of evidence impact the likelihood of an illness so the network can calculate an initial probability of the patient having the syndrome. The network can then be manipulated after more evidence is gathered and pieces of information are known for certain. The Bayesian network recalculates the probabilities and gives a new set for the likelihood of each illness. This type of network is also useful for state proliferation pathways because initial beliefs can be inserted and then further evidence changes the likelihood of the outcomes.

II.C. Detailed Description of Freeman Network

The Bayesian network designed by Freeman is shown in Fig. 1. The network was designed in the software package Netica.[22] The user defines, connects, and designates probabilities for self-created nodes and Netica then calculates values that represent the belief that a given state is true based on Bayes' theorem.

Equations can be typed into Netica for a given node, or the corresponding truth table could be filled out. Examples of these are shown in Figures 2 and 3.

The equations themselves do not define the relationship between nodes, they merely fill out the truth tables and the Bayes' equation determines the mathematical relationship.[7] The truth tables are tables that give the probabilities of a state being true or false depending on a piece of evidence.

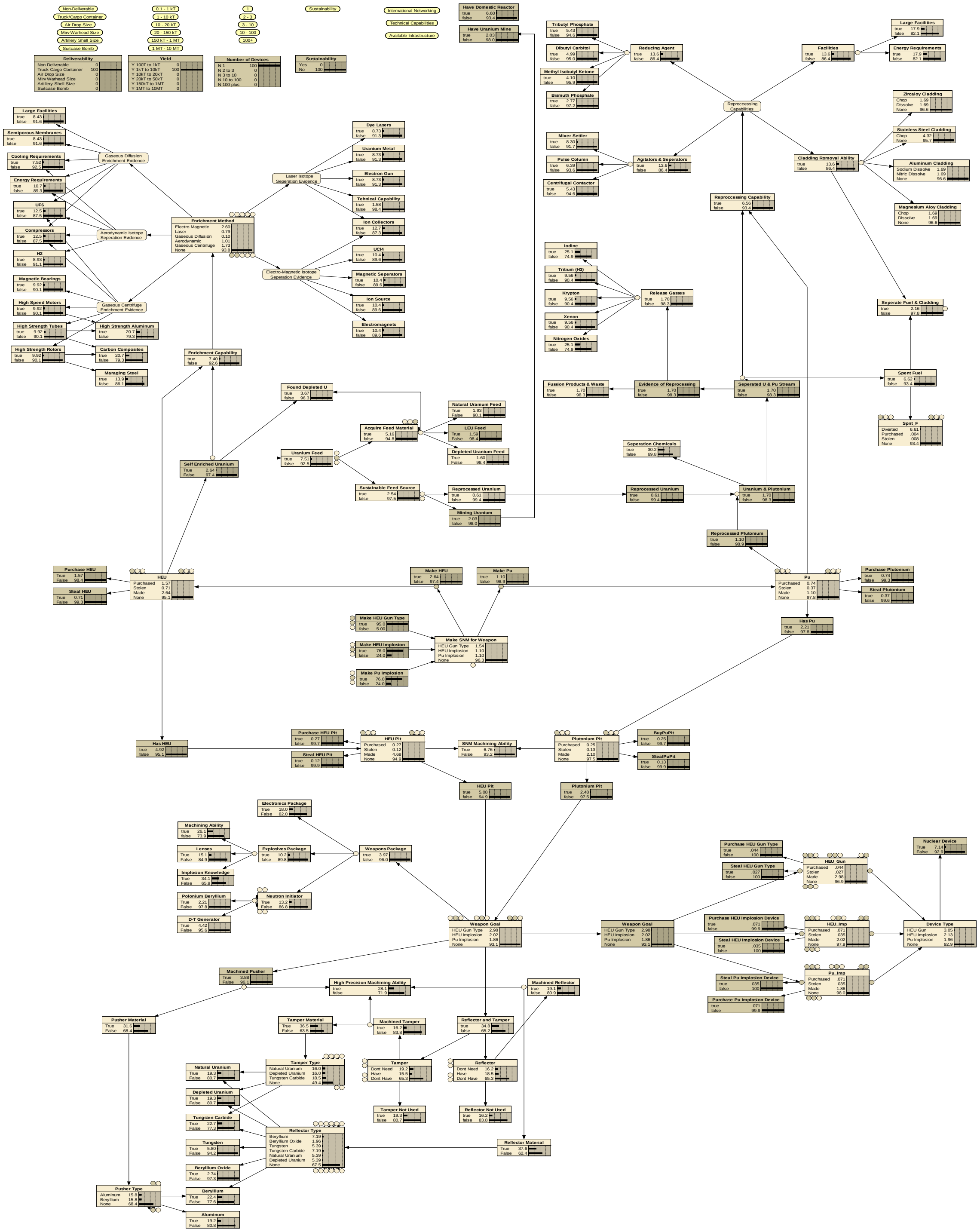

Fig. 1. The Bayesian network designed by Freeman.

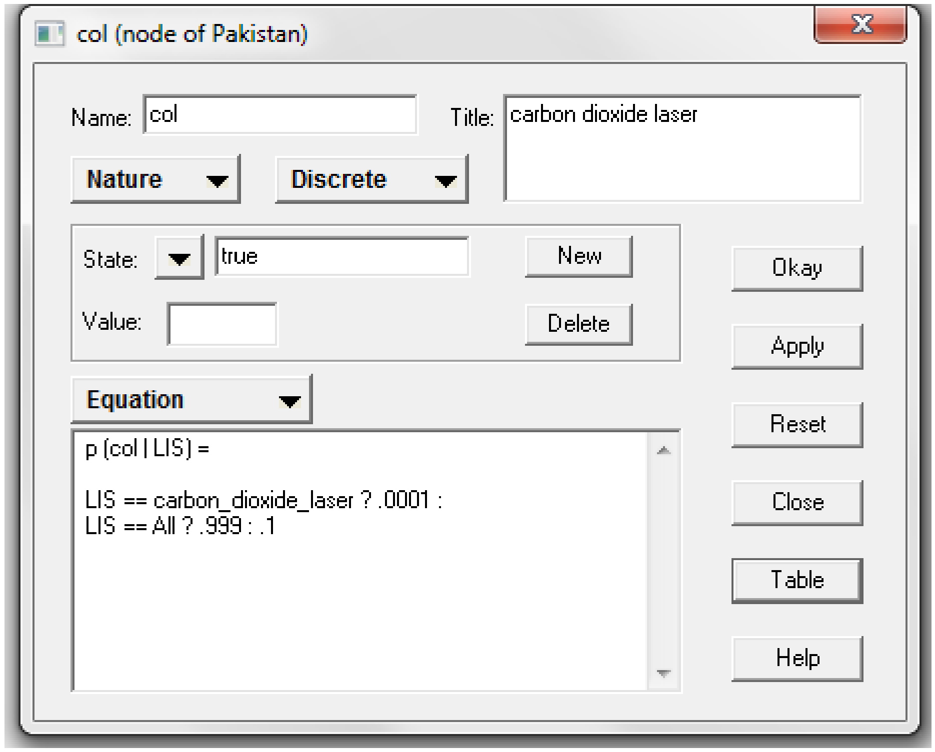

Fig. 2. An example showing how equations can be directly typed into Netica.

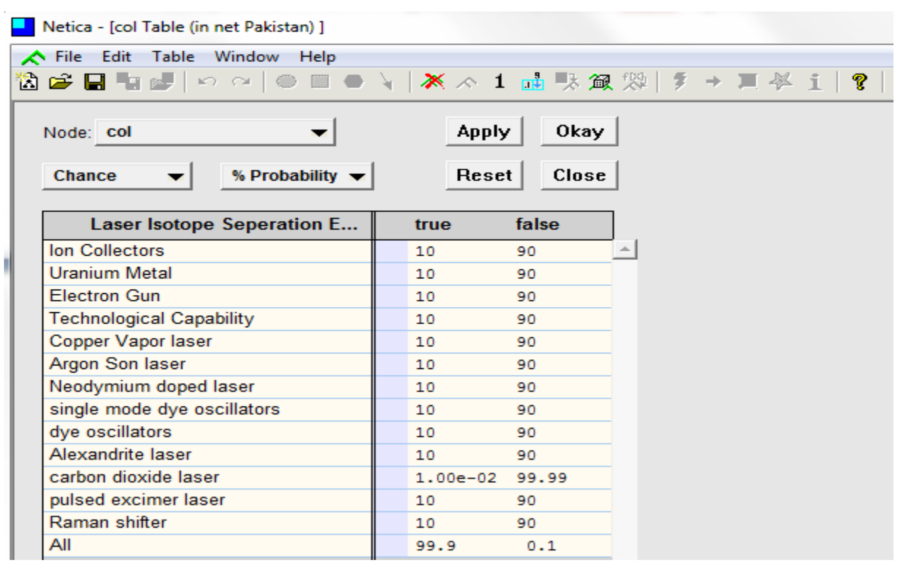

Fig. 3. An example of a truth table in Netica.

Nodes can be activated (turned on to 100% true state) or de-activated (turned to 100% false state) simply by clicking on these respective states (see Fig. 4). This allows the user to incorporate evidence into the network by using the evidence to reflect knowledge about states.

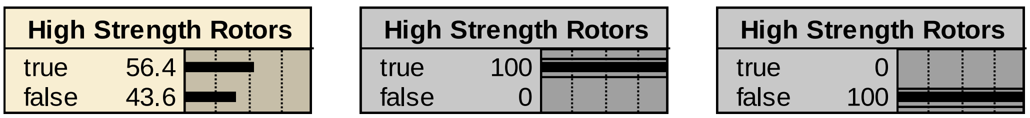

Fig. 4. Example of an activation and a de-activation of a node in the network.

The network designed by Freeman was set up so that the nodes were connected going from general, meaning pathway nodes, to specific, meaning pieces of evidence. This construct, shown in Fig. 5, was established for a number of reasons. First, designing the network this way allows pieces of evidence to impact each other. Second, this construct allows evidence that supports a given pathway to bolster the probabilities of other nodes leading to that pathway. Third, when a given pathway is chosen, the evidence node probabilities increase at different rates, without having all the probabilities equally likely.

As a result of this set-up, activating an evidence node made both the pathway and all other evidence nodes leading to that pathway true and any other pathways false. In order to correct for this non-sensible result, another node was added at the branching points between pathway nodes and evidence nodes. This node is known as an inverted node, and its states are those of the evidence nodes plus one state which represents all of the states. The node is inverted because when a given evidence node is true, it is false in the inverted node. When all the evidence nodes are true, the state which represents all of the evidence nodes is then true so that the according pathway is indicated to be true. In order to determine the impact that a given evidence node has on a given pathway node, the truth table for each evidence node must be written to have a small chance of being false if the corresponding inverted node state is saying it is true and vice versa. The amount the evidence node differs from being absolutely true or absolutely false determines the evidence node's impact on the pathway node. The Freeman thesis provides more detailed description of the network behavior.[7]

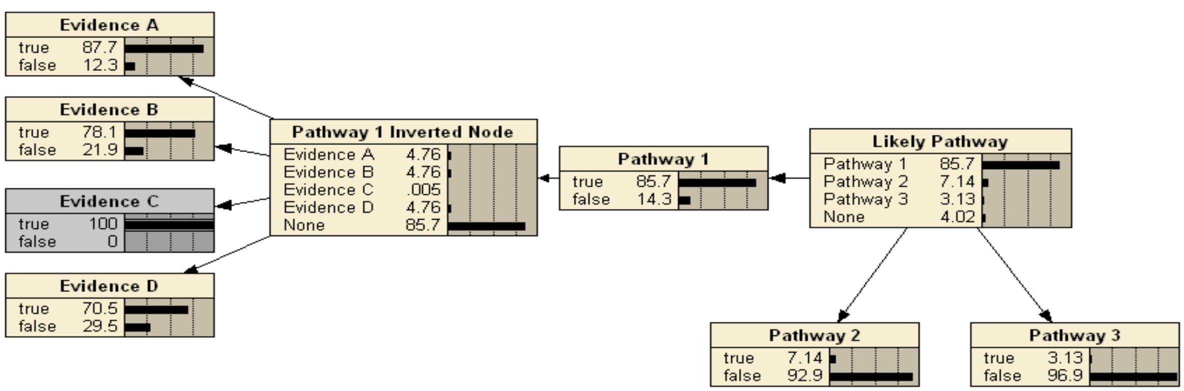

Fig. 5. The design of the Freeman network in Netica.

II.D. Expansion of the Bayesian Network

One of the goals of the current work was to explore the impact loose export control rules have on the likelihood of a country's proliferation. This can be performed in a Bayesian network by adding nodes that represent export controlled technologies and then seeing how they impact the probabilities of other nodes as their probabilities are changed. The Netica software facilitates this process through simple activation and de-activation of nodes. By switching the nodes, one can see the impact of such technologies on the network as a whole.

The first step in this research was the expansion of the currently existing Bayesian network to include export controlled technology. A detailed list of such items was obtained from an IAEA document on nuclear related dual-use technology transfers.[23] The list was broken up into sections that included materials, uranium isotope separation equipment and components, heavy-water production plant related equipment, implosion systems development equipment, explosives and related equipment, and nuclear testing equipment and components. The Bayesian network was analyzed to see where these items and categories would best fit. The nodes were then added into their appropriate locations.

Under the materials category, high-purity calcium and high-purity magnesium, used for converting the uranium and plutonium into metallic form, were added. They were placed in the network near the uranium and plutonium pits as shown in Fig. 6.

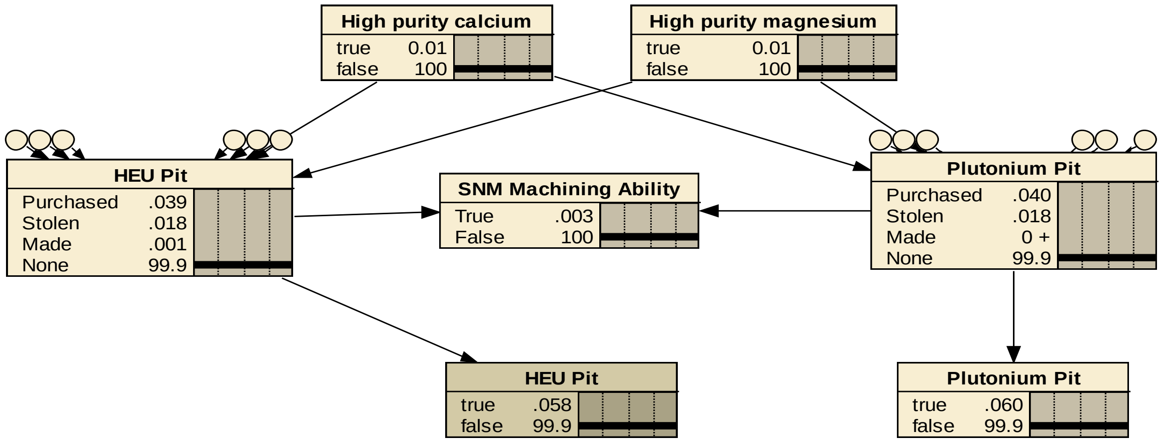

Fig. 6. The addition of high purity calcium and magnesium to the network.

The enrichment section had numerous nodes added. These included electrolytic cells, rotor and bellows equipment, centrifugal multiplane balancing machines, filament winding machines, bellows, maraging steel, carbon composites, and high-strength aluminum. For laser enrichment, the following nodes were added: neodymium doped laser, argon son lasers, copper vapor lasers, Alexandrite lasers, pulsed excimer laser, carbon dioxide laser, single mode dye oscillators, regular dye oscillators, and Raman shifters. The complete enrichment section is shown in Fig. 7.

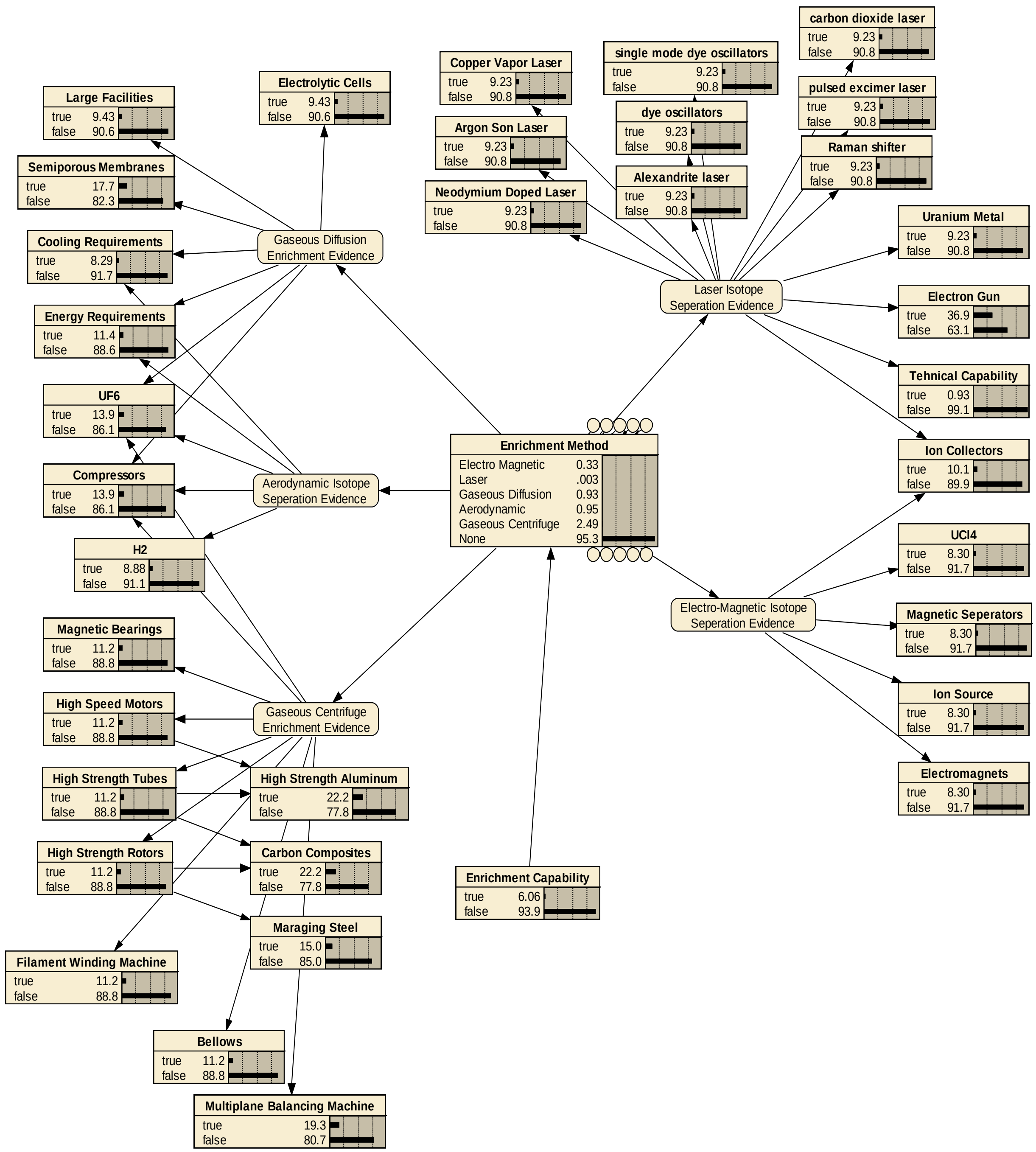

Fig. 7. The enrichment section of the network.

Another section that was greatly expanded upon was the explosives package. The additions to this section included capacitors, high-current pulse generators, detonators, flash x-ray generators, pulsed electron accelerators, multi-stage light gas guns, mechanical rotating mirror cameras, electronic streak and framing cameras, velocity interferometers, manganin gauges, quartz pressure transducers, explosive substances, cold cathode tubes, and triggered spark gaps. This is shown in Fig. 8.

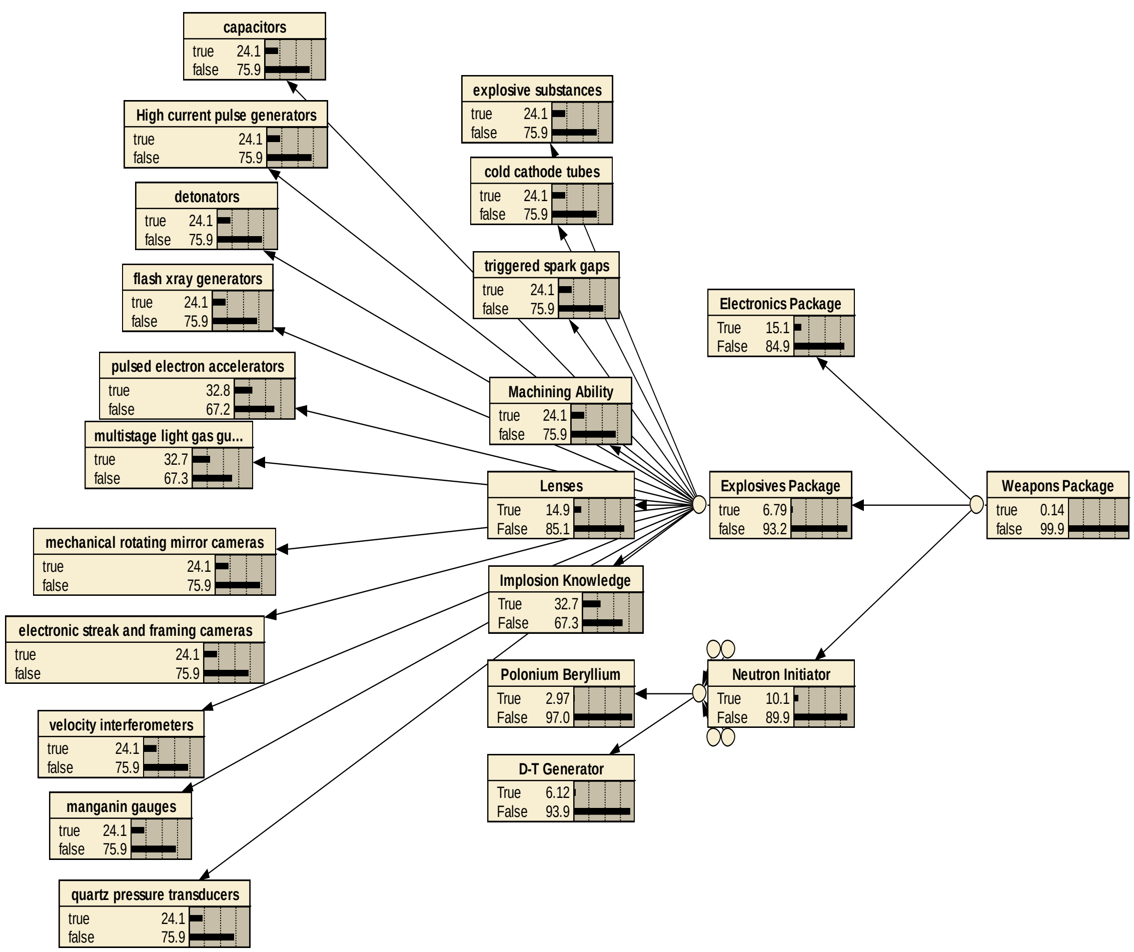

Fig. 8. The expansion of the explosives package section.

A section added that was not in the previous existing Bayesian network was the heavy water production plant. The nodes that were added to this section included specialized packages, pumps, exchange tray columns, distillation columns, and ammonia synthesis convertors. The heavy water section was connected to the plutonium implosion node as it facilitates making plutonium and is shown in Fig. 9.

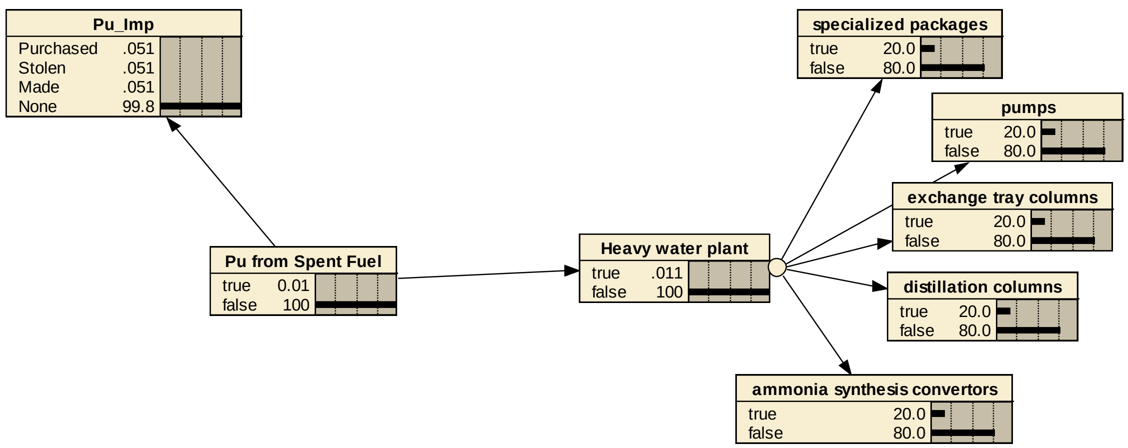

Fig. 9. The heavy water production plant section of the network.

Another section added was nuclear testing. It was added to the node that gave the probability of a state having a nuclear device. The associated equipment and components included non-modular analog oscilloscopes, modular analog oscilloscopes, analog sampling oscilloscopes, digital oscilloscopes, transient recorders, photomultiplier tubes, and pulse generators. These are shown in Fig. 10.

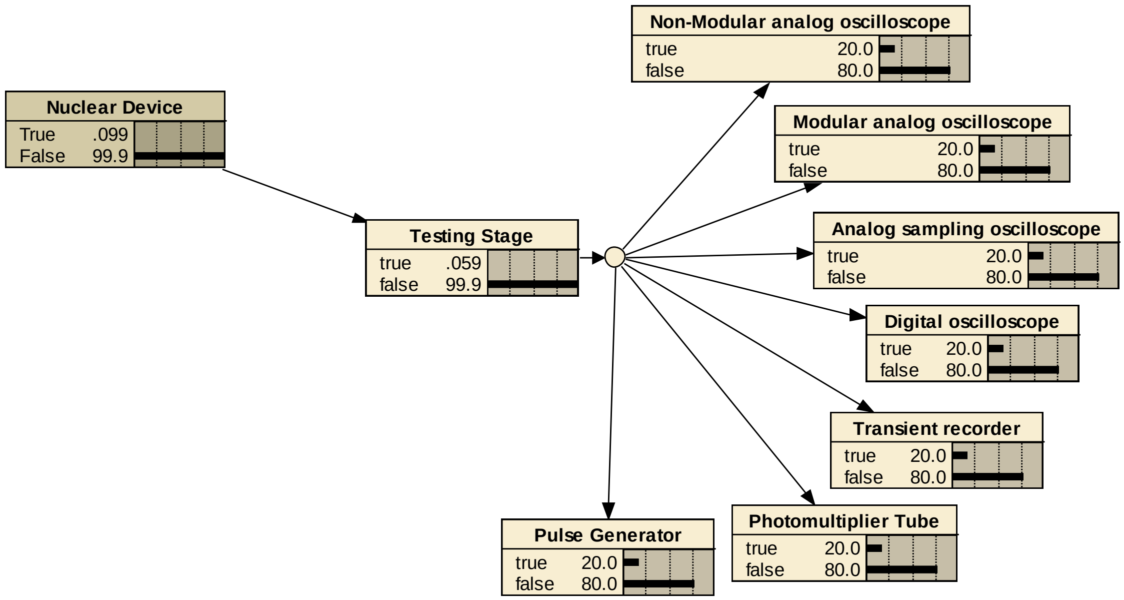

Fig. 10. The nuclear testing part of the network.

The completed network is shown in the Fig. 11. The yellow nodes at the top of the network are intention nodes and the constant nodes representing available infrastructure, international networking, and technical capability, which feed values into the network at key locations. The top left of the network is the enrichment section and the top right of the network is the reprocessing section. The middle right of the network is the weapons package section and the bottom right of the network is the tamper, pusher, and reflector section. The bottom left of the network is the weapon and testing section. The nodes that appear in blue are activated in this picture.

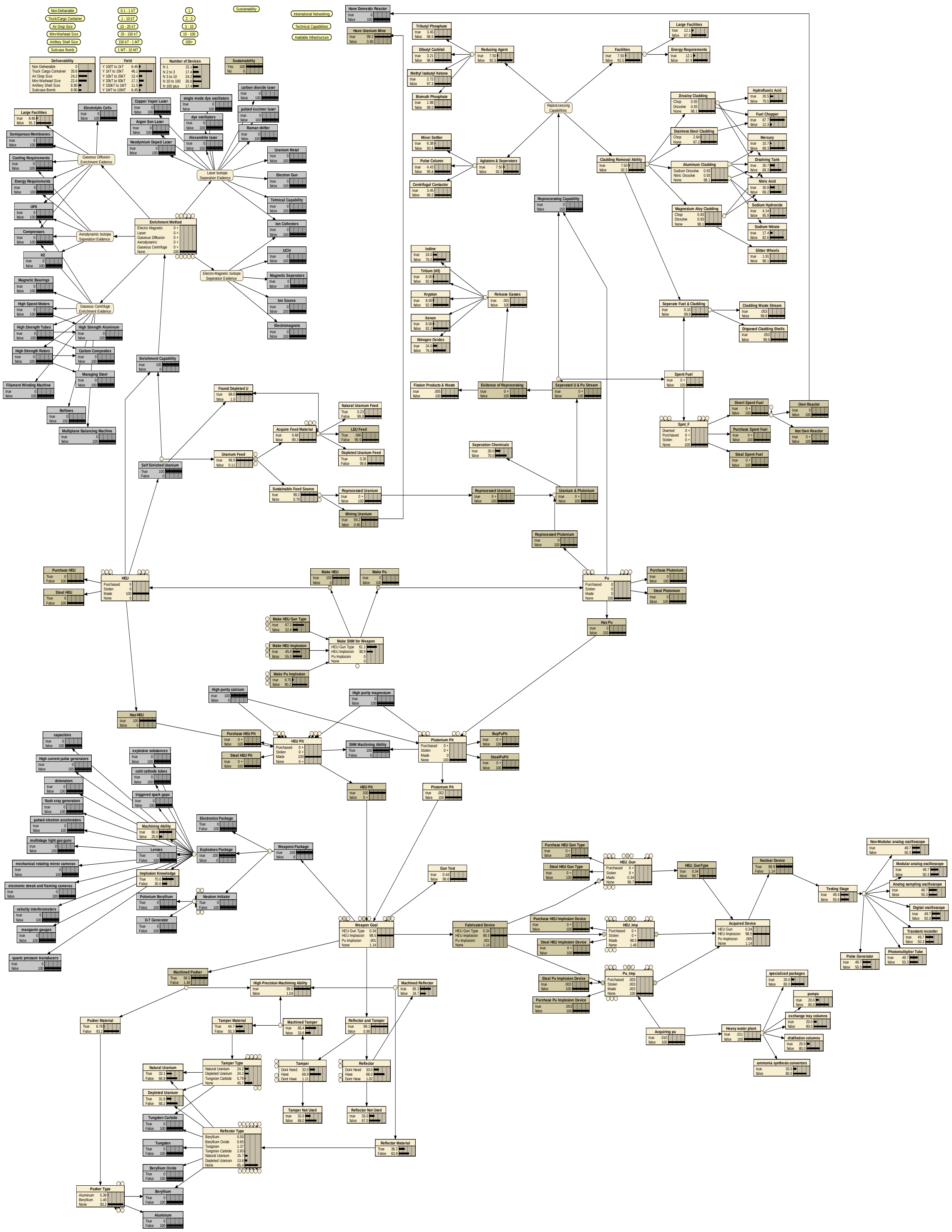

Fig. 11. The completely expanded Bayesian Freeman-Mella network.

CHAPTER III

METRIC DEVELOPMENT FOR CONSTANT NODES

The Freeman network includes three constant nodes: international networking, technical capability, and available infrastructure. The individual using the network would rank these three categories on a scale from zero to one based on the evaluation of the relative strength of these characteristics for the state. Freeman did not provide any methodology for consistently assessing the value for these nodes. This could lead to an unwanted degree of subjectivity in the analysis. In an effort to eliminate this subjectivity, a method was developed to estimate the values of the constant nodes based on published metrics for a state.

III.A. Calculating the Metrics

The value of each constant node was estimated using multi-attribute utility theory.[24]

$$M = \sum_{i=1}^{n} w_{rel_i} u_i(x_i) \tag{8}$$

Eq. (8) represents the value of the constant node. The variable x_i is a metric for a given attribute i, u_i is a function that maps the metric x_i to a value between zero and one, and w_{rel_i} is a weighting factor for the importance of the attribute to the overall constant node value. The weights are relative weights which are constrained by

$$\sum_i^n w_{rel} = 1. \tag{9}$$

The values of x_i have a minimum and maximum possible value:

$$x_1 \in [x_{max}, x_{min}] \tag{10}$$

A linear functional was used for the utility of the attributes which has the form:

$$u(x_i) = \left(\frac{1}{x_{max} - x_{min}}\right) x_i + (1 - \frac{x_{max}}{x_{max} - x_{min}}) \tag{11}$$

This function is zero when the value of x equals the minimum and one when x equals the maximum. For simplicity, a set of weights were established for each attribute that ranged from 0 to 1. This implied that the value of w_{rel} was a normalized weight such that:

$$w_{rel} = \frac{w_1}{\sum_1^n w_i} \tag{12}$$

The calculations for these metrics were performed using a Microsoft Excel spreadsheet. An example of this spreadsheet is shown in Appendix A.

III.B. Attributes

Much of the literature on the topic of nuclear proliferation has more to do with proliferation determinism than it does with attributes that measure a state's available infrastructure, technical capability, and international networking as applied to nuclear weapon proliferation. It was also desirable that the number of attributes be as small as possible, and focused on those most pertinent to proliferation pathways. The data for the metrics were collected from a variety of sources.[25-31]

Technical Capability Attributes

There are numerous measures of technological capabilities at the national level. Indices such as the WEF Technology Index, UNDP Technology Achievement Index, UNIDO Industrial Development Scoreboard, and the RAND Science and Technology Capacity Index rank nations based on a number of characteristics.[21] The characteristics are classified under categories such as the generation of technology and innovation, infrastructure and technology diffusion, human capital, and competitiveness. It was concluded that the RAND Science and Technology Capacity measure had the most relevant characteristics.[26] The RAND measure takes into account eight indicators that include GNP per capita, tertiary science enrollment, research and development expenditures, number of institutions and universities, number of scientists and engineers, number of patents from both the USPTO (United States Patent Office) and EPO (European Patent Office), and the number of science and technology publications and co-authored scientific and technical papers.[26] Using these indicators, a synthetic index was created through a standardized formula with different outcomes occurring according to the weights assigned to each indicator.

The RAND index is useful to this study because it combined numerous informative indicators. However, it was decided that additional metrics were needed to tailor this category to the construction of a nuclear device. A set of metrics were added that reflected the existence of types of nuclear facilities in a country. The relevant facilities are uranium enrichment plants, uranium mines, uranium conversion plants, and heavy water plants. It was determined that the number of such facilities was not related to nuclear weapons capability. The next question to answer was whether the number of such facilities indicated more or less ability. Thus, it was decided to place the maximum at one and the minimum at zero. Using binary values makes the input for the facility attribute a simple one for 'yes' the country has one or more of such a facility or zero for 'no' the country does not have that facility.

The final attribute added was the number of nuclear engineering university programs in a country. Technical capability for creating a nuclear weapon is dependent on the number of nuclear engineering program for the obvious reason that more programs lead to more people who are capable of working on such projects. For this reason, the characteristic is not a simple binary value like the facilities. The characteristic is relatively easy to find and it is a good measure of training for nuclear weapon construction. The number of nuclear engineering programs complements the RAND index, which takes into account institutions and universities in general.

Weightings and Rankings of States Based on Technical Capability Attributes

Proper weights were established for each of the six attributes for technical capability. This was determined by choosing a set of weights for the attributes by intuition, and evaluating the country rankings produced by those weights, and then modifying the weights such that the country rankings match present day and historical case data. The RAND index was weighted high from the start due to the large amount of information it takes into account. The number of nuclear engineering programs was also deemed to be ranked high. Due to the difficulty of enrichment and heavy water production, having these facilities says much about a nation's technical capability. The conversion plants and mines were ranked the lowest. The initial listing of nations was compared to expert opinions on the rankings and the metric weightings were adjusted to set the rankings to match those opinions. The finalized weightings and are shown in Table I and the finalized country ranking is shown in Table II.

TABLE I

Weighting of Technical Capability Attributes

Attribute	Weights
Number of Nuclear Engineering Programs	0.8
Uranium Enrichment Capability	1.0
Uranium Mining Capability	0.1
Conversion Capability	0.5
Heavy Water Production Capability	0.65
RAND Index	1.0

TABLE II

Ranking of Countries due to Weighting of Technical Capability Attributes

Country	Value
1. United States	0.852
2. China	0.599
3. Japan	0.585
4. India	0.584
5. Argentina	0.574
6. Russia	0.573
7. United Kingdom	0.536
8. France	0.519
9. Brazil	0.450
10. Pakistan	0.428
11. Iran	0.420
12. South Africa	0.420
13. Australia	0.370
14. Sweden	0.122
15. Taiwan	0.117
16. Switzerland	0.099
17. Israel	0.096
18. Turkey	0.021
19. Saudi Arabia	0.011
20. Syria	0.009
21. Iraq	0.004
22. Libya	0.002
23. Algeria	0.001
24. Myanmar	0.000

The rankings in Table II agree with our general intuition. The U.S. tops the list followed by China and Japan. India, Argentina, Russian, the UK, and France are next. Brazil, Iran, Pakistan, and Australia are in the middle of the list.

International Networking Attributes

Unlike technological capability, there was not a list of well-researched indices quantifying international networking between states. From an economic perspective, however, the best overall measure was foreign direct investment (FDI).[32] The two categories of FDI are FDI at home and abroad. FDI at home is defined as the cumulative value of all investments in a given country by residents, usually companies, of other countries.[28] Similarly, FDI abroad is defined as the cumulative value of all investments in foreign countries made by residents, usually companies, of the home country.

To tailor the category to the nuclear weapon field, more characteristics needed to be considered. The best way to tailor the category was to introduce the number of connections to nuclear supplier nations. There is a finite list of capable nuclear supplier countries and several sources that give the links between a given nation and the supplier nations.[17,27] Another useful characteristic that directly applies to nuclear weapons is the number of treaties and nuclear cooperation agreements a nation has signed. The treaties and nuclear cooperation agreements that were considered for this study include the following:

- African Nuclear-Weapon-Free Zone Treaty
- Comprehensive Test Ban Treaty
- Intermediate-Range Nuclear Forces Treaty

- Latin American Nuclear-Weapon-Free Zone Treaty
- New Strategic Arms Reduction Treaty
- Nuclear Non-Proliferation Treaty
- Open Skies Treaty
- Outer Space Treaty
- Peaceful Nuclear Explosions Treaty
- Seabed Arms Control Treaty
- South Pacific Nuclear-Weapons-Free Zone Treaty
- Strategic Arms Limitations Talk
- Strategic Arms Limitations Talk II
- Strategic Arms Reduction Treaty
- Strategic Arms Reduction Treaty II
- Strategic Offensive Reductions Treaty
- Threshold Test Ban Treaty

These four characteristics succinctly defined the international networking related to nuclear weapons.

Weightings and Rankings of States Based on International Networking Attributes

When initiating the weighting process, weighted values were selected for the four international networking attributes. These were again iterated upon until a finalized set of weights were established that produced country rankings that matched subject matter intuition. These are shown in Tables III and IV.

TABLE III

Weighting for International Networking Attributes

Attribute	Weights
FDI at home (US $)	1.0
FDI abroad (US $)	1.0
Nuclear Treaties/Agreements	0.5
Connection to Nuclear Supplier Countries	0.75

TABLE IV

Ranking of Countries Due to Weighting of International Networking Attributes

Country	Value
1. United States	0.961
2. France	0.589
3. United Kingdom	0.545
4. Russia	0.430
5. Australia	0.264
6. Switzerland	0.252
7. Japan	0.204
8. Sweden	0.194
9. China	0.144
10. Brazil	0.116
11. Iran	0.108
12. India	0.104
13. South Africa	0.087
14. Iraq	0.085
15. Turkey	0.084
16. Libya	0.076
17. Algeria	0.066
18. Argentina	0.064
19. Myanmar	0.064
20. Saudi Arabia	0.058
21. Taiwan	0.053
22. Syria	0.052
23. Israel	0.038
24. Pakistan	0.033

The rankings shown in Table IV made intuitive sense. The United States was in the number one spot followed by France. The UK and Russia are subsequent. Near the bottom are countries which are in fact much more isolated such as Myanmar, Syria, and Pakistan. The list gave a ranking which makes sense on the international stage.

Available Infrastructure Attributes

The available infrastructure of a state is a broad category that can comprise of many attributes. In the work by Singh and Way,[12] an industrial capacity index that was based on both aggregate and per capita electricity and steel production was used as a correlate of nuclear proliferation. Steel production and electricity production alone are not sufficient for describing a nation's available infrastructure for developing a nuclear weapon. This lacks several attributes for overall industrial capacity and any metrics for infrastructure.

The attributes were gross domestic product (GDP), GDP from industry, electricity production, industrial production growth percentage, uranium mine production, power reactor capacity, and research reactor capacity. The first two characteristics are general indicators of infrastructure. Electricity production is important due to the tremendous electrical input and output from nuclear facilities. The industrial production growth percentage was included because it serves as a future indicator. Also, a project the size of a nuclear weapon program would thrive better in a nation whose growth percentage was high, indicating expansion. The uranium mine production shows the base resource for nuclear activity available. Power reactor capacity is a good measure of overall nuclear activity. Power reactor capacity is a measure of overall power resources available and that which can be diverted to weapons activity. Research reactor capacity is a good measure of a nation's infrastructure regarding the creation of knowledge about nuclear-related activity. The capacity of other nuclear facilities such as conversion, enrichment, and heavy water plants was left out of this category because these facilities were already taken into account in the technical capability category.

Weightings and Rankings of States Based on Available Infrastructure Attributes

These weights were achieved using the same process as that used above. GDP, GDP from industry, and electricity production were all given the highest weight because they are the simplest measure of a country's overall infrastructure. The industrial production growth rate was weighted low since it also is not as pertinent to nuclear activity. Both power and research reactor capacity were weighted high since they are large indicators of nuclear infrastructure. Uranium mining capacity is weighted below the reactor capacities since it is easier to have compared to reactor infrastructure. The finalized ranking of these weights are shown in Table V.

TABLE V

Weighting of Available Infrastructure Attributes

Attribute	Weights
GDP ($US)	1.0
GDP from Industry ($US)	1.0
Electricity Production (kWh)	1.0
Industrial Production Growth Rate (%)	0.2
Uranium Mining Capacity (tU/a)	0.5
Power Reactor Capacity (MWe)	0.8
Research Reactor Capacity (MWth)	0.8

TABLE VI

Ranking due to Weighting of Available Infrastructure Attributes

Country	Value
1. United States	0.804
2. China	0.558
3. Russia	0.346
4. Japan	0.287
5. France	0.236
6. India	0.210
7. Australia	0.145
8. United Kingdom	0.097
9. Brazil	0.092
10. Iran	0.059
11. Taiwan	0.054
12. South Africa	0.046
13. Argentina	0.043
14. Sweden	0.041
15. Turkey	0.041
16. Saudi Arabia	0.041
17. Algeria	0.035
18. Pakistan	0.034
19. Switzerland	0.032
20. Iraq	0.028
21. Israel	0.026
22. Libya	0.023
23. Syria	0.022
24. Myanmar	0.020

The ranking shown in Table VI is in accord with intuition. The list correctly displays the developed nations at the top and the less developed nations lower down. The United States is again at the top of the list. China, Russia, Japan, France, and India follow, all very capable nuclear powers. As expected, less developed countries such as Libya, Syria, and Myanmar rank near the bottom. Nations such as Iran, Sweden, and Argentina, rank near the middle. Nations such as Switzerland and Israel rank low because of their size and resources available. The list displayed in Table VI shows an appropriate ranking of states regarding their available infrastructure as it pertains to nuclear weapon manufacturing.

CHAPTER IV

NETWORK SIMULATIONS

IV.A. Countries and Reasons Why Chosen

In order to study how the network shows pathways of countries over time, eight nations were selected to run through the network. Different nodes were activated, or in some cases de-activated, depending on the acquisition or blocking of technologies pertaining to nuclear weapon development. Numerous historical studies of nuclear histories of the countries were analyzed, and the important dates along the way were tracked in order to plot the pathways. The purpose was to see how accurately the network reflected the history of the countries' weapons programs to verify the network. The countries selected for this purpose were the Soviet Union, France, Israel, South Africa, India, Pakistan, Iraq, and Iran.

The Soviet Union was selected because it was one of the first to develop the bomb. The technology was young and it would be interesting to see how the pathways look in this nascent age of nuclear technology. France was chosen because their path to the bomb involved much technological momentum in which the problem was explored by a commission until it was solved perhaps before it was politically desired. Israel was selected due to its significance in the Middle East. South Africa was chosen to see if the network accurately modeled a technology transfer having a large impact on pathway choice. The transfer of interest was the aerodynamic enrichment technology from a German company. India was chosen because it was interesting to see what the model indicated about the pathways at the time of their first test in the late 1970s. Pakistan was selected to see the impact of the A.Q. Khan network on the pathways and to see what present day paths they may be on. Iraq was chosen to see how close they were to the bomb prior to the Kuwaiti invasion. Finally, Iran was chosen due to their present day relevance as a proliferation concern and the wide range of nuclear technologies they explored.

In addition, to the eight countries run in an attempt to validate the network to an extent, one country was selected that gave up its nuclear weapon pursuits in order to model a null case. Sweden was selected because of their surprising advances towards being a nuclear armed nation and their dissolution of the program with their signing of the NPT.

In addition to the nine cases listed above, four hypothetical cases were tested on present day countries. The testing of the hypothetical cases was done in order to assess the impact of technology transfer on pathways and to see how useful the network is as a learning tool. The transfers of importance were reactor, enrichment, and reprocessing technologies. Also, the strength of export control laws were modeled by adding the above three technologies with the export control item nodes both on and off. The nations that were selected for this were Saudi Arabia, Syria, Myanmar, and Japan.

Saudi Arabia was a good candidate to run a hypothetical case on due to their geographic location in the Middle East and their relationship with United States. Saudi Arabia's position in an area of the world where proliferation is of great concern gives them potential motivation for nuclear proliferation. Also, the United States has a relationship with Saudi Arabia and nuclear technology transfer in the future is a possibility. It is important from a policymaker standpoint to be able to somehow measure the impact giving the Saudis certain nuclear technologies would have on their likelihood of acquiring nuclear weapons.

Syria was chosen because it is another Middle Eastern country that has been interested in nuclear technology. Due to their rivalry with Israel, there is substantial international consequence if they were to acquire nuclear weaponry.

Myanmar was chosen because it is in a slightly different part of the world and has near the bottom of the metrics. This nation has interest in nuclear technology and has possible connections with North Korea.

Finally, Japan was selected due to its nuclear advancement. The purpose was to see the impact of technology transfer on a nation with sufficient nuclear capabilities.

IV.B. Motivations of Countries

The Freeman network was driven by motivations leading to intentions which in turn led to pathways. A spreadsheet was made in Microsoft Excel whereby the user could relatively rank a list of motivations a state would have for acquiring a nuclear weapon. In addition to motivations, there were also intentions for deliverability, yield, and number of nuclear weapons. Each intention is assigned a probability for a given motivations that could be adjusted. This value, designated ν_i^m, represents the probability that motivation m causes the state to pursue intention i. Each motivation was assigned a weight, which is inserted by the user. The weights can be any value from zero to infinity and the user is to assign them relative to one another. For instance, if one motivation is twice as likely the reason a given nation is pursuing the bomb as another motivation then its value would be weighted twice as large. The weights for a given nation, w_m, are normalized as shown in Eq. (13).

$$k_m = \frac{w_m}{\sum_m^M w_m} \tag{13}$$

The normalized weights were then combined with the probability that a given motivation causes a state to pursue a given intention by Eq. (14). This equation yields the probability that *i* is the intention of the state.

$$u_i = \prod_{m=1}^{M} (v_i^m)^{k_m} \tag{14}$$

This attribute aggregation method was chosen because it went to zero if any of its inputs are zero unlike an additive aggregation but it is not as stringent as straight multiplication.[7] The intention values for delivery, yield, and number calculated in the above manner were inserted into the Bayesian network.

The next step in this work was to come up with motivations for the above selected countries and give each motivation a relative weight. The following motivations for nations who have sought or have considered seeking nuclear weapons were inferred from several sources.[11,12,17,33,34,35] In order to improve the accuracy and relative ranking of the motivations, expert advice was elicited from faculty and graduate students at Texas A&M's Nuclear Science and Security Policy Institute (NSSPI) in the form of a survey.

Soviet Union Motivations

The Soviet Union's motivations for developing a nuclear weapon were born after witnessing the atomic blasts at Hiroshima and Nagasaki. The Soviets saw it necessary to develop the bomb to counter the United States. To a lesser degree the Soviet Union may have been motivated by the intimidation factor it would provide to those nations that got in the way of the spread of communism.

TABLE VII

The Soviet Union Nuclear Motivations

Motivation	Value
Deter Attack From Nuclear Adversary	4
Seek Military Superiority	2
Intimidate Non-Nuclear Rivals	1

Deterring an attack from the United States was weighted the most important factor. The Soviets were seeking military superiority for defense and to project power to spread communist interests. Intimidating non-nuclear rivals was another tactic that also served those purposes. Table VII shows the Soviet motivational profile.

French Motivations

After losing to Germany in World War II, the nation of France had great incentive to prove itself once again as a major world power. France needed to reestablish their credibility as one of the Big Four European victors and the development of a nuclear weapon seemed to be necessary to achieve that.[33] Another event that further propagated the belief that their image as world power was slipping away was the French Army's defeat at Dien Bien Phu in 1954.[33] The final tipping point, however, was the

Suez Crisis. During this event, Israel invaded Egypt and was backed up by Britain and France. The United States completely opposed the operation and the three nations were forced to halt the operation. France took this as a sign that they could not count on the United States.

TABLE VIII

The French Nuclear Motivations

Motivation	Value
Enhance General International Status	4
Enhance Bargaining Position w/in Alliance w/ Nuclear Powers	3
Rise to Global Power Status	3
Demonstrate National Viability	2
Intimidate Non-Nuclear rivals	1
Assert political independence	1

The international embarrassments the French faced leading to feelings of slipping from consideration as a world power makes the enhancement of general international status the key motivator for France. France felt that joining the nuclear club would put them in a better bargaining position with the other nuclear powers, especially when it came to incidents like the Suez Crisis. Such a position would allow them to regain their global power status.

Regaining global power status also tied in with the French need to feel more independent of the United States. The whole concept of de Gaulle's Force de Frappe was to have a striking force that was without any strategic consideration of the United States.[33] National viability, especially on the issue of nuclear defense, was another motivation. To a lesser degree, the ability to intimidate non-nuclear rivals also had a role in the French nuclear decision. The issues France had been having with countries such as Algeria, Vietnam, and Egypt may have been resolved in a more favorable manner had France had its own nuclear arsenal to project power. Table VIII shows the French motivations.

Israeli Motivations

Since its birth, the nation of Israel has been at war or amidst high tensions in the Middle East. The Arab-Israeli war of 1948 indicated that the region was hostile to the Jews inhabiting. In this conflict, the nations of Egypt, Syria, Jordan, Iraq, Saudi Arabia, and Yemen attacked Israel and were defeated. Israel's then Prime Minister David Ben-Gurion anticipated future conflicts.[17] Deterring a second Arab invasion was believed to be near impossible since the Arab world had more resources and a greater population.[17] The motivation for obtaining nuclear weapons began with the need to redress the overwhelming conventional asymmetry the Arab world posed. Israel's non-nuclear rivals needed to be too intimidated to attack again and nuclear weapons seemed like the necessary deterrent.

It was during the midst of the Cold War that the Israeli bomb was being desired. The United States and the Soviet Union both had reasons why they did not want Israel obtaining the weapon, which in turn provided added motivation for the development of the bomb. From United States perspective at the time, there was no existing rivalry between the U.S. and the Arab nations, which caused some U.S. officials to speculate that if Israel acquired nuclear weapons, they would not only be less subject to American influence but might also be in a position to force the United States to intervene on their behalf in a crisis.[17] After the Suez Crisis in which the French, British, and Israelis tried to attack Egypt, the Israelis were left feeling that they could no longer count on their once reliable American ally.[33] If Israel had nuclear weapons, they would enhance their bargaining position with the United States.

The Soviet Union, on the other hand, was worried because they felt that a nuclear Israel would constrain their ability to project conventional military power in the region and reduce the effectiveness of Moscow's coercive diplomacy on behalf of the Arab states and against Israel.[17] This geopolitical situation added to the final motivation seen in Table IX of deterring regional intervention by a superpower, namely the Soviet Union.

TABLE IX

The Israeli Nuclear Motivations

Motivation	Value
Redress Conventional Military Asymmetry	4
Intimidate Non-Nuclear Rivals	4
Enhance Bargaining Position w/in Alliance w/ Nuclear Powers	1
Deter Regional Intervention by Superpower	1

The notable motive was the overwhelming conventional threat posed by the coalition of Arab states.[11] The redressing of conventional military asymmetry and the intimidation of non-nuclear rivals was the more pressing issue for Israel whereas the enhancement of bargaining position and the deterrent of regional intervention were secondary motivations. The former two motivations are weighted three times more than the latter two because due to this reason.

South African Motivations

The roots of South Africa's nuclear weapon ambitions begin in the 1960s with the formation of the Organization of African Unity, an economic pact that isolated South Africa on the continent.[11] South Africa was additionally isolated on the global front from the United Nations trade embargo. Around 1974, the Portuguese colonies of Angola and Mozambique gained independence and joined the other African states allied against South Africa.[11] In addition, Cuban and Soviet troops were placed in the region.[11] South

Africa began to fear a major attack from the Soviet Union and strongly pushed the nuclear program forward in 1975.[35]

TABLE X

The South African Nuclear Motivations

Motivation	Value
Seek Military Superiority	3
Redress Conventional Military Asymmetry	2
Intimidate Non-Nuclear Rivals	2

Several motives can be listed for South Africa's pursuit of nuclear weaponry. The most important was for South Africa to have had military superiority in a region of the world that was allied against them. South Africa had to redress a conventional military asymmetry between the African states and the perceived threat from the Soviet Union. Finally, they felt a need to intimidate the African states that did not possess such weapons. Table X shows these motivations.

Indian Motivations

India has long had border disputes with its neighbors China and Pakistan. Since the British left India, the border had not been clearly defined.[33] In 1962, the Indians lost a one month war to the Chinese that caused resentment from India that is still around today and a determination within China to support India's enemies.[33]

India has always had a desire for great power status.[11,33] This desire coupled with China's detonation of an atomic bomb in 1964 was the tipping point for their motivation to seek a nuclear weapon.

TABLE XI

The Indian Nuclear Motivations

Motivation	Value
Deter Attack From Nuclear Adversary	4
Rise to Global Power Status	3
Enhance General International Status	2
Demonstrate National Viability	2

Deterring another attack from China is weighted the highest because India's defeat by them resonated so deeply. The rise to global power status is a close second due to the Indian mentality. India has an urge to enhance their overall international status and to demonstrate their viability as a powerful country. The Indian motivational profile is in Table XI.

Pakistani Motivations

The impetus for the Pakistani nuclear bomb came after Pakistan was soundly beaten by India in less than two weeks. The defeat made it clear that there was a serious conventional military asymmetry. It was this incident that motivated A.Q. Kahn to start initiating his quest to give Pakistan the bomb.[34] China helped solidify the project by giving Pakistan a nuclear weapon design in the early 1980s.[17] This move by the Chinese can also be seen as acting to counter India's development of a nuclear weapon.

TABLE XII

The Pakistani Nuclear Motivations

Motivation	Value
Deter Attack From Nuclear Adversary	4
Redress Conventional Military Asymmetry	3

Pakistan wanted to be able to deter the nuclear armed India. Given the crushing defeat at the hands of the Indians, Pakistan needed to redress the conventional military asymmetry. These two motivations and their weighs are shown in Table XII.

Iraqi Motivations

Before the Gulf War in 1991, Iraq was motivated by several factors. The first motivation was the nuclear capability that Israel possessed. When considering the broader region, India's development of the bomb in 1974 was another motivating factor. Iraq also needed such a weapon to alleviate the defense burden that was occurring in the late sixties and early seventies. In 1982, Iraq lost a war with Iran and it became clear that there was a strong conventional asymmetry between not just Israel, but also Iran. The motivational profile of Iraq is shown in Table XIII.

TABLE XIII

The Iraqi Nuclear Motivations

Motivation	Value
Deter Attack from Nuclear Adversary	3
Redress Conventional Military Asymmetry	2
Reduce Economic Defense Burden	1

Iranian Motivations

Over the past decade, the statements made by the government of Iran indicate that the nuclear armed state of Israel is a prime motivator for Iran's nuclear motivations. In addition to this motive, Iran also seeks to keep the United States from interfering.

TABLE XIV

The Iranian Nuclear Motivations

Motivation	Value
Deter Attack from Nuclear Adversary	4
Redress Conventional Military Asymmetry	3
Deter Regional Intervention by a Superpower	3

Deterring an attack from their enemy, Israel, is the main reason behind their pursuit of nuclear weapons. Iran also needs to redress the conventional military asymmetry that exists between them and their rivals in the Middle East. Deterring United States intervention in the region is also ranked equivalently because of the strategic importance it holds for Iran. The motivations and weights are shown in Table XIV.

Swedish Motivations

In Sweden, atomic research was conducted by a company that was explicitly connected to the defense ministry and it is also known that decisions were made by cabinet-level officials to develop dual-use technology with high potential utility for any future nuclear weapons program.[12] To deter an attack from a nuclear adversary was the main motivation. Table XV shows the motivations of Sweden.

TABLE XV

Swedish Nuclear Motivations

Motivation	Value
Deter Attack from Nuclear Adversary	2
Redress Conventional Military Asymmetry	1

The main nuclear adversary was the Soviet Union. There was obviously a serious conventional military asymmetry between the Swedes and the Soviets that needed to be redressed.

Saudi Arabian Motivations

The ranking of Saudi Arabian motivations was done by assessing the present-day situation and considering the *potential* motivating factors that could drive them to developing a nuclear weapon. The two motivating factors that were decided upon were to deter an attack from a nuclear adversary and to go nuclear before their rival. The main nuclear rival for Saudi Arabia is Israel. Nuclear-armed Israel has not proved to be sufficient enough of a motivation thus far but it is definitely of concern for the Arab nation. The other motivation is to go nuclear before rival. A rival that is pursuing nuclear weapons is the nation of Iran. The need for assurance of security in the face of Iran prompted the largest arms deal in history between the United States and Saudi Arabia.[36] The arms deal was largely done willingly on the part of the United States to deter Saudi Arabia from developing a nuclear weapon. The relative rankings of these two are shown in Table XVI.

TABLE XVI

Potential Saudi Arabian Nuclear Motivations

Motivation	Value
Go Nuclear Before Rival	2
Deter Attack from Nuclear Adversary	1

Syrian Motivations

The only tenable motivation that Syria would have for developing a nuclear weapon, shown in Table XVII, would be to deter an attack from Israel. Syria is another Arab nation that has had a long standing feud with Israel.

TABLE XVII

Potential Syrian Nuclear Motivations

Motivation	Value
Deter Attack from Nuclear Adversary	2

Myanmar Motivations

There are several potential motivations that Myanmar could have for wanting to acquire a nuclear weapon. Unlike other nations, there is no one overwhelming motivation but rather a list of several that may equally contribute to the desire to attain a bomb. Given the fact that Myanmar is ruled by a military junta, the development of the bomb to increase military morale was ranked slightly higher than the rest. While they are a military junta, if they had to fight a war they would have a conventional military disadvantage. Given the importance on military projection of power in this country, this factor may play into the motivations. Myanmar perceived that North Korea gained a greater voice in the international community with their pursuit of nuclear weapons and they show signs of wanting to emulate this.

Due to the human rights violations in Myanmar, it is also possible that their weapons program might be intended to divert that attention. Another possibility is their desire to show the world that they are capable of such a feat, again giving them a greater voice on the world's stage. These motivations are shown in Table XVIII.

TABLE XVIII

Potential Myanmar Nuclear Motivations

Motivation	Value
Increase Military Morale	2
Acquire Position in International Forums	1
Redress Conventional Military Asymmetry	1
Demonstrate National Viability	1
Divert Domestic Attention	1

Japan

As with Syria, the only potential motivation Japan, shown in Table XIX, would have would be to deter an attack from a nuclear adversary, namely China.

TABLE XIX

Potential Japanese Nuclear Motivations

Motivation	Value
Deter Attack from Nuclear Adversary	2

Expert Elicitation

In addition to ranking motivations based upon information found in a number of literary sources pertaining to nuclear weapons programs, it was decided to elicit expert advice in the form of a survey. The survey sought expert advice for the nuclear weapon motivations of Russia prior to 1949, France in the 1950s, Israel in the 1960s, South Africa in the late 1960s and early 1970s, India before 1974, Pakistan after the return of A.Q. Kahn in 1976, Iraq before the 1991 Gulf War, and Iran from 2000 to the present. Seventeen faculty and graduate students took the survey and the results were compared with the motivations in the tables above. The results from the faculty and students were averaged. To best reconcile the rankings based off of the literature review and those of the survey of experts an average was performed. The averaged values were rounded to the nearest decimal and then utilized to generate intentions to insert into the Bayesian network. The results of this survey in addition to the actual values used to generate intentions are in Appendix B.

IV.C. Verification with Historical Proliferation Cases

Russia

Of the selected countries that were studied through the network, the Soviet Union's development of a nuclear weapon came first historically. The USSR first detonated a nuclear weapon on August 29th of 1949. The weapon was based off of the U.S. plutonium-implosion design and it had a yield of 20kt.[37] Fig. 12 shows the weapon pathway for the Soviet Union starting in 1939 and finishing with the successful detonation of a plutonium implosion weapon in 1949.

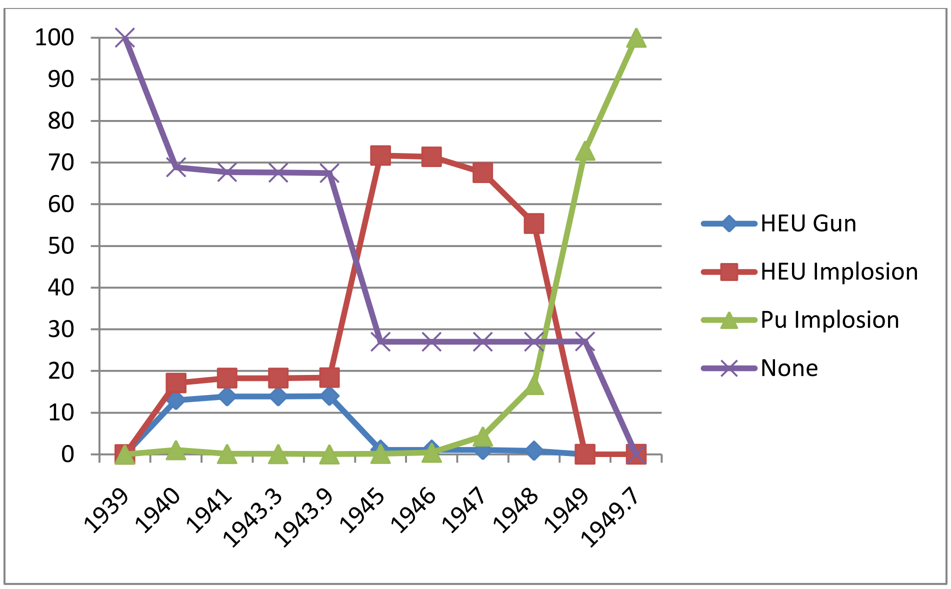

Fig. 12. The weapon pathways for the Soviet Union.

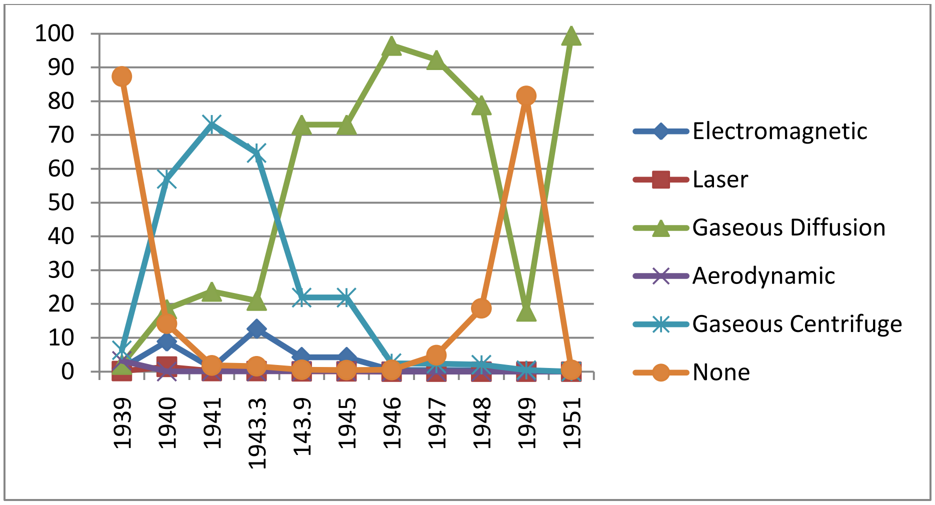

Fig. 13. The enrichment pathways for the Soviet Union.

The first decision that initiated the pathway towards the bomb came in mid October of 1940. The Presidium, which was a Soviet government institution, allocated funds for 1.5 metric tons of uranium compounds per year and to buy up the industry's supplies of uranium salts, which totaled about 300 kg.[37] In the network the uranium mine node was then turned on. The relative probabilities for both the HEU gun and the HEU implosion weapon increase to the mid-teens, while the probability for plutonium implosion remains negligible. The enrichment pathway begins to lean heavily toward gaseous centrifuge, with this choice increasing to 57%, as seen in Fig. 13. The next enrichment path that is not negligible is gaseous diffusion which increases to nearly 20%. The next historical piece of evidence to the network is the addition of UF_6 after the Soviet biogeochemical lab begins preparing for use in separation.[38] The addition of UF_6 does not change the weapon pathways by much but it does increase gaseous centrifuge to 73% and gaseous diffusion to 23.7%. In 1943 the Russians began to request

UCl_4, an indicator that they may be looking into the electromagnetic isotope separation enrichment method. The activation of UCl_4 increases the probability of that path to nearly 13% while decreasing gaseous centrifuge to 65%. Gaseous diffusion decreases only marginally to 21%.

Later in 1943, the decision was made to focus on gaseous diffusion over other types of enrichment methods. By turning on the energy requirements node that is necessary for this path, the pathway for gaseous diffusion jumps to 73% while gaseous centrifuge decreases to about 21%. The rest remain drop down to negligible values. The Russian spy Klaus Fuchs was transferred to Los Alamos and was able to transfer knowledge about the plutonium implosion weapon. Throughout the year 1945, Fuchs was able to give to the Soviets information about the polonium initiator, the tamper, and the high explosive lenses.[38] By turning on the respective nodes, the HEU implosion path jumps up to 71.4%.

The decision was made by Stalin to pursue the plutonium implosion weapon. In 1947, production began on a reactor and a reprocessing facility. The precipitation method, which involves the chemistry behind the reprocessing of plutonium, was perfected. The activation of this node caused a jump in the likelihood of the plutonium weapon path to 4.33%. By 1948 the reprocessing facility was complete. The activation of the reprocessing node caused the same path to increase to 16.7% at the expense of the HEU implosion path. The tipping point came when the reactor, known as Chelyabinsk-40 started to produce plutonium. The plutonium node was turned on causing the plutonium weapon pathway to drastically increase to 72.1% while the HEU implosion path drops to a negligible 0.15%. The weapon was tested in 1949 and when the testing node is turned on the network indicates that it was indeed a plutonium weapon.

It is interesting to note that the same nodes that were causing the plutonium weapon path to increase were causing the enrichment pathways to decrease. This makes intuitive sense since HEU is not needed for a plutonium weapon and hence if that path is pursued the uranium enrichment paths should decrease. Even the gaseous diffusion pathway decreased to 17.8% once the plutonium was obtained. In 1951, however, the path increases again as the plant was successfully completed and operational. This behavior of the network brings to light two important points. The first is that due to the nature of the Bayesian network being normalized to one, an increase in one path necessitates a decrease in another. This behavior does not allow parallel paths to be shown in the network. Second, the results the network delivers is in fact the most likely path in a given instant of time. The network is not to be used as a predictive tool but rather one that gives a probability assessment at a given date.

France

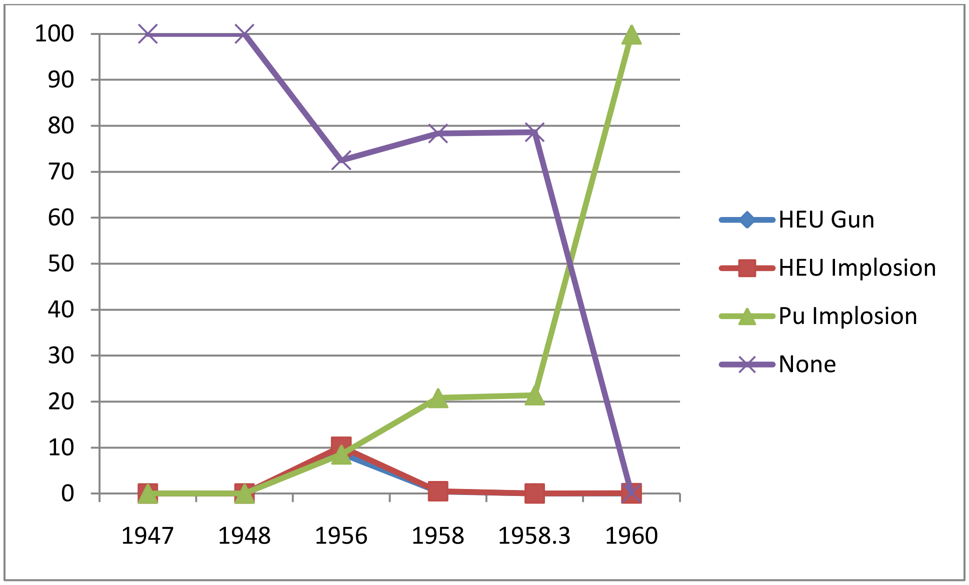

Fig. 14. The weapon pathways for France.

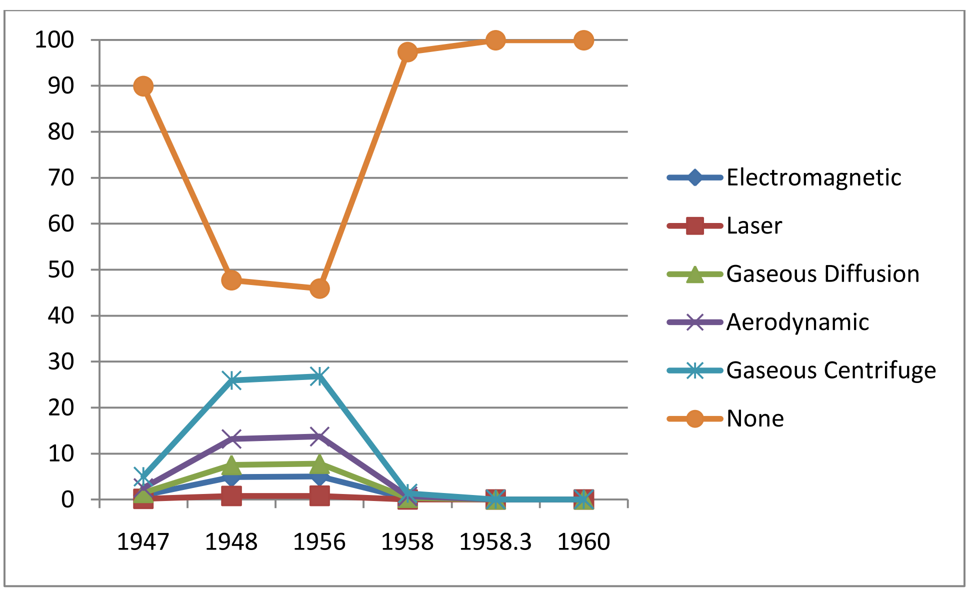

Fig. 15. The enrichment pathways for France.

French interest in a nuclear weapon began after World War II. A domestic uranium mine was discovered near the end of 1948 in La Crouzille, Limousin, and the Autun region. The uranium mine node was activated making the most likely enrichment pathway gaseous centrifuge at 25.8%. In 1956 the domestic reactor node was added when the plutonium production reactor at Marcoule went critical.[37] The addition of the reactor node caused the plutonium weapon pathway to increase to 8.51% as seen in Fig 14. Given the French intentions, the network still was giving non-negligible probabilities for the enrichment pathways. The non-negligible enrichment pathways were keeping the weapons pathways for HEU gun and implosion types at 8.72% and 10.2% respectively. In 1958 the plutonium reprocessing facility became operational and later that year they begin to produce plutonium at 0.67 lbs per day.[37] The activation of the reprocessing and plutonium nodes essentially dropped all of the enrichment paths to zero, as seen in Fig. 15, along with the HEU gun and implosion paths while the plutonium weapon path increased to 21.6%. The weapons test itself occurred on the February 13th and was in fact a 70kt plutonium implosion weapon.[37] Turning on the testing stage node increased this path to 100%, hence accurately describing the outcome.

In the French case, only the large technologies such as the reactor and reprocessing facility were activated and no smaller weapons components. Until the testing node was activated, the likelihood for the weapons path was slightly above 20%. This indicates that the large facilities contribute, but to not drastically increase the belief in weapon acquisition. Inputting the large-scale technologies show a definite start down a weapons path, but the belief is relatively low due to lack of weapons components. The above result demonstrates that the network behaves as it should while providing insight into the degree to which large facilities contribute to the likelihood of taking certain weapons paths. This behavior is to be seen in the examples below too.

Israel

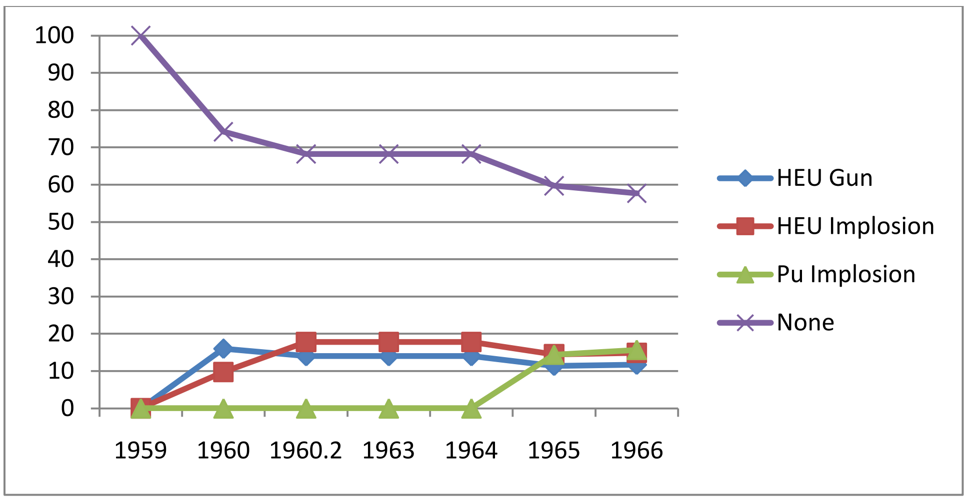

Fig. 16. The weapon pathways for Israel.

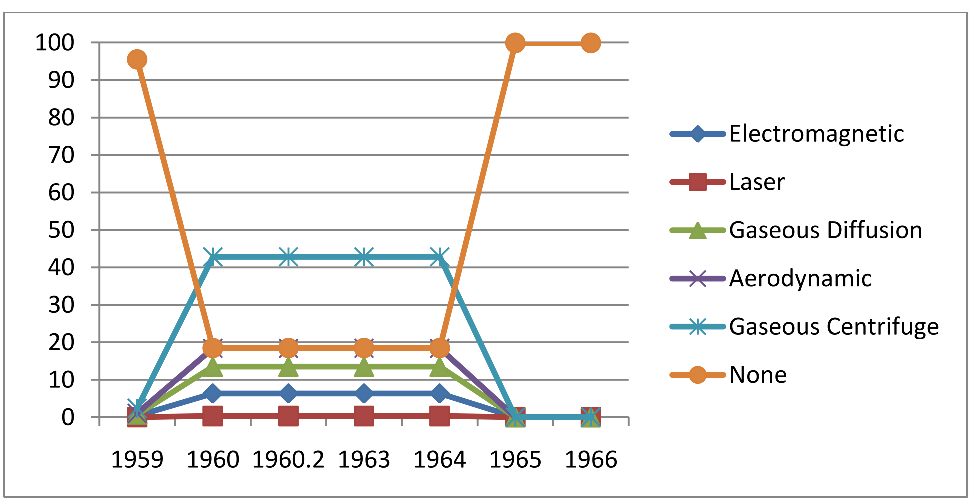

Fig. 17. The enrichment pathways for Israel.

The Israeli weapons program was given a tangible impetus in 1960 when Israel received 50kg of 90% enriched HEU from the United States intended for use in a research reactor.[39] The HEU node was turned on in the network. It is interesting to note that due to the structure of the network, the activation of the HEU also caused the enrichment paths to increase, the greatest one of these being by gaseous centrifuge. As would be expected, the weapons paths for both types of HEU bombs increased with the reception of the HEU material. The gun type increased to 16% and the implosion type increased to 9.76% as seen in Fig. 16.

The collaboration with the French significantly helped the Israelis. The French need for Israeli computer expertise prompted caused them to trust the Israelis with very sensitive knowledge. It has even been said that when the French detonated their first implosion weapon in February of 1960, it implied the birth of two nuclear powers because the collaboration with Israel was so great.[40] The unrestricted access to the implosion test on that day in addition to the detailed entwinement of the countries since the French began their pursuit of the implosion weapon sufficiently implied that the Israelis possessed implosion knowledge. The implosion knowledge node was turned on making the HEU implosion path surpass the gun type path by a comparison of 17.8% to 14%.

At the end of December 1963, the Dimona reactor purchased by the Israelis from the French went into operation. This node was turned on but does not have any effect on the weapons pathways. Less than a year later the plutonium separation facility was completed. The reprocessing node was turned on without effect. In early 1965 the first plutonium starts to be extracted.[37] The plutonium node was turned on which causes the plutonium implosion weapon pathway to increase to 14.4%. This increase puts the plutonium weapon pathway on par with the HEU implosion weapon which dropped to 14.5%. The gun type also dropped to 11.4%. The activation of the plutonium node also causes the enrichment paths to decrease to negligible values as seen in Fig. 17. These numbers make intuitive sense since Israel at this point had access to both types of special nuclear material and knowledge of implosion weapons. The way the network is structured, the plutonium implosion weapon pathway did not increase with the reactor or the reprocessing facility until the plutonium node was activated because the HEU node was already activated. Once one of the special nuclear material nodes are activated, it gives the network a strong bias towards the type of weapon that utilizes that material until the other material is also activated. This behavior of the network is also the same reason that the enrichment paths decrease as more nodes associated with the plutonium weapon are activated.

In 1966 the Israelis had produced enough plutonium for a weapon. The plutonium pit was added causing the plutonium implosion weapon pathway to increase to 15.7%, slightly edging out the HEU implosion weapon path which was at 14.9%. These numbers are low but that is because there is a lack of evidence of direct of domestically developed weapons packages for the implosion weapons.

Unlike the other cases, the Israeli case does not clearly indicate one path over the other. The lack of indication of one path over the other is due to the activation of both the HEU and plutonium nodes, and a lack of information regarding other weapons components the Israelis acquired.

South Africa

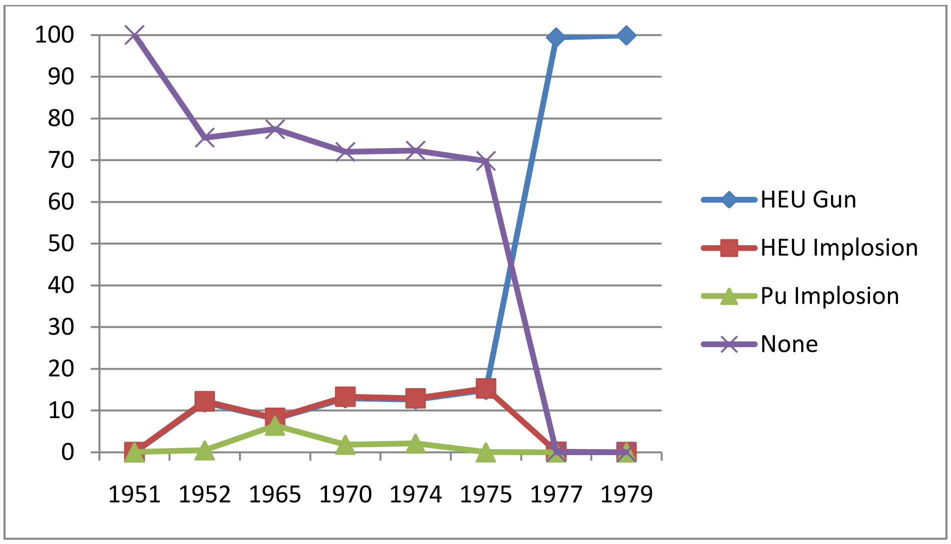

Fig. 18. The weapon pathways for South Africa.

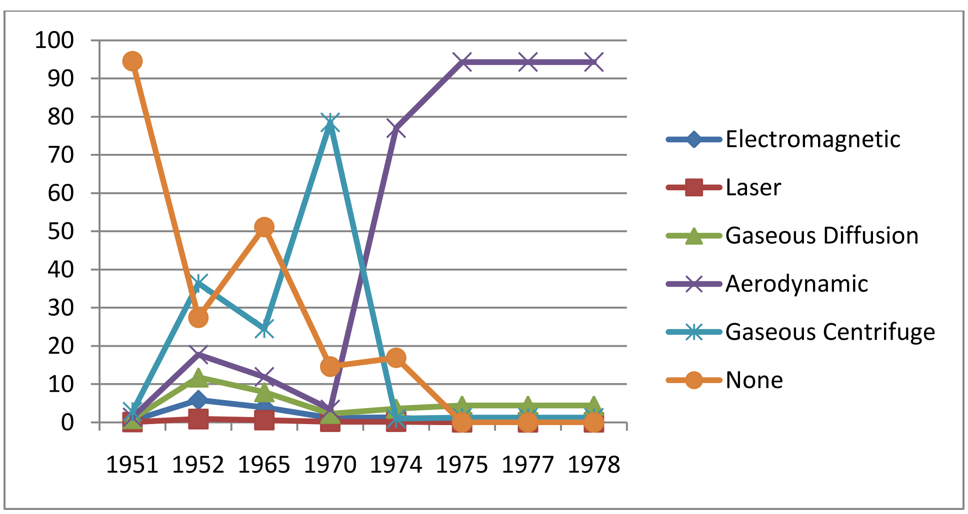

Fig. 19. The enrichment pathways for South Africa.

The first step in South Africa's program was the domestic uranium mine discovery at West Rand's Consolidated Mines near Johannesburg.[35] At this point all of the weapons paths are around 7%, as seen in Fig. 18, making it unclear what is the most likely path. Based on the intentions, the leading pathway for enrichment was gaseous centrifuge at 36%. The second highest percentage pathway was aerodynamic isotope separation at 17%. The next significant step in the program was the reactor Safari-1 given to South Africa by the United States in 1965. As shown in Fig. 19, turning on the domestic reactor node decreased the gaseous centrifuge to 24.5% and aerodynamic to 11.9%.

In 1970, South Africa began to do research with ultracentrifuge technology.[40] The high speed motor node was activated as a result of this as these are an essential component to this technology. This activation caused a spike in the gaseous centrifuge pathway to 78.5% while the other pathways dropped to negligible amounts. This also caused the HEU weapons to separate themselves from the plutonium weapon by increasing to the early teens while the plutonium weapon dropped to 1.84%.

Four years later, the enrichment paths take another turn when a government-owned German firm named Steinkohlen Elektrizitaia AG (STEAG) gave Becker jet nozzle technology to South Africa.[40] The aerodynamic component nodes were turned on as a result of the technology transfer and the aerodynamic pathway increased to 77%. The other enrichment pathways dropped to minuscule values. The weapon pathway percentages did not significantly alter as a result of this, the bias still being towards the HEU paths. Further bolstering the aerodynamic enrichment path, the UF_6 node was turned on when in 1975 the South Africans opened a production plant in Pelindaba.[40] The activation of the UF_6 node resulted in the aerodynamic enrichment path increasing to 94.3% while causing the gun type weapon to increase to 14.9% and the HEU implosion weapon to increase to 15.3%. In 1977 the South Africans obtained tungsten from Rhodesia, Zaire, and Zambia and they gained expertise in internal ballistics, igniters, and propellants.[35] A gun test without HEU was conducted later that year. The gun test node was activated resulting in an increase in the HEU gun type path to 99.4%. It was clear at this point in history that an implosion weapon was not being sought and the network accurately reflected this by decreasing the implosion weapons to zero.

The South African case demonstrated how the network portrays a clear decision for a given path being made as a result of a technology transfer. In 1974 the acquisition of the German aerodynamic technology caused them to take that enrichment path. The network shows this by increasing the aerodynamic path drastically while all other paths drop to negligible values. This is a case in which the normalized nature of the network that adds to one path at the expense of another lucidly demonstrates the strong impact of a technology transfer on pathway choices.

India

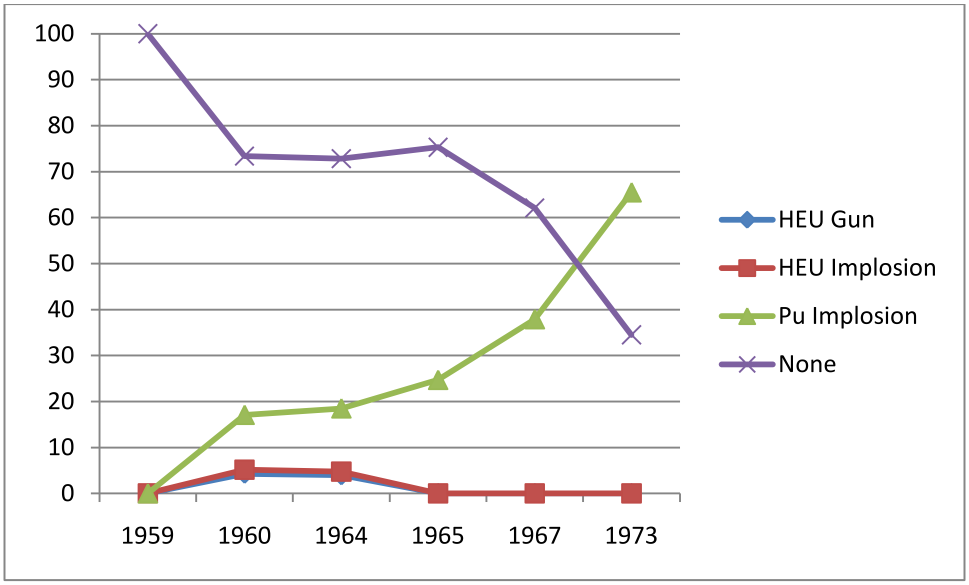

Fig. 20. The weapon pathways for India.

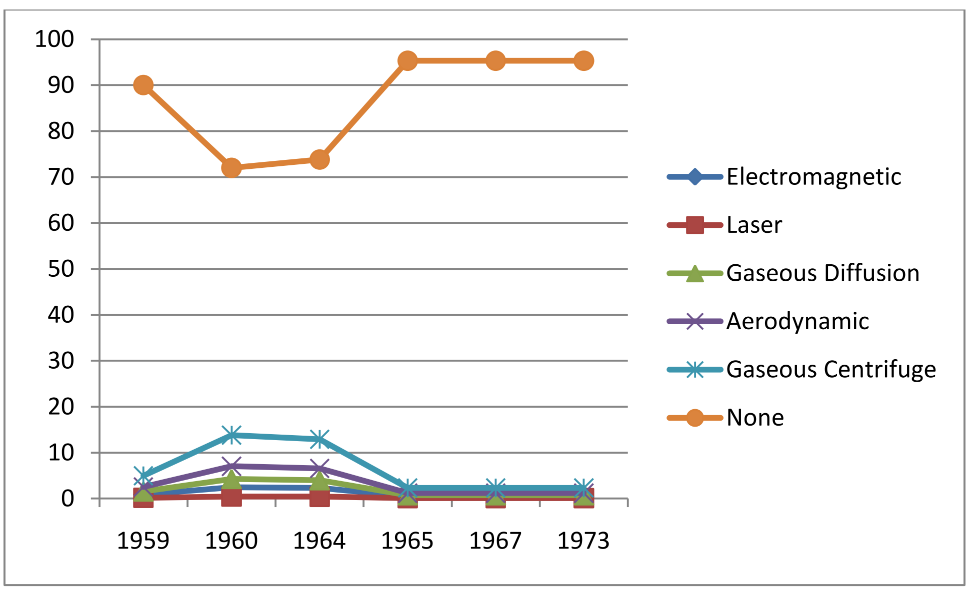

Fig. 21. The enrichment pathways for India.

In 1955, Canada offered to give India an unsafeguarded 40MW research reactor on the condition that they would use it for peaceful purposes.[41] The reactor was called CIRIUS and burned natural uranium fuel. The reactor went critical in the summer of 1960. The largest jump in the weapon pathway as a result of the activation of the reactor node was the plutonium implosion weapon pathway which increased to 17.1% as seen in Fig. 20. The HEU gun and implosion paths were around 4% and 5% respectively. The enrichment paths remained low, the highest being the gaseous centrifuge at 13.8%, shown in Fig. 21.

The next node activated was the reprocessing capability after the first spent fuel from the CIRIUS reactor entered the plant at Trombay.[33] The plant was based off of the PUREX process and blueprints were supplied by a U.S. firm albeit Indian engineers modified them during construction.[40] The largest difference caused by the addition of the reprocessing node was a 1.5% increase in the plutonium implosion weapon pathway. Subsequent to the initiation of the reprocessing plant, plutonium began to be separated. The plutonium node was activated and there was a further increase of the plutonium weapon pathway to 24.5%. The plutonium node activation also caused the gun type and HEU implosion pathways to drop to zero.

In 1967 a scientist named Chidambaram was asked to develop the equation of state for plutonium in order to determine how much high explosive is necessary to compress the plutonium to the necessary density for the implosion weapon to function properly.[37] Shortly after Chidambaram begins to recruit other Indian scientists and engineers to design the components of the chemical high explosive device that would be needed.[37] This was sufficient evidence to imply that implosion knowledge was being obtained at this time. The implosion knowledge node was turned on causing the plutonium pathway to further increase to 37.9%. All of the enrichment pathways are miniscule at this point in time again showing that when one path is being followed, either plutonium or uranium, there is devaluation in the nodes contributing to the other.

By 1973 a non-nuclear chemical explosives test is performed in the forests of Andrha Pradesh.[40] The explosives package node was activated and the plutonium pathway increased to 65.5%. A year later the Indians executed their first test of a nuclear weapon. If the testing stage was activated at this point in the network, it is obvious that the weapon pathway was the plutonium implosion route. The network accurately showed a steady increase in the plutonium path and essentially the null case for the enrichment paths.

Similar to the previous cases, the reactor and reprocessing nodes increased the plutonium pathway to the upper teens in value. Once these nodes were activated, the pathway greatly increased with the addition of the implosion knowledge and the explosives package. This implies that the sensitivity of a pathway to other nodes greatly increases once foundational technologies such as reactors and reprocessing facilities are activated.

Pakistan

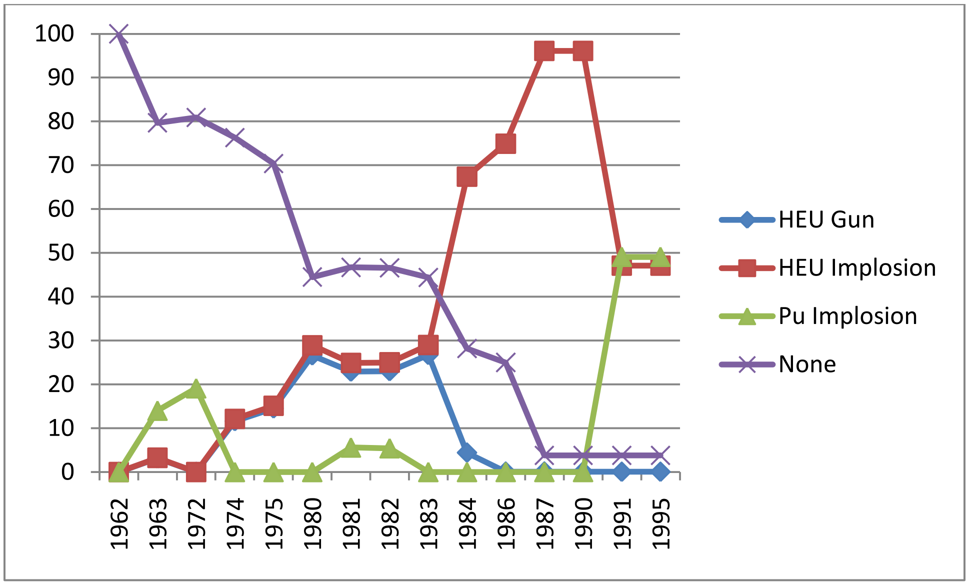

Fig. 22. The weapon pathways for Pakistan.

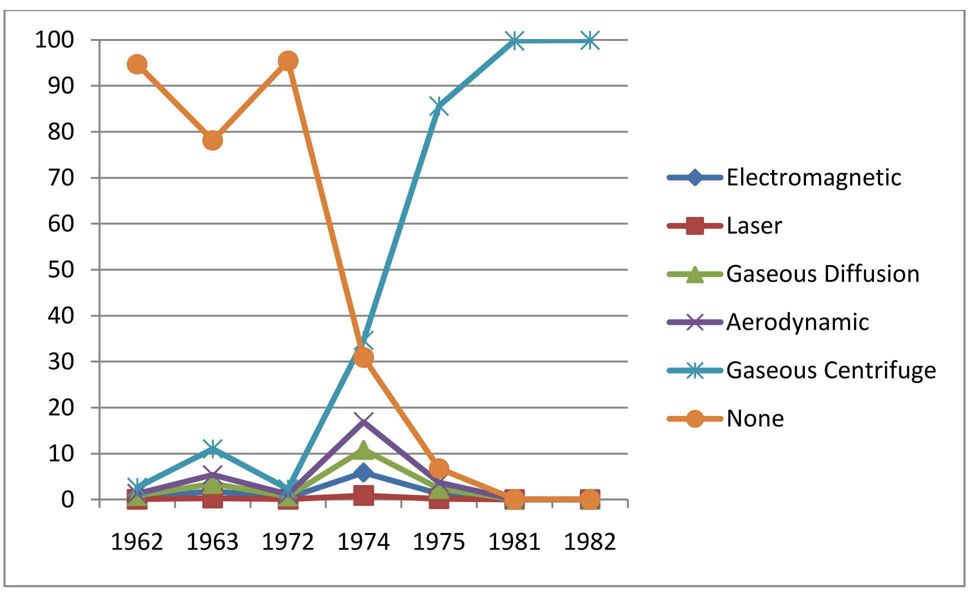

Fig. 23. The enrichment pathways for Pakistan.

The Pakistan Institute of Nuclear Science and Technology was established in 1961 and two years later a 5MW research reactor and reprocessing facility were opened.[37] The network reflected these installations by increasing the plutonium weapon pathway to 14%. The highest percentage at this point for the enrichment pathways was a miniscule 11% for gaseous centrifuge. The next milestone in the program was when Canada agreed to give Pakistan a 137MW heavy water reactor called KANUPP. This became operational in 1972. What is also significant about this year is the desire expressed by President Bhutto of having a bomb in three years.[37] As seen in Fig. 22, there was a spike in the plutonium route in the year 1972. However, it dips down in 1974 and the HEU bomb paths begin to increase. Several key historical events happened in that two year period to explain that transition. After the reactor was opened, Pakistan contacted the French to buy a large-scale reprocessing facility.[42] Pakistan went as far as signing a contract for a plant. However, in 1974, as noted above, the Indians tested their first nuclear weapon. The Indian test caused an overall tightening of export controls. At around this same time, A.Q. Khan returned to Pakistan and proposed to Pakistani officials an initiation of a uranium enrichment program. The program, called Project 706, was soon initiated and proved to be more promising than the plutonium-reprocessing route.[42] The associated activations caused the plutonium weapon path to drop near zero and the HEU paths to increase to around 12%. The necessary components for centrifuges begin to be collected and it is discernible from Fig. 23 that the enrichment paths spike up in 1974, the greatest being gaseous centrifuge at 35.6%. In the early 1980s Khan procured 6000 tubes of maraging steel from the Netherlands. The maraging steel and high strength tube nodes are activated and it is evident from the percentage of 99.9% that the enrichment pathway chosen and being followed from this year onward is gaseous centrifuge. This decision affected the weapon pathway by decreasing the plutonium weapon route to zero and increasing the HEU gun and implosion types to 26.6% and 28.9% respectively.

Also in the early 1980s, Pakistani interested in reprocessing revived. There were reports of a Swiss company assisting Pakistani in developing reprocessing technology.[40] Pakistan also established two facilities, an experimental and plutonium extraction plant.[37] The plutonium node now had a probability of 14%, increasing the plutonium weapon pathway to 5.6%.

Further assistance from the A.Q. Khan network came when a UF_6 plant was established in the first years of the 1980s decade. The plant parts were transferred piece by piece from a West German company.[37] The UF_6 node was turned on and there was a miniscule decrease in the plutonium weapon pathway and a miniscule increase in the HEU weapon pathways since the centrifuge pathway was so high to begin with.
For the year 1982, the HEU node was activated because there were enough centrifuges to make six bombs per year. This activation caused the plutonium pathway to drop to zero again and the HEU gun and implosion paths increased to 26.7% and 29% respectively.

In 1984, the program made a decisive step in the implosion direction when a high explosive device was tested. The explosives package node was activated and the HEU implosion pathway increases to 67.4% while the gun type drops to a mere 4.41%. A few years later, a non-nuclear implosion device is tested. The weapons package was now activated and the HEU implosion path continued to increase to 74.9%. The gun type path joined the plutonium path at a negligible amount near zero.

In 1987 oscilloscopes were purchased.[34] The activation of these nodes increased the HEU implosion pathway to 96.1%. The next node turned on was the HEU pit after U.S. intelligence reported that Pakistan was machining the uranium metal into bomb cores.[37]

In the 1990s, China helped Pakistan with its reprocessing plant at Chasma. The reprocessing capability node was turned on as a result of this. This placed both implosion weapon paths on equal par at around 50%.

The enrichment graph clearly shows the decision point to pursue gaseous centrifuge upon A.Q. Khan's return. The weapon paths graphed in Fig. 22 show a state that has changed direction in its pursuit of the bomb. The Pakistani case shows the network's ability to demonstrate changes in paths.

Iraq

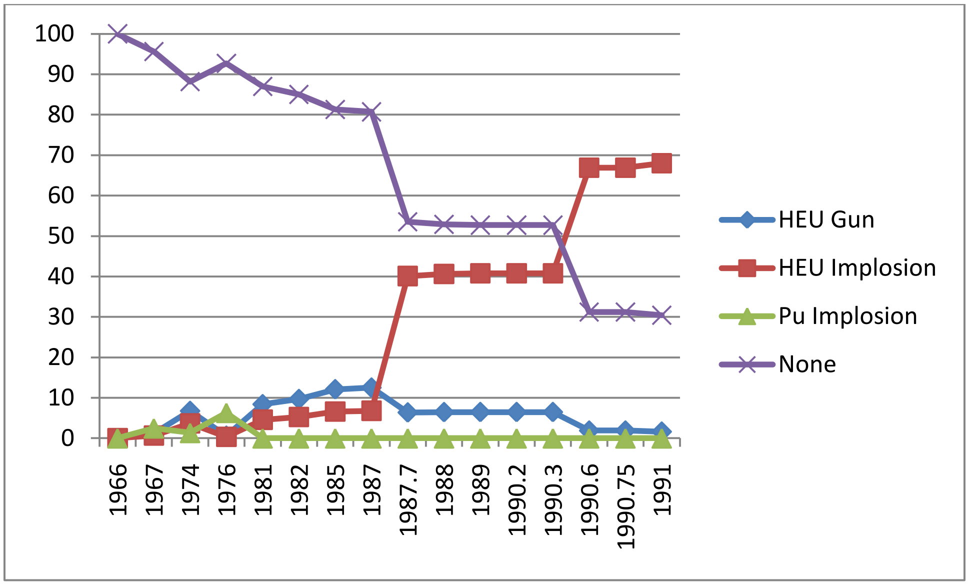

Fig. 24. The weapon pathways for Iraq.

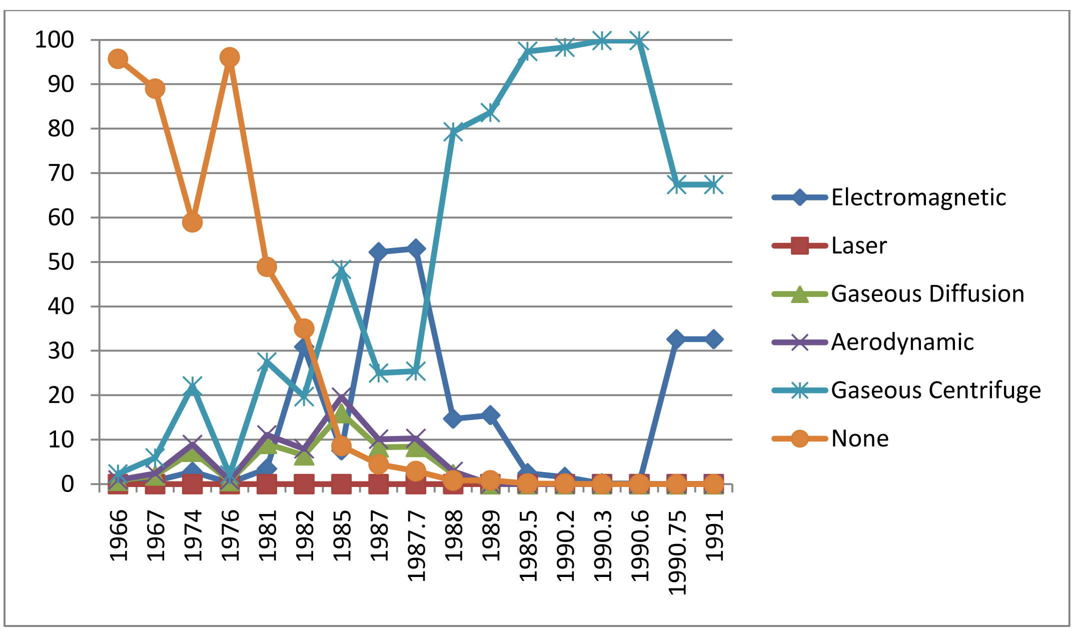

Fig. 25. The enrichment pathways for Iraq.

In 1967, the 2MW research reactor supplied by the Soviets to Iraq went critical.[40] The reactor node was turned on but the initial pathways for both weapon and enrichment remained low. In 1974 Iraq found a uranium mine near Al Qaim which was located near the Syrian border.[37] The leading enrichment pathway at this point was gaseous centrifuge at 22%. Italy built Iraq a radiochemistry lab with three lead-shielded hot cells capable of reprocessing plutonium in 1976.[17] The reprocessing capability node was activated causing the enrichment paths to decrease to miniscule values. The only non-negligible weapon pathway at this point was plutonium implosion which was at 6.31% as seen in Fig. 24.

France agreed to build Iraq a 70MW reactor. During the construction process however, the reactor was destroyed by Israeli fighter jets.[37] The reactor node was de-activated as a result of this. The plutonium weapon route drops to near zero as a result.

In 1982, research and development began on a UCl_4 plant.[40] The UCl_4 node was turned on as a result of this exploratory work. The network responds by showing that electromagnetic enrichment was the most likely path at 30.9%, as seen in Fig. 25. Gaseous diffusion also entered the realm of possibilities for Iraq in the early eighties. By 1985 progress was made with the barrier material for the gaseous diffusion process with special emphasis on the compressor, diffuser, and heat exchange design.[40] The progress prompted the activation of the compressor and energy requirements node. As a result of this, gaseous diffusion increased from 6.49% to 16%. The electromagnetic pathway decreased below 8%.

The electromagnetic pathway rebounded to 52.2% when the design work for the EMIS production phase was finalized. Iraq was planning to have 70 R120 separators for the production of 20% enriched uranium and 20 R60 separators for the production of 93% enriched uranium. The separator node was activated as a result of this.

In August of 1987, Iraqi scientist Khidhir Hamza went to Germany to purchase a list of bomb components and $120 million dollar deal was signed. One of the mentioned items on the list was an x-ray flash camera that has the ability to penetrate the explosive plume of compression charges.[40] By activating this node, the HEU implosion weapon pathway increased to 40.1%. This did not affect the enrichment paths.

The next node activation that affected the enrichment paths was the high strength tubes when, in 1988, Iraq was successful in manufacturing a barrier tube suitable for operation in UF_6.[40] This was the point in the timeline where the gaseous centrifuge pathway began to win out. The gaseous centrifuge pathway increased to 79.3% at the expense of the EMIS route. In 1989, Iraq cancelled its gaseous diffusion project.[36] The nodes associated with the gaseous diffusion path were turned off and the gaseous centrifuge route increased to 83.6%. The gaseous centrifuge route continues to increase when Iraq obtained twenty-five pieces of maraging steel, 19 of them used for centrifuge performs. About one year later in 1990, they obtain 20 carbon fiber centrifuge rotors. The carbon fiber rotor node was turned on. By this time the gaseous centrifuge path is at 98.3%. Later that year UF_6 started to be run through the centrifuges. The UF_6 node was activated and the pathway for gaseous centrifuge was at 99.8%.[40]

In 1990 it became apparent that Iraq was in fact pursuing the HEU implosion path. Iraq had the design details for a beryllium-polonium neutron initiator that would be placed at the center of the bomb.[40] The design included a reflector/tamper that was made of natural uranium. The according nodes were activated and the HEU implosion path increased to 66.9%.

Later that same year, eight electromagnetic isotope separators began operation. They were only able to produce hundreds of grams of uranium with a maximum enrichment of 7.2%.[40] The network responded to the activation of the rest of the electromagnetic nodes by increasing its percentage to 32.6% at the expense of the gaseous centrifuge pathway. The network was able to show the oscillations between two competing enrichment technologies.

Finally, In January of 1991, Iraq specified the exact dimensions of the explosive lens.[40] The explosive lens node was activated and the activation increased the HEU implosion weapon pathway to 68%.

Iran

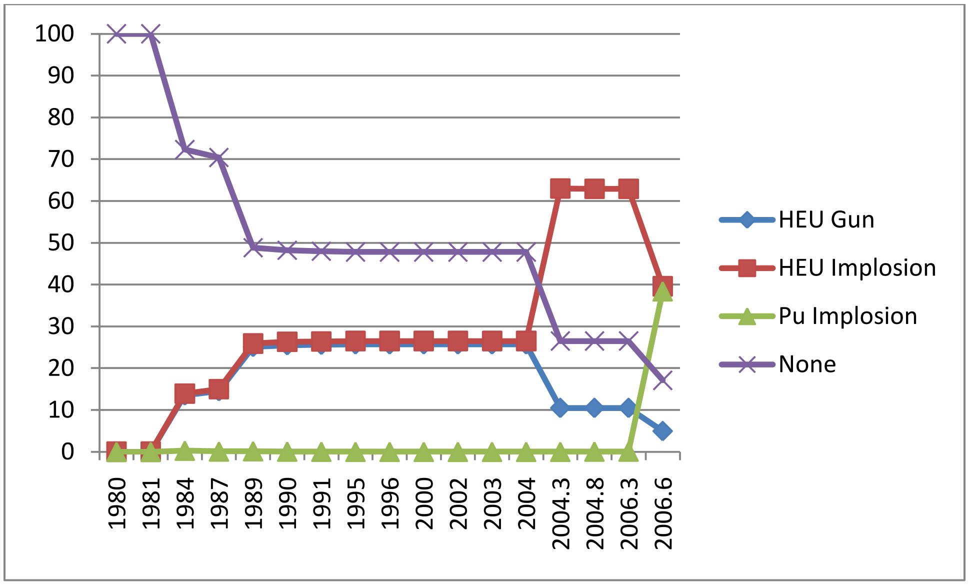

Fig. 26. The weapon pathways for Iran.

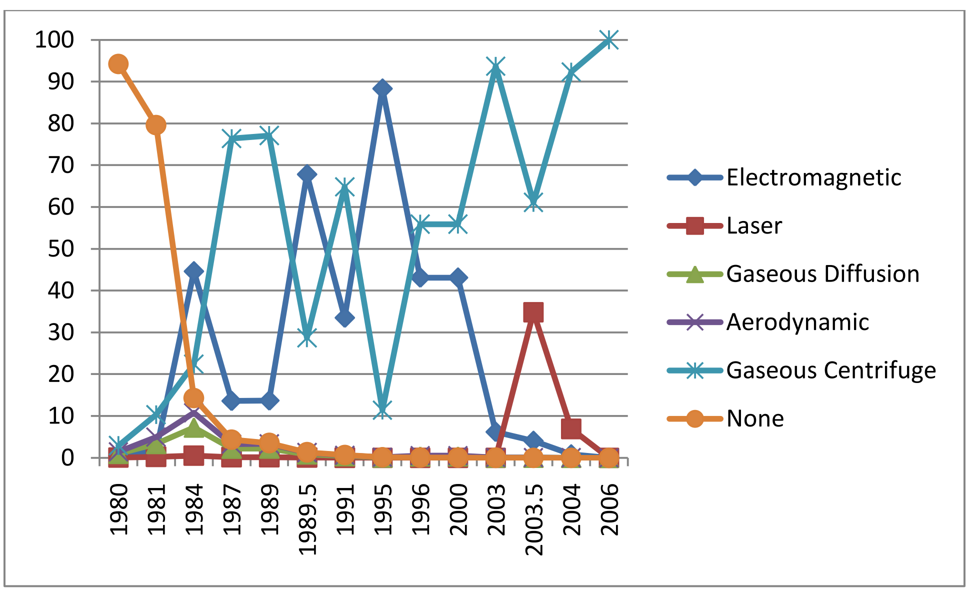

Fig. 27. The enrichment pathways for Iran.

In 1981, the head of the Atomic Energy Organization of Iran announced the discovery of four uranium mines.[40] The domestic mine node was activated and the most likely enrichment path was gaseous centrifuge at 10.3%. China gave Iran a small calutron in 1984. This technology transfer increased the electromagnetic isotope separation path to 44.6%.

As a result of the A.Q. Khan network, Iran in 1987 received drawings and specifications for a complete gaseous centrifuge plants including components such as the electrical drive equipment. The high speed motors node was activated causing the gaseous centrifuge path to increase to 76.4% at the expense of the electromagnetic path which dropped to 13.6%. During these early oscillations in the enrichment paths, the HEU paths have increased to the mid-teens in percentage while the plutonium path remained near zero.

The next node that was activated was the pulse generator when in 1987 two Iranian nationals illegally exported this item along with electronic equipment.[40] As expected, this activation had no impact on the enrichment paths but it did increase the HEU weapon paths to about 25% as seen in Fig. 26.

The Chinese delivered the electromagnets to Iran in 1989 and this pushed the electromagnetic path ahead of the centrifuge path by a comparison of 67.8% to 28.7%, as seen in Fig. 27. However, in 1991 the Iranians received balancing machines, a component in gaseous centrifuge technology, from Germany.[30] The activations of the balancing machine node made the most likely path gaseous centrifuge by increasing this path to 64.8% while the electromagnetic path decreased to 33.5%. However, in 1995 it was reported that the Chinese installed a calutron system.[40] More of the electromagnetic components were added and again the electromagnetic pathway increased to its highest percentage of 88.3%, shown in Fig. 27. At this point it seemed like electromagnetic enrichment was the path to be pursued. The most likely enrichment path switches again between these two choices when in 1996 it is discovered that Iran imported anhydrous fluoride, a chemical used to make uranium hexafluoride, from China and Russia. China was also helping them build a UF_6 conversion plant.[40] The UF_6 node was activated and again electromagnetic dropped below gaseous centrifuge to 43.1% while gaseous centrifuge jumped ahead to 55.9%. The weapon pathways are insensitive to these changes in enrichment paths. After concerns by the U.S., Russia halted the transfer of a copper vapor laser to Iran. This node was turned off in the network having negligible effects on the enrichment paths.

In 2003, U.S. diplomats report that the gaseous centrifuge plant near Natanz was more advanced than thought. Diplomats said that hundreds of centrifuges were prepared to enrich uranium and that parts, such as the high strength tubing, for thousands of others were ready to be assembled.[40] The high strength aluminum and tube nodes were activated causing the gaseous centrifuge pathway to increase to its highest percentage to date at 93.7% while the electromagnetic pathway decreased to 6.91%.

Also in 2003, another enrichment pathway emerges when the IAEA said that Iran has made a pilot plant for laser enrichment and had success in enriching tiny amounts of uranium. Researchers in Iran were experimenting with several types of lasers including copper vapor and carbon dioxide. The nodes for these lasers were activated and as seen from Fig. 28 there was a jump in the laser pathway to 34.8%. The activation of the laser nodes decreased gaseous centrifuge to 61.1% while decreasing the electromagnetic to a miniscule 4.04%. The weapon pathways continued to be insensitive to the enrichment pathway alterations.

The IAEA discovered the blueprints and equipment for the more advanced P-2 centrifuges which are made of maraging steel.[37] The discovery shed light on a previously unknown project which was testing the advanced centrifuges. The maraging steel node was activated in the network and the gaseous centrifuge pathway increased to 92.3%.

Another nuclear program in Iran was discovered in February 2004, this time by the United Nations. Iran had been experimenting with polonium, which has use as a neutron-initiator is a nuclear weapon.[40] The polonium-beryllium initiator node was activated. This time the enrichment paths stayed the same and the weapons paths were modified. The gun type path dropped to 10.5% while the HEU implosion path dramatically increased to 63%.

By 2004, the Russians declared they had finished building the Bushehr reactor for Iran.[37] The domestic reactor node was turned on but it had negligible effects on the pathways.

In mid-April of 2006 Iran announced they had 164 fully operational centrifuges and planned to have a total of 54,000 online.[37] This caused the pathway for gaseous centrifuge to increase to 100% while all others drop to negligible values. Later that year, the president of Iran inaugurated the heavy water plant.[40] The addition of the heavy water plant node changes the weapons path to a considerable degree. The plutonium implosion path increases to 38.4% at the expense of the HEU implosion path which decreases to 39.6%. Expectedly, this has no effect on the enrichment pathway.

The Iranian case provided insight into how the network responds when many paths are pursued over time. In the enrichment paths there are several large oscillations due to various technology transfers over time. The weapons paths are steadier, but one also sees that the acquisition of a large technology such as a heavy water reactor can have a nontrivial impact on pathways.

Sweden

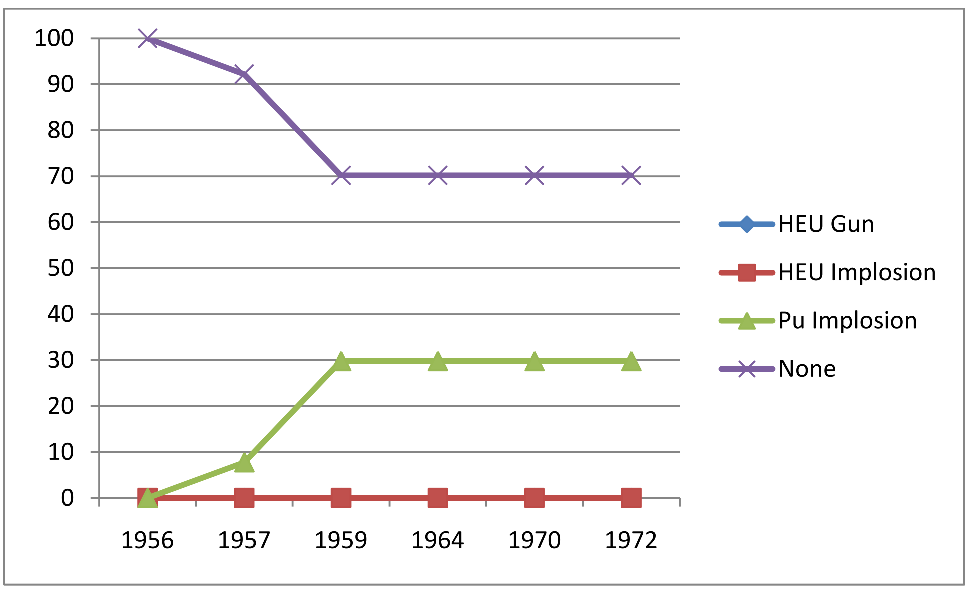

Fig. 28. The weapon pathways for Sweden.

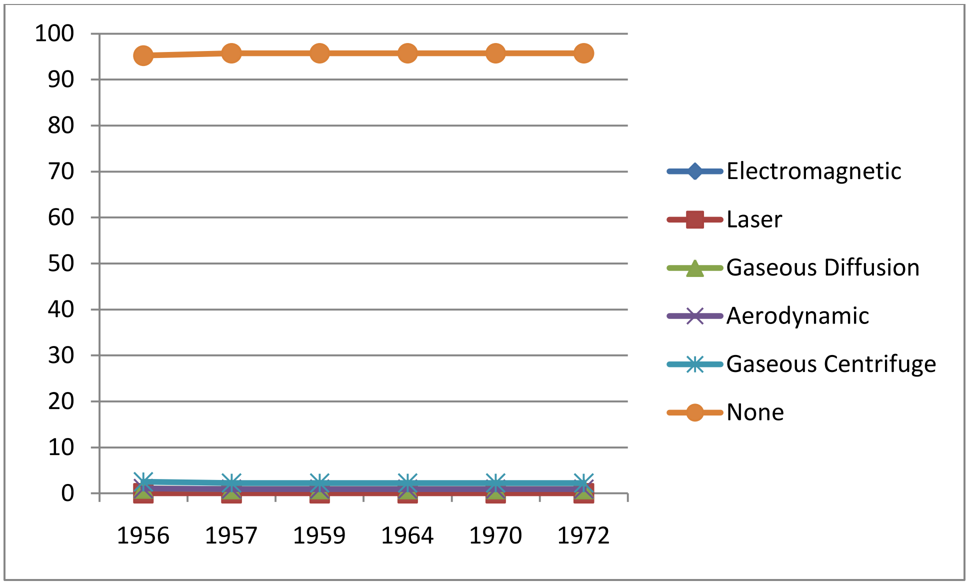

Fig. 29. The enrichment pathways for Sweden.

An interesting historical case to consider was that of Sweden, a nation that put serious thought and attempts into a nuclear weapons program but eventually abandoned the pursuit.

Interest in the development of nuclear weapons in Sweden began during the early days of the Cold War. The threat from the Soviet Union prompted initial interest in the late forties and by the early fifties some Swedish military officials were making public statements about nuclear weapon acquisition. The first step in that direction came in 1957 when a small amount of plutonium was obtained from England.[43] The plutonium node was activated and the reactor node was left untouched. The percentage for the plutonium weapon increased to 7.78% while the HEU weapons expectedly remained at zero as seen in Fig. 28. By the end of the decade, Swedish weapon designers had perfected implosion technology.[43] The implosion knowledge node was activated and the plutonium weapon pathway further increased to 29.8%.

Steps were made to create a research reactor and there were plans set to build a reprocessing plant. However, in 1964 nuclear officials abandoned the reprocessing plant idea due to the cost.[44] The reprocessing capability node was de-activated. The reactor project was also cancelled in 1970 due to both cost and design complexity.[44] The reactor node was turned off. The weapon pathway stayed the same because the plutonium node was still activated. The enrichment pathway remained at negligible values the entire time as seen in Fig. 29. The negligible values show that the network does model a null case in which a weapon was pursued but not all the way through. It is interesting to note that when Sweden signed the NPT in 1972, they had no technical barriers to producing such a weapon.[43] While the likelihood of having the plutonium weapon was low at around 30%, the fact that it was non-negligible shows an accurate reflection of the path that would be taken if the Swedes did choose to have a weapon.

IV.D. Conclusions on Verification and Validation

The above cases show that there is a correlation between national security need and a strong choice of one path. In the case of Russia for example, once the United States had the bomb, the Russians pursued one path through to completion. India also pursued one path after China had the bomb. The above cases show that the choice of path is linked to the technology transfer they had access to. For example, India received a reactor from Canada so they began heading down the plutonium path. Choice of pathway in general is influenced by technology transfer as is shown by the South

African case and the oscillations in pathways for several of the Middle Eastern countries. The network best demonstrates proliferation in a peaceful world, meaning a world in which not every pathway is attempted at once such as the United States during World War II. Also, it is best at showing the pathways leading to the first successful development of a weapon. Once a state has a certain type of weapon and they begin to go down another path, the already activated nodes will still be on and it will lead to a balancing of the paths as was seen in the case of Pakistan after they received a reprocessing plant. At this point, it will not be as clear what the most likely path will be. From looking at the historical cases, any pathway value above 50% implies a serious pursuit of that pathway. It should be cautioned that values below 50% should be viewed as emerging pathways which are often accompanied by several others.

The network presented in this work does not have the ability to ever truly be validated due to an insufficient amount of historical cases. There simply is not enough historical data to obtain sufficient statistics. However, the above nine cases demonstrate that the network has been verified to a sufficient degree. The behavior of the network is in accordance with what is expected is such situations and ultimately gives the same outcome as the historical cases. A network such as this, while never being able to validated, can be useful to learn from. The hypothetical cases that follow support the use of this network as a learning tool.

CHAPTER V

ASSESSMENT OF NETWORK RESULTS

V.A. Hypothetical Cases

The results of the historical cases concluded that the network does in fact behave as it should and the network can be used as a learning tool to assess the impact of technology transfers. In order to test the impact of nuclear technology transfer in the network, a few hypothetical cases were tried using Saudi Arabia, Syria, Myanmar, and Japan. The goal was to see the impact technologies such as reactors, enrichment facilities, and reprocessing plants had on the likelihood of being on certain weapon paths. Another goal was to assess the impact export control laws have by seeing how pathways change depending if these nodes are activated or not. The intent of the activations and de-activations of the export control nodes was to see how sensitive pathways are to certain technologies in order to give policymakers more informed information regarding nonproliferation matters.

In performing the sensitivity of pathways to the access a state has to technologies, two worlds were considered. The first was a world in which the export control laws were extremely loose, meaning that a state has easy access to any of the export control items. Loose export control laws were modeled in the network by activating all of the export control components and materials. The second world was one in which there were tight export controls, meaning that a nation was effectively blocked from acquiring any of the export control items. Tight export controls were modeled in the network by de-activating all of the export control components and materials.

Saudi Arabia

The weapons pathways for Saudi Arabia with loose export controls and no reactor, enrichment, or reprocessing technology are shown in Fig. 30, indicating Saudi Arabia is more than twice as likely to pursue the HEU implosion pathway as the plutonium implosion pathway. Given the need for two facilities, a reactor and a reprocessing plant, to make a plutonium weapon as opposed to just the enrichment facility for an HEU weapon, the result makes sense. The gun type and HEU implosion type are of similar value.

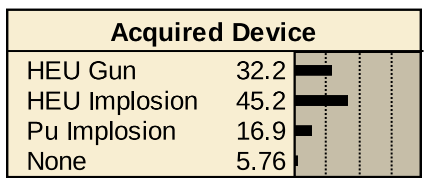

Fig. 30. Loose export controls but no reactor, enrichment, or reprocessing for Saudi Arabia.

Supposing Saudi Arabia is given or domestically builds a reactor, the reactor node was activated. What is seen in Fig 31is close to an increase in the plutonium weapon pathway to 63.5%. Accordingly, the HEU implosion and gun type path decrease to the single digits. The network indicates that the plutonium path has a remarkable degree of sensitivity to the reactor node when all of the export control items are activated. This sensitivity to the reactor node makes sense since it is the reactor that begins to breed plutonium.

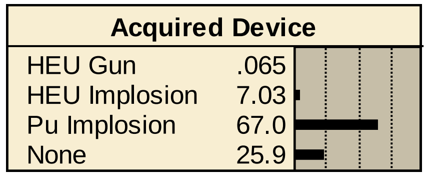

Fig. 31. Loose export controls and a reactor for Saudi Arabia.

If Saudi Arabia also acquired reprocessing technology, thus activating the reprocessing capability node, the plutonium implosion path continued to increase to 74.1% as seen in Fig. 32. Both of the HEU paths drop to zero. Again this result makes sense because the reprocessing facility extracts the plutonium from the spent fuel, allowing it to be used for the weapon.

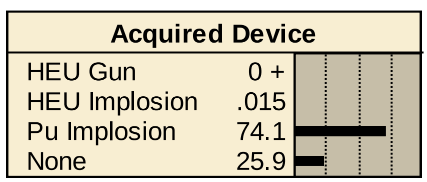

Fig. 32. Loose export controls with a reactor and reprocessing facility for Saudi Arabia.

Now, suppose Saudi Arabia is in a world with loose export controls but they do not have a reactor or a reprocessing plant but instead acquire enrichment capability. Fig. 33 shows that the HEU implosion path increases to almost 58.4% and the gun type increases to 41.6% while the plutonium and gun-type remain close to zero. The plutonium path's decrease to zero is sensible because if a state does have enrichment capability, the HEU weapon would become the most likely path.

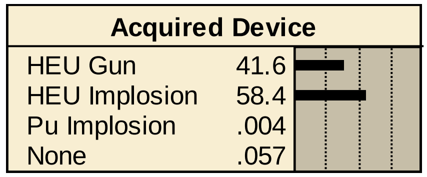

Fig. 33. Loose export controls and enrichment capability acquired by Saudi Arabia.

The next hypothetical scenario is Saudi Arabia in a world with very tight export controls. Tight export controls are modeled in the network by de-activating all of the export control materials and components.

Initially Saudi Arabia has no reactor, reprocessing, or enrichment capabilities. The results in Fig. 34 show negligible values for all weapons path indicating that not proliferating is the most likely path. Already this is a substantial difference from the world with loose export controls.

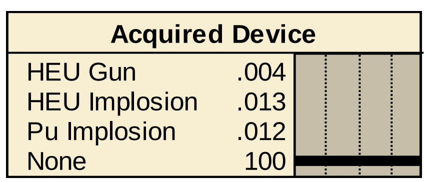

Fig. 34. Tight export controls but no reactor, enrichment, or reprocessing for Saudi Arabia.

As simulated before, Saudi Arabia is now given a reactor. Fig. 35 shows that nothing increases with any of the weapons paths. The lack of increase in the pathways says that having the ability to breed plutonium does not increase the likelihood of acquiring a nuclear weapon if all the other technologies towards weapons manufacturing are blocked.

Acquired Device	
HEU Gun	.004
HEU Implosion	.013
Pu Implosion	.012
None	100

Fig. 35. Tight export controls and a reactor for Saudi Arabia.

A reprocessing plant is given to Saudi Arabia in addition to the reactor in Fig. 36.. Even the addition of the reprocessing plant does not make the pathways in the network increase if all of the components and materials are turned off.

Acquired Device	
HEU Gun	0 +
HEU Implosion	.013
Pu Implosion	0.11
None	99.9

Fig. 36. Tight export controls with a reactor and reprocessing facility for Saudi Arabia.

What is being modeled here is a theoretically perfect world in which there is no way that Saudi Arabia can obtain this material from another country. The reality is that no security regime is perfect and items can and do slip through. There is also the possibility of technologies being transferred through black market networks such as the A.Q. Khan network. Lastly, there is the possibility of a nation making some of the necessary materials or components themselves. These two hypothetical scenarios serve as a learning simulation that continues to show that the network behaves as it should.

Continuing the scenario shown in Fig. 37, suppose that Saudi Arabia domestically created high purity magnesium and are given an explosives package from an underground network. The corresponding nodes in the network are activated and there is a jump in the plutonium implosion path to 46%.

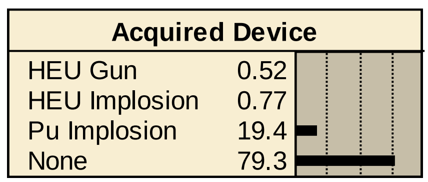

Fig. 37. Saudi Arabia pathways with a reactor, reprocessing plant, high purity magnesium, and explosives package.

What the above scenario reminds is that the world is not perfect and technologies do get transferred or manufactured. Once large facilities are in place that can be used for weapons purposes, the pathways to a nuclear weapon are highly sensitive to transfers of material and components.

Now suppose that Saudi Arabia does not have a reactor or reprocessing capability but are now given enrichment capability. Fig. 38 shows that with tight export controls, this transfer does not have an effect on the pathways.

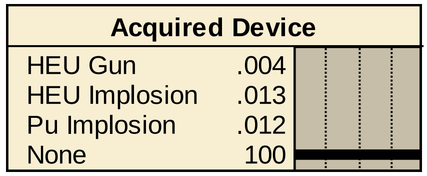

Fig. 38. Tight export controls and enrichment capability acquired by Saudi Arabia.

Now suppose Saudi Arabia acquires high purity calcium and a tamper.

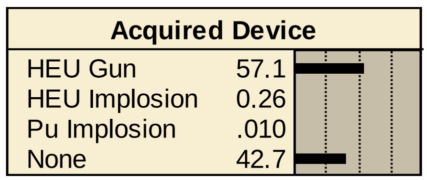

Fig. 39. Saudi Arabia with enrichment capability, high purity calcium, and a tamper.

The activation of the high purity calcium and tamper nodes caused a large jump in the HEU gun path if Saudi Arabia had enrichment capability as seen in Fig. 39. This result is sensible because the enrichment plant makes HEU which the high purity calcium puts into metallic form for the weapon pit, and the tamper is a key component to the gun weapon.

If they acquire a weapons package instead of a tamper, the HEU implosion path jumps to 98.5% in Fig. 40. As expected, the other pathways remain negligible.

Acquired Device	
HEU Gun	0.34
HEU Implosion	98.5
Pu Implosion	.005
None	1.14

Fig. 40. Saudi Arabia with enrichment capability, high purity calcium, and a weapons package.

These results continue to demonstrate the sensitivity of the pathways to components and materials once large technologies are activated.

Syria

In order to compare a country with similar available infrastructure, technical capability, and international networking but different motivations, Syria was chosen. The same methodology used with Saudi Arabia was followed.

Loose export controls were modeled first with none of the large facilities such as reactors, reprocessing plants, or enrichment facilities. Fig. 41 shows that the HEU gun-type path is the most likely path. The difference in values for Syria and Saudi Arabia with loose export controls and no other large-scale facilities can be accounted for in the network by two reasons. While the available infrastructure metric for both countries is extremely low, Saudi Arabia's is twice as large as Syria. This difference is important to note since the plutonium path requires twice as many large scale facilities to follow and the HEU gun-type is the least sophisticated. Another reason the results differ is that the motivations used slightly differ. Syria would be primarily motivated by deterring an attack from Israel while Saudi Arabia would be primarily motivated by going nuclear before their rival Iran. An HEU gun-type weapon would be sufficient for both of these reasons but the Saudi Arabian motivation is slightly more biased on the side of plutonium especially if their rival is pursuing such a path. For Syria, any weapon would be sufficient.

Acquired Device	
HEU Gun	79.2
HEU Implosion	15.2
Pu Implosion	2.92
None	2.61

Fig. 41. Loose export controls but no reactor, enrichment, or reprocessing for Syria.

When Syria was given a reactor, the plutonium path increased to 17.5%, which is much less than the 67% that Saudi Arabia increased to. This is shown in Fig. 42.

Acquired Device	
HEU Gun	62.4
HEU Implosion	12.0
Pu Implosion	17.5
None	8.11

Fig. 42. Loose export controls and a reactor for Syria.

If Syria was also given a reprocessing plant, and Fig. 43 shows that it became even more obvious that the plutonium path was the one being taken with a likelihood of 71.5%. The HEU paths decrease to zero. The plutonium path was now roughly the same as it was for Saudi Arabia in the identical scenario.

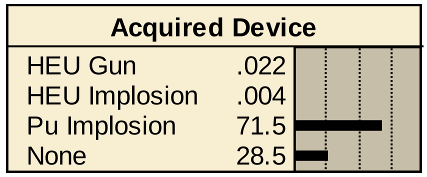

Fig. 43. Loose export controls with a reactor and reprocessing plant for Syria.

If Syria was given enrichment technology instead of a reactor and reprocessing plant, the HEU gun path increased to 83.5% and the HEU implosion path to 16.1% as seen in Fig. 44. Due to the lack of advancement of Syria, their most likely pathway is the less sophisticated gun-type device.

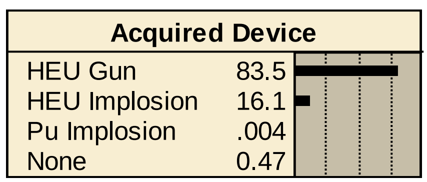

Fig. 44. Loose export controls with an enrichment facility for Syria.

The Syrian network was modeled with tight export controls. The initial pathways are shown in Fig. 45. As with Saudi Arabia, the addition of reactor, reprocessing, or enrichment capability has no effect on the pathways if all of the export control materials and components are effectively blocked.

Acquired Device	
HEU Gun	0 +
HEU Implosion	.014
Pu Implosion	.014
None	100

Fig. 45. Tight export control and the addition of either reactor, enrichment, or reprocessing technology for Syria.

Supposing that Syria had enrichment capability and they were given a complete weapons package and high purity calcium, the pathway for the HEU implosion increased to 71.2% as shown in Fig. 46. This increase is roughly the same percentage that Saudi Arabia had in the same scenario and it again indicates the sensitivity of the HEU pathway once the calcium and package components were added given that enrichment ability is attained.

Acquired Device	
HEU Gun	0.19
HEU Implosion	71.2
Pu Implosion	13.6
None	15.0

Fig. 46. Tight export controls with enrichment capability, high purity calcium, and weapons package acquired by Syria.

If Syria has enrichment capability and they steal a tamper the HEU gun path increases to 23.7% in Fig. 47. While a tamper is also a component of an implosion device, the blocking of all the other pieces in that path has prevented it from increasing.

The limited pieces necessary for a gun type caused the addition of this key node to have a substantial impact.

Acquired Device	
HEU Gun	23.7
HEU Implosion	0.11
Pu Implosion	.012
None	76.2

Fig. 47. Tight export controls with enrichment capability, high purity calcium, and tamper acquired by Syria.

If Syria has a reactor and reprocessing technology and they illicitly obtain an explosives package and high purity magnesium, the pathway for the HEU paths remain at zero and the pathway for the plutonium path increases to 3.89% as seen in Fig 48. Under the same scenario, the Saudi Arabian plutonium pathway increased to nearly 20%. This difference could again be accounted for by the difference in infrastructure and motivations.

Acquired Device	
HEU Gun	0 +
HEU Implosion	0 +
Pu Implosion	3.89
None	96.1

Fig. 48. Syrian pathways with a reactor, reprocessing plant, high purity magnesium, and explosives package.

Myanmar

Myanmar ranked at the very bottom of the technical capability and available infrastructure metrics. They did however, rank slightly above Saudi Arabia and Syria when it came to international networking. Myanar's potential motivations were not as lucid as Saudi Arabia and Syria, making several motivations a possible impetus.

The loose export control scenario was run and it yielded the results shown in Fig. 49. The HEU gun-type was the most likely path with a value similar to Syria. The different metrics and motivations can account for the difference.

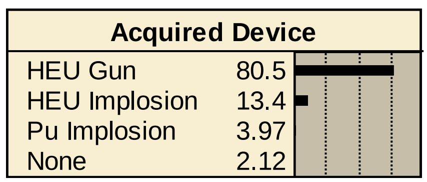

Fig. 49. Loose export controls with no reactor, reprocessing, or enrichment technology in Myanmar.

When a reactor was added the HEU and plutonium implosion path changed positions so that the plutonium path was the most likely at 61.1% and the HEU path was next at 26.1% as seen in Fig. 50.

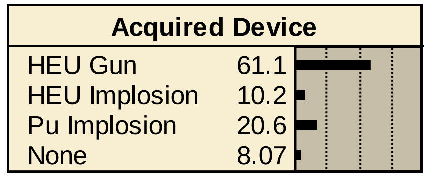

Fig. 50. Loose export controls with a reactor given to Myanmar.

These values show that Myanmar was slightly more likely to pursue a plutonium path than Syria but much less likely than Saudi Arabia. When reprocessing was added to Syria the pathway for plutonium implosion increased to 73.2% in Fig. 51.

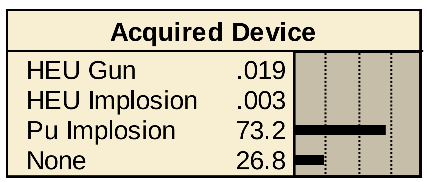

Fig. 51. Loose export controls and a reactor and reprocessing plant given to Myanmar.

Also like Syria, if Myanmar is given an enrichment plant instead, the pathway for the HEU gun-type implosion increases to 85.5%% while the other paths decrease to near zero as seen in Fig 52.

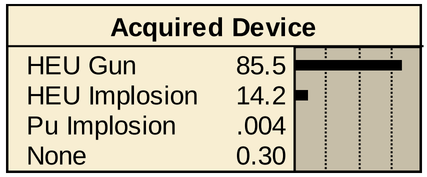

Fig. 52. Loose export controls and an enrichment facility given to Myanmar.

The same scenarios run with tight export controls yielded the same results as with the past two countries, as seen in Fig. 53.

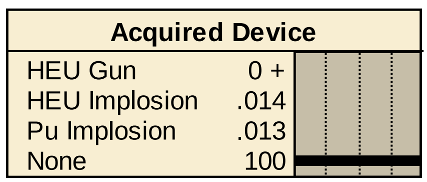

Fig. 53. Tight export controls effectively block Myanmar weapon pathways regardless of transferring reactor, enrichment, and reprocessing technologies.

Also similar to the other countries, the pathways are sensitive to component and material acquisitions if the large-scale facilities are given. For example, if Myanmar acquires a weapons package and high purity magnesium while they have a reactor and reprocessing plant, their likelihood of a plutonium implosion weapon increases to 74.7% as seen in Fig. 54. This is approximately the same percentage as for the respective scenarios with Saudi Arabia and Syria.

Acquired Device	
HEU Gun	0 +
HEU Implosion	.016
Pu Implosion	74.7
None	25.2

Fig. 54. Myanmar pathways with a reactor, reprocessing capability, high purity magnesium, and a weapons package.

If Myanmar has access to high purity magnesium and a weapons package and have an enrichment plant instead of a reactor or reprocessing plant then the HEU implosion path increases to 97%. This is shown in Fig. 55.

Acquired Device	
HEU Gun	0.30
HEU Implosion	97.0
Pu Implosion	.005
None	2.66

Fig. 55. Myanmar pathways with an enrichment plant, high purity magnesium and a weapons package.

If instead they acquire high purity calcium and a tamper with the enrichment capability, then the pathway for the gun-type increases to 33.8% as seen in Fig. 56.

Acquired Device	
HEU Gun	33.8
HEU Implosion	0.32
Pu Implosion	.011
None	65.9

Fig. 56. Myanmar pathways with an enrichment path, high purity calcium, and a tamper.

Japan

Now considering the world actually lived in, the nation of Japan possesses reactor, enrichment, and reprocessing technology.

Acquired Device	
HEU Gun	9.48
HEU Implosion	20.3
Pu Implosion	3.30
None	66.9

Fig. 57. Japan with enrichment, reprocessing, and reactor technology, and all other nodes left alone.

Fig. 57 shows the most likely path is the HEU implosion. If Japan now acquires a tamper, all paths nearly double, as seen in Fig. 58.

Acquired Device	
HEU Gun	17.6
HEU Implosion	37.6
Pu Implosion	6.12
None	38.7

Fig. 58. Japan with a tamper.

If instead of a tamper they are given a weapons package, the implosion path quadruples while the gun path drops near zero as seen if Fig. 59. This result again demonstrates that the network sides with the HEU path if all major technologies are acquired. To correct for this, both the HEU and plutonium nodes were activated.

Acquired Device	
HEU Gun	.038
HEU Implosion	81.9
Pu Implosion	13.3
None	4.71

Fig. 59. Japan with a weapons package.

When the plutonium and HEU nodes are activated in addition to the reactor, enrichment, and reprocessing nodes the plutonium and uranium implosion paths are nearly equivalent with the gun path being about half the amount as shown in Fig. 60. The activations of the plutonium and HEU nodes correct for the discrepancy in values that the network gives to the HEU and plutonium pathways as a result of the reactor, reprocessing, and enrichment nodes being activated.

Acquired Device	
HEU Gun	9.19
HEU Implosion	19.6
Pu Implosion	17.2
None	54.0

Fig. 60. Japan with both HEU and plutonium nodes activated.

The tamper node was activated and the plutonium implosion path was roughly the same value as the HEU implosion path as seen in Fig 61.

Acquired Device	
HEU Gun	13.9
HEU Implosion	29.6
Pu Implosion	26.0
None	30.6

Fig. 61. Japan with both HEU and plutonium nodes activated in addition to a tamper.

The weapons package was then activated instead of the tamper and again one sees that the implosion paths were again similar in value in Fig. 62.

Acquired Device	
HEU Gun	.022
HEU Implosion	46.0
Pu Implosion	40.4
None	13.6

Fig. 62. Japan with a weapons package.

V.B. Assessment of Results

There are three main conclusions that can be drawn from the examples from Saudi Arabia, Syria, Myanmar, and Japan. The first is that, in a world with loose export controls where a state proliferator has easy access to nuclear weapon components and materials, technology transfers such as reactors, reprocessing plants, and enrichment facilities greatly increase the likelihood of pursuing weapons paths. Second, in a world with tight export controls where a state proliferator is restricted from obtaining nuclear weapon components and materials, technology transfers such as reactors, reprocessing plants, and enrichment facilities do not increase the likelihood of pursuing weapons paths but make the paths highly sensitive to component and material acquisitions. Finally, different states' paths will increase in likelihood differently depending on their motivations, available infrastructure, technical capability, and international networking.

It is important to remember when analyzing the above results regarding the pathway probabilities that these value represent, at a given instant in time, the likelihood of a given nation being on a given path. The probability values represent the user's belief that a nation is pursuing a pathway given the available infrastructure, technical capability, international networking, motivations which are linked to intentions, and prior beliefs about how likely a given piece of evidence impacts a path. What was presented in this work was a learning tool that has the ability to give insight into the pursuit of different pathways leading towards the acquisition of a nuclear weapon. This tool and the graphs and values generated above are not intended to be used to predict what path a nation will take. Instead, it assesses the likelihood at a given moment in time that a given path is being pursued.

V.C. Insights and Advantages

The results the network yields are insightful for several reasons. First, the results take into account how technical ability and transfers impact pathways in addition to other motivating factors, providing a quantitative way to test the impact of proliferation factors that can be ascribed to both realist and idealist proliferation theories. Second, the network allows one to see the extent of impact of technologies by comparing the values of the probabilities. Third, inclusion of metrics describing available infrastructure, technical capability, and international networking as is relevant to nuclear weapon acquisition insures that a detailed assessment of each country tested is performed before evidence is even added.

Two key advantages the network has is its ease of use and the flexibility the user has in modifying the various weights. The graphical user interface of Netica clearly displays all of the nodes with their associated probabilities and they can easily be activated or de-activated by clicking on them. The weights on how the motivations effect the intentions, those associated with the available infrastructure, technical capability, and international networking, and a given evidence node's impact on a pathway node can all be easily changed too. The subjectivity in the weights associated with the different motivations, resources, and components allows not only flexibility in use but also can mirror an adversary's decision process. While it takes expert elicitation on a grander scale to pin down the most appropriate weights, considering which pieces matter more by looking at historical cases is also beneficial to the learning process and will be similar to the thought patterns used by a present-day nation that is considering choosing a given pathway. This consideration highlights the nature of the network as a learning tool as opposed to a code to be validated. A network such as this will never be able to have sufficient statistics to be validated in any scientific sense of the word. There are simply not enough historical cases, and the decision process itself is subjective. However, running the network through a number of historical cases has shown that the network does act as it should given certain inputs. Thus, what was demonstrated in this study was an adequate verification of a network that gives insight into the most likely path a nation would take in making a nuclear weapon.

V.D. Limitations

In addition to the insights and advantages provided by the network, there are limitations. As with any network, the results output are only as good as the data input. This not only means the accuracy of the information detailing the infrastructure, technical ability, international networking, and motivations, but also whether a nation does in fact have a certain component or material. While data such as GDP and number of nuclear agreements signed may be easy to access with a high confidence of it being correct, knowing for sure whether they are motivated by a specific reason or if they secretly acquired a technology will not be. As with any intelligence assessment tool, it is limited by what is not known, and this database of unknowns could go on indefinitely. However, given what is known for sure, the network is able to assess the most likely path taken at a given period of time. The only other caveat involved with this statement is that it does in fact give the *most* likely path. Since the probabilities are normalized to one, if evidence is added to increase one path, there is a necessary decrease in the other paths. Therefore, if multiple paths are being pursued, this will not be as clearly evinced by the probabilities. The network gives the relative probability of one path compared to the others. The inability to show parallel paths is a key limitation of the network.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

We effectively developed a computational tool to assess the most likely path a state proliferator would take in developing a nuclear weapon. A previous Bayesian network based on nuclear weapon proliferation was expanded to include dual-use export controlled technologies. The constant nodes in the network quantifying technical capability, international networking, and available infrastructure were developed to be based off of pertinent characteristics that were appropriately weighted. A literature review and expert elicitation were used to determine weighted motivations for a number of countries which would be run through the network. To see if the network gave accurate results, nine historical cases of state proliferation were run through the network over time and the weapon and enrichment pathways were graphed. The network sufficiently modeled the cases so it was concluded that, while never truly being able to sufficiently validate a network of this type, sufficient verification was achieved. The tool was then used to gain knowledge and insight concerning technology transfers with four countries in hypothetical cases. What was proven by this was that the network can in fact be used to learn about state proliferation under different policies and conditions.

What was created was a computational tool that sufficiently modeled historical cases of state proliferation and can facilitate in learning from a variety of hypothetical scenarios. A network of this form is not designed to be validated due to a statistically insignificant amount of historical data however by modeling nine different historical cases of proliferation it was sufficiently verified. The historical cases showed that the network gives the most likely path at a given instant in time. The network puts a quantitative value on the affect that a developed or acquired nuclear technology has on proliferation paths. In performing the hypothetical cases, the values gave insight into the extent of the impact a technology transfer or development has under varying conditions. We learned that proliferation pathways are sensitive to technology transfers. The path chosen is dependent on the type of large scale technology (reactor, enrichment, or reprocessing facility) the given state has and the rigidity of the export control regime. Even in a world with tight export controls, transfers of weapon components greatly affects the likelihood of weapon paths. This insight makes the network a useful learning tool to not only assess the most likely path a state proliferator might take but also to understand the type of policies that can deter proliferation in the future.

There are several avenues for future work. The network can continue to be analyzed to improve upon weighting factors. If the appropriate weights on the dual-use items can be attained, it will give even more credence to the importance of export control rules. The network can continue to be run on a number of countries, both historical for further verification purposes and hypothetical to assess present-day proliferation concerns. The network itself can be expanded to include nodes for different types of reactors and fusion and fission boosted weapons can be added to the weapons paths.

Given the insights the network provided in the hypothetical cases, it can also be used to assess the impact of different U.S. policies towards nations. For example, section 123 of the U.S. Atomic Energy Act details the agreements set forth by the U.S. regarding nuclear cooperation with other nations concerning the exchanging of technology, the sharing of scientific research, and engaging in safeguard discussions. The tool can be used to learn the impact of the U.S. engaging problematic nations aspiring to have nuclear technology compared to neglecting to have any involvement.

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APPENDIX A

METRICS SPREADSHEET

Available Infrastructure	Nation	Max	Min	Normalized value	Weight	Relative Weight		
GDP (U.S. dollars)	5.75E+10	1.43E+13	1.50E+06	0.004031452	1.00E+00	1.89E-01	7.61E-04	
GDP from industry (U.S. dollars)	1.14E+10	4.11E+12	2.70E+06	0.002766026	1.00E+00	1.89E-01	5.22E-04	
Electricity Production (kWh)	6.29E+09	4.20E+12	60000	0.001496652	1	1.89E-01	2.82E-04	
Oil Production (BBL/day)	1.89E+04	1.00E+07	0	0.001888	0	0.00E+00	0.00E+00	
Oil Reserves (BBL)	5.00E+07	2.64E+11	0	0.000189251	0	0.00E+00	0.00E+00	
Natural Gas Production (cubic meters)	1.24E+10	6.63E+11	0	0.018716381	0	0.00E+00	0.00E+00	
Natural Gas Reserves (cubic meters)	2.83E+11	4.35E+13	0	0.006510345	0	0.00E+00	0.00E+00	
Industrial Production Growth Rate (%)	1.20E+00	30	-27	0.494736842	0.2	3.77E-02	1.87E-02	
Uranium Deposits (tonnes)	0.00E+00	7.25E+05	0	0	0.5	9.43E-02	0.00E+00	
Power reactors (total Mwe)	0.00E+00	1.01E+05	0	0.00E+00	0.8	1.51E-01	0.00E+00	
Research Reactors (total MWth)	0.00E+00	5.38E+02	0	0.00E+00	0.8	1.51E-01	0.00E+00	
					5.30E+00		**Available Infrastructure Metric:**	#####
	Nation	Max	Min	Normalized value	Weight	Relative Weight		
Technical Capability								
number of nuclear engineering programs	0	36	0	0	0.8	1.98E-01	0.00E+00	
number of enrichment facilities	0	1	0	0	1	2.47E-01	0.00E+00	
number of uranium mines	0	1	0	0	0.1	2.47E-02	0.00E+00	
number of conversion facilities	0	1	0	0	0.5	1.23E-01	0.00E+00	
number of heavy water plants	0	1	0	0	0.65	1.60E-01	0.00E+00	
RAND metric	-0.51	5.03	-0.51	0	1	2.47E-01	0.00E+00	
					4.05		**Technical Capability Metric:**	#####
	Nation	Max	Min	Normalized Value	Weight	Relative Weight		
International Networking								
Stock of Direct Foreign Investment at home (U.S. dollars)	7.33E+09	2.40E+12	2.00E+06	0.003058826	1	0.307692308	0.000941177	
Stock of Direct Foreign Investment abroad (U.S. dollars)	4.18E+08	3.32E+12	4.00E+07	0.000113994	1	0.307692308	3.50751E-05	
Nuclear cooperation agreements	3	1.80E+01	0.00E+00	0.166666667	0.5	0.153846154	0.025641026	
Connection to nuclear suppliers	2	1.80E+01	0.00E+00	0.11111111	0.75	0.230769231	0.025641026	
					3.25		**International Networking Metric:**	0.0523

APPENDIX B

EXPERT ELICITATION ON STATE MOTIVATIONS

	Russia (Pre-1949)	France (1950s)	India (Pre-1974)	Israel (1960s)	Pakistan (after A.Q. Kahn returned, 1976)	Iraq (pre-1991)	Iran (2000-present)	South Africa (late 1960s-1970s)
Deter Attack From Nuclear Adversary	4	1	4	4	3	4	1	2
Seek Military Superiority	2	1	2	2	2	2	2	3
Redress Conventional Military Asymmetry	1	1	1	4	3	3	3	2
Go Nuclear Before Rival	1	0	2	2	1	1	1	1
Intimidate Non-Nuclear Rivals	1	1	2	4	1	2	2	2
Acquire Position in International Forums	1	1	1	1	1	1	2	2
Rise to Global Power Status	2	3	3	1	1	2	2	1
Enhance General International Status	1	3	3	1	2	2	2	1
Demonstrate National Viability	1	2	3	1	2	2	2	2
Assert military/political independence	1	1	2	2	2	2	1	1
Divert domestic attention	0	0	1	1	1	1	2	1
Enhance Bargaining Position w/in Alliance w/ Nuclear Powers	1	3	1	1	1	1	1	1
Deter Regional Intervention by Superpower	1	1	1	2	3	2	3	1
Increase Military/Scientific Morale	1	1	1	1	2	1	2	2
Increase Domestic Morale	1	1	1	1	2	1	1	1
Reduce Economic Defense Burden	0	0	1	1	1	2	1	1

VITA

Name: Michael Reece Mella

Address: Texas A&M University
Department of Nuclear Engineering
3133 TAMU
College Station, TX 77843-3133

Email Address: mella.1@tamu.edu

Education: B.S., Physics, The Ohio State University, 2009
M.S., Nuclear Engineering, Texas A&M University, 2011