ABSTRACT

CREVAR, CHRISTIAN. A Quantitative Risk Assessment for the Proliferation of Nuclear Weapons in Non-Nuclear Weapon States (Under the direction of Dr. Mihai A. Diaconeasa).

Many are turning to nuclear energy as more states seek to expand their population centers and global conflict limits access to oil reserves. This has the potential to increase the proliferation of nuclear weapons in non-nuclear weapons states as tacit knowledge and infrastructure become more accessible. The problem with the current methodology is it attempts to predict when a country will build a nuclear weapon or examines affects after detonation. A new method, which is built on previous literature, is needed to evaluate a country's potential proliferation of nuclear material over time. This thesis seeks to use the quantitative risk assessment framework to build a model capable of quantifying risk associated with each state's nuclear and military capabilities. This model will be updated to determine whether a country's nuclear latency has increased or decreased based on recent activity. This method was applied in four case studies analyzing Nigeria, Saudi Arabia, Japan, and Pakistan at two time periods of their weapon's program. The results displayed the current risk levels for each country and how it could increase with the addition of more nuclear technology or updated delivery system capabilities. As expected, countries with access to fissile material, delivery systems, and technological determinants had a higher risk of starting a nuclear weapons program. Large uncertainties exist in the current dataset because the information is open source. Though this model will not predict if a country will build or use a nuclear bomb, it does provide data points to analyze if a country is trending toward a nuclear weapons program; replacing ineffective qualitative risk assessments.

A Quantitative Risk Assessment for the Non-Proliferation of Nuclear Weapons in Non-Nuclear Weapon States

by

Christian Crevar

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APPROVED BY:

Dr. Mihai A. Diaconeasa Committee Chair	Dr. John Mattingly
Dr. Dmitriy Anistratov	Dr. William Boettcher

DEDICATION

To my wife Sarah, my daughters Annabelle and Emilia, and my family and friends, I would not be here without you.

BIOGRAPHY

Christian attended North Carolina State University from 2009-2013, earning a BS in Biochemistry. Upon graduation, Christian commissioned as Second Lieutenant in the Ordnance Corps. He then graduated from the Explosive Ordnance Disposal (EOD) school before serving as a Platoon Leader with 761st Ordnance Company (EOD) at Fort Sill, Oklahoma. Once promoted to Captain, Christian moved to Fort Wainwright, Alaska where he commanded the 65th Ordnance Company (EOD) and deployed to Iraq in support of Operation Inherent Resolve. Upon return, he transitioned to command the Headquarters and Headquarters Company for US Army Garrison Alaska he was selected to serve as a Nuclear and Counter Weapons of Mass Destruction Officer. Christian then transitioned to Nuclear Disablement Team 1, 20th CBRNE Command at Aberdeen Proving Ground, Maryland. He was selected to attend North Carolina State University's Department of Nuclear Engineering in Fall 2022 to study Probabilistic Risk Assessment under the direction of Dr. Mihai Diaconeasa. Upon completing his degree, he will return to the US Army and be promoted to Major.

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CHAPTER 1. Introduction

1.1. Background and Motivation

World energy consumption is expected to increase over the coming decades as population centers expand. Fuel supply issues due to war and economic sanctions have caused energy prices to skyrocket across Europe in 2021 [1]. Expanding cities and energy scarcity have many countries looking toward nuclear energy as a reliable solution. The International Atomic Energy Agency, IAEA, predicts nuclear energy production is expected to increase by 23% by 2030 and double by 2050 [2]. This expansion leads to an increased risk of proliferation as the nuclear supply chain grows to meet market demand. The addition of nuclear reactors and power plants is not a benchmark to measure proliferation activities. The tacit knowledge which comes with operating a peaceful nuclear program increases the risk of starting a weapons program if the state feels as though they are threatened. To better understand this, quantitative risk assessment techniques are applied to monitor a country's nuclear program to determine their level of risk. This method differs from the current qualitative measures of extremely low probability and high consequence risk of a nuclear weapons program by providing quantitative results which can be tracked over time to determine the success or failure of the safeguards. The International Atomic Energy Agency (IAEA), who is responsible for safeguarding nuclear materials, does not have the budget nor resources to conduct verification of all new nuclear programs. There needs to be a new method, which builds on current practices, to evaluate a country's potential proliferation of nuclear material.

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) lists five nations as nuclear weapons states and bans other all countries who have signed the treaty from pursuing nuclear weapons [3]. The United Nations (UN) cannot force countries to sign the NPT. The treaty is also vague in nature allowing countries to take steps to reduce the time it takes to create a nuclear weapon, also called the breakout period. It is up to the IAEA to determine if the country's program is following the NPT for signatory states [4]. Of the 195 nations in the world, four have never signed the NPT. Of those four states, Pakistan, India, and possibly Israel have nuclear weapons. South Sudan is the remaining state and they have not signed the NPT because are still developing their government [3].

Private companies are combatting the problem with proliferation resistant designs for their advanced reactors. Many of these reactor designs are not new, but are being modified to be smaller, modular, and more versatile in all environments. Unfortunately, the IAEA does not have procedures in place to safeguard these reactors. Many companies have not publicized how they will monitor fuel burn up nor built their reactors to test them. This makes the IAEA's job difficult as they need to develop new methods for monitoring material diversion at nuclear infrastructure sites when their resources are already strained. These new reactor designs allow for the fuel to remain in the core longer than pressurized water reactors which leads to decreased utility for proliferation. These steps have helped reduce the amount of possible nuclear materials, but some still create fission products used in nuclear weapons.

1.2. Nuclear Fuel Cycle for Weapons Production

The nuclear fuel cycle is a double-edged sword. On the one side it is needed to produce fuel for nuclear power plants for clean, renewable energy. On the other side, it can be used to create nuclear weapons in both open and closed forms. The open, or once through, nuclear fuel cycle starts with mining the uranium from the ground, refining it and converting it to gaseous form for enrichment. There are many processes to enrich the amount of U-235 in the fuel. Once the desired level is achieved, the uranium is converted into fuel pellets, spheres, or other forms for reactors to create energy. The fuel reaches a level of burn-up where it is no longer capable of producing energy and it is considered waste. This waste contains many highly radioactive short-lived isotopes and are placed into storage for the remaining time. A closed fuel cycle varies because it takes the spent nuclear fuel and reprocesses it to reclaim roughly 95% of the original fuel to be recycled in a mix oxide (MOX) fuel form for nuclear reactors. This process is shown in Figure 1 with the additional steps showing how this process can be used to create nuclear weapons [5]. The figure shows uranium and plutonium weapon production, but minor changes to this process can be used to isolate neptunium and a different uranium isotope which can also be used as fissile material for a weapon.

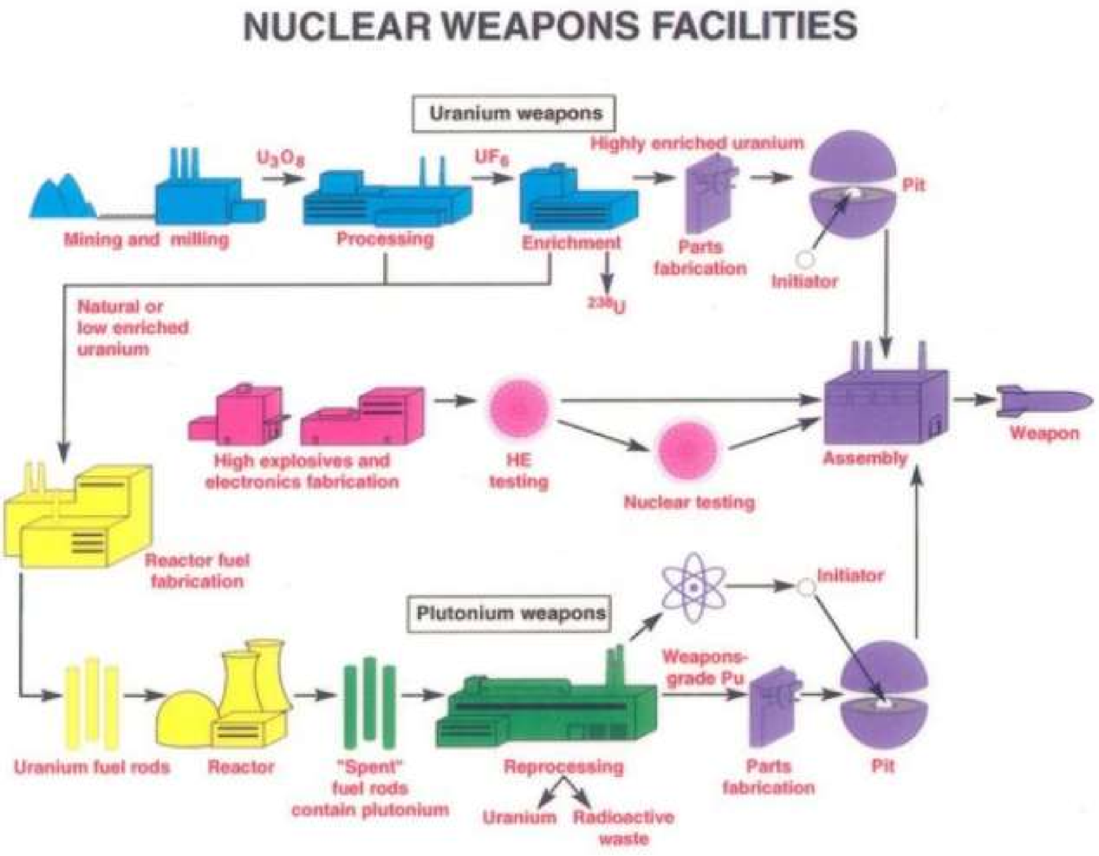


Figure 1. Nuclear Fuel Cycle Used to Create Fissile Material for Nuclear Weapons [5]

Nuclear weapons use nuclear reactions to release large amounts of energy to cause harm to people, animals, and plants. This definition also includes the latent effects of the fallout after the detonation [6]. The nuclear weapons themselves can either be fission or fusion based. Fission weapons were used on Japan during World War II. Fusion weapons, also called thermonuclear weapons or hydrogen bombs, have never been used in combat and are at least five times more powerful than a fission bomb. Figures 2 and 3 show both types of fission weapons. Figure 2 shows an implosion design where the high explosive (HE) is initiated at a desired time or altitude which uniformly compresses the spherical subcritical mass of fissile material. Once the fissile material reaches a supercritical state, the fission chain reaction generates an enormous release of energy creating an explosion.

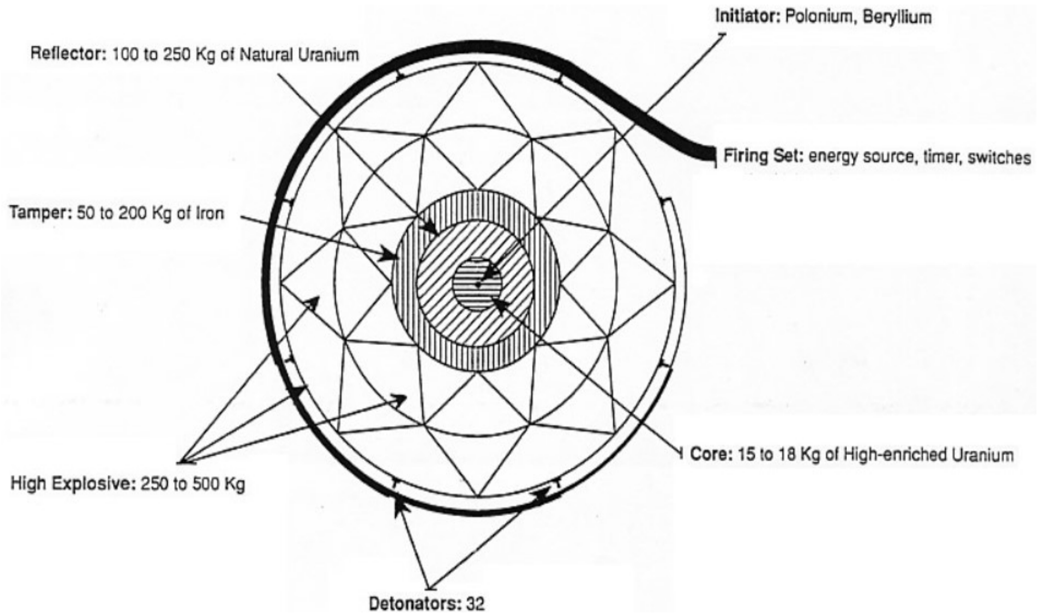


Figure 2. Implosion Nuclear Weapon Core with List of Necessary Components [7]

The second fission nuclear weapon is called a gun type. This weapon got its name because at a designated time a subcritical mass of uranium is shot down a barrel, landing inside another subcritical mass creating a supercritical mass. Creating the supercritical mass results in the same explosion as the implosion weapon. Figure 3 graphically demonstrates this assembly process. This weapon design is so simple, no explosives are technically needed to rapidly pair the two subcritical masses of fissile material. It could be dropped from a ten-story building and achieve enough speed to rapidly assemble the two masses. Going too slowly could result in a premature detonation which would create less than the desired yield. This can also happen when using a fissile material with a high spontaneous fission rate like Pu-240. Both implosion and gun-type weapons can be boosted with the addition of deuterium and tritium gas, releasing more energy via fusion.

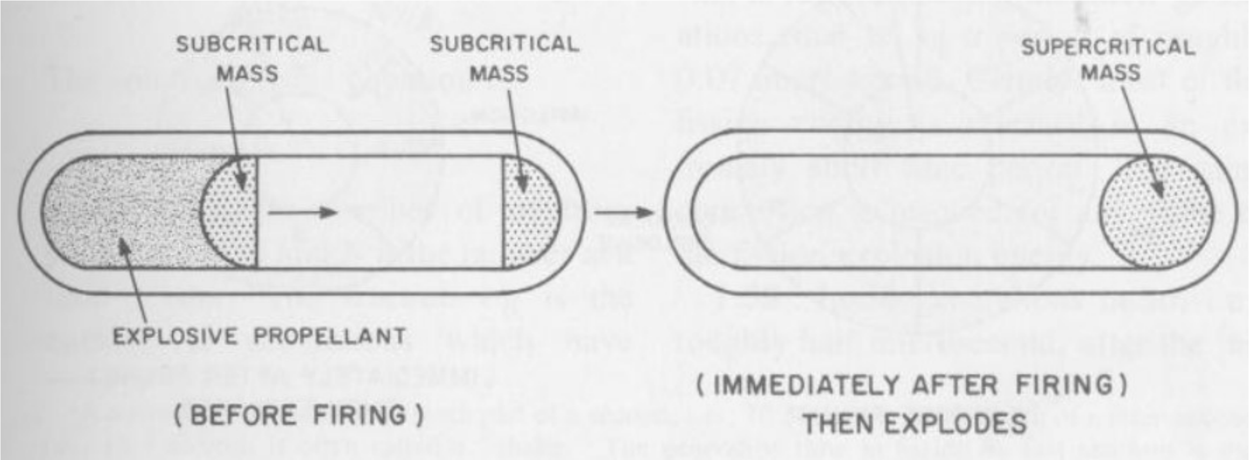


Figure 3. Gun-Type Nuclear Weapon Core Assembly Diagram [7]

When a thermonuclear weapon is initiated, it starts the explosive train resulting in a fission core detonation called the primary stage. The energy released during this explosion is equivalent to the energy of the sun where fusion primarily occurs. Fusion is the combining of two light atomic nuclei to create a heavier one occurring in the second stage of the detonation. This process releases more energy than a large atomic nuclear splitting into two. Fusion is completed fusing the hydrogen isotopes deuterium (H-2) and tritium (H-3) to create helium and a neutron. Edward Teller designed the first thermonuclear weapon shown in Figure 4. His idea was to create a nuclear explosion which would continuously burn until it ran out of fuel, like a candle. The light nuclei would be supplied using both gas and Li-6 which combines with deuterium to create a solid form more suitable for a weapon.

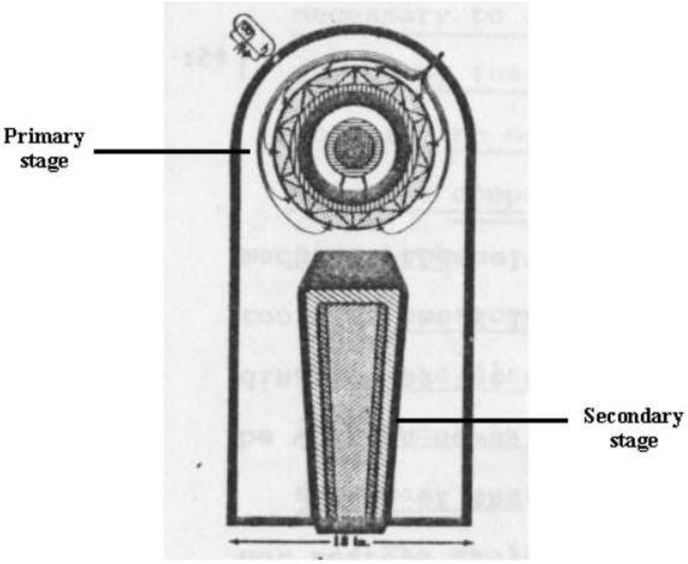


Figure 4. Thermonuclear Core Design by Edward Teller

1.3. Scope

This thesis examines the abilities and limitations of the current counter proliferation regime. The IAEA and NPT are at the foundation of non-proliferation, but each have major limitations which lead to failure. Examining the development of a nuclear weapon has not been done using probabilistic risk assessment, PRA, techniques in the past. This is in part due to data uncertainty and the complex decision making a state would need to undergo before starting their program. A model is created in this paper which shows this process. Chapter 2 delves into the successes and failures of the non-proliferation regime. Chapter 3 explains the methodology used to analyze a country's nuclear weapons program. This chapter starts with a literature review covering both international relations and technical studies and computer programs that attempt to quantify the problem. This method is then applied in Chapter 4 as case studies surrounding four countries with various levels of nuclear latency. One of the countries chosen as Pakistan over two time periods to show how the model changes based on new information. Chapter 5 discusses the results from the various case studies and highlights any outlier information. Lastly, Chapter 6 concludes the paper with future work opportunities and this method's application to military operations.

The focus of this thesis is on the risk of a state developing their own strategic nuclear weapon program. A strategic nuclear weapons program is one what has or had more than five nuclear weapons which were deliverable via one or more modes of the nuclear triad: intercontinental ballistic missiles, submarine launched ballistic missiles, and air-dropped bombs. Non-state actors are not considered because it is estimated they lack the resources necessary to build a nuclear weapon's program and would likely rely on stealing an already made nuclear weapon. Nonstrategic nuclear weapons, such as low yield artillery projectiles, are also not considered in an effort to simplify the possible delivery systems. Examining possible nonstrategic nuclear weapons is only limited by one's imagination. Lastly, this thesis only focuses on nuclear weapons and disregards all other forms of weapons of mass destruction, such as chemical, biological, radiological, or cyber weapons.

CHAPTER 2. Non-Proliferation Regime

The non-proliferation internation regime primarily consists of the Treaty of the Non-Proliferation of Nuclear Weapons (NPT) and the International Atomic Energy Agency (IAEA). The NPT is considered the cornerstone for nuclear non-proliferation as it outlines what states can and cannot do in regards to nuclear technology. It also solidifies the requirement of safeguards for access to assistance. The IAEA enforces these safeguards by monitoring states' compliance with the NPT and peaceful use of radiological material. They both serve as deterrants for nuclear proliferations, but neither can stop a country from pursuing a nuclear weapons program.

2.1. Treaty of the Non-Proliferation of Nuclear Weapons

The NPT entered into force in 1970 by the United Nations (UN) to limit nuclear technology for peaceful purposes. 191 of the 195 countries have signed the NPT. This includes two states which are not recognized by the UN. The remaining four countries (India, Pakistan, North Korea, and Israel) have or are believed to have nuclear weapons and refuse to disarm. The other country is South Sudan which is a new state and must form their government before signing international treaties. The documents is only five pages long and contains eleven articles [10].

The primary purpose of the treaty is nonproliferation, nuclear arms reduction, and peaceful use of nuclear energy. The first two articles outline what nuclear weapons states (NWS), and non-NWS are allowed to do. There are only five recognized nuclear weapons states (United States, Russia, England, France, and China) because they completed nuclear tests prior to 1967. These states are not allowed to transfer any material, equipment, nuclear weapons, etc. to non-NWS. Likewise, non-NWS cannot receive the same from an NWS. Article three requires each non-NWS to accept safeguards to monitor any forms of special nuclear material. NWS cannot transfer special nuclear material to non-NWS who do not accept these safeguards. Transferring equipment and special nuclear material must not affect a states' inalienable rights to pursue peaceful nuclear energy as outlined in article 4. Article five allows for the peaceful detonation of nuclear explosions for all signatories to the treaty. Articles six and seven require states to end the nuclear arms race and allow for states to engage in regional treaties to remove nuclear weapons. The last four articles discuss procedure to modify the treaty, defines procedures for NWS and non-NWS to withdraw from the treaty, and authenticates the treaties written in the approved five languages [10]. Though this is a short synopsis of the document, it does highlight several naïve traits of the treaty.

The NPT was a step forward to eliminate nuclear weapons, but it fails in three ways: creates animosity, no disarmament timetable, and does not specify equipment is for nuclear weapons and what is for peace. Though the NPT has served as a deterrent for some states, it is seen as a method of control by others. Having only five countries, primarily countries who have colonized many parts of the world, separates the world into have and have nots. The non-NWS believe they can be targeted or coerced by countries with nuclear weapons. This has caused countries, such as India, to pursue nuclear weapons despite not being recognized as an NWS for both prestige and fear of Chinese aggression. This fear could be mitigated by Article VI if there was a timetable for disarmament.

The countries who have nuclear weapons have reduced their arsenals over the last several decades, but they continue to maintain their stockpiles because their perceived enemy does as well. There are currently no treaties limiting the number of nuclear weapons allowed for each country. Russia suspended their participation from New START in 2023, eliminating bilateral inspections of the US and Russia strategic arsenals [9]. The NPT is the last agreement between the US, Russia, and all signatories to reduce nuclear weapons. Without a timetable, there is no incentive to reduce their weapons stockpiles and it is more wishful thinking than a demand. The UNSC cannot punish states for failing to reduce their stockpiles.

Lastly, the treaty specifies NWS cannot share special nuclear material or explosives with non-NWS but are allowed to share equipment for peaceful energy purposes if the recipient agrees to safeguards. This is challenging because the US has assisted several countries with starting peaceful nuclear energy programs which includes operating nuclear reactors and tacit knowledge of nuclear systems. Enriching uranium is one method of creating large quantities of fissile material which can be used for a nuclear weapon. It is almost impossible to limit one without the other. It is also challenging, because the NPT says the sharing of peaceful nuclear energy must not economically hinder the recipient. The economics of selling enriched fuel to non-NWS or selling equipment to enrich fuel is challenged by international law. It requires roughly the same amount of energy to produce LWR fuel as it does to enrich LWR fuel to weapons grade levels. Giving a country the equipment and material to create nuclear fuel is almost equivalent to giving them a nuclear weapon. The more challenging aspect is creating a nuclear weapon without being detected by IAEA safeguards.

2.2. International Atomic Energy Agency

The IAEA was created in 1957 to assist nations with peaceful applications of nuclear energy and to prevent its use for any military purpose [10]. They are responsible for monitoring all aspects of the nuclear fuel cycle to determine if nuclear material is being diverted towards a potential nuclear program. Though their mission is simple, the IAEA is struggling to perform their tasks due to budget constraints and lack of resources and personnel. Article XII of their statute states they must approve any nuclear reactors based on health and safety standards and ensure it will not further any military purpose [13]. This becomes more challenging as countries without current nuclear infrastructure purchase approved reactors or future advanced reactors before safeguards can be developed. The IAEA needs assistance if they want to continue deterring proliferation of nuclear material.

2.3. Problems with the Non-Proliferation Regime

The nuclear non-proliferation regime is vulnerable to states violating international law and avoiding safeguards to pursue nuclear weapons programs if they feel it is the best way to secure their power. The international community believes countries will follow the treaties they have signed, but this has been shown to be false. Iran evaded nuclear safeguards for decades despite being a signatory of the NPT, monitoring from the IAEA, and signing the Joint Comprehensive Plan of Action. Threats of sanctions or military actions have not deterred all states as they pursue their ultimate goals of regional power.

The UN Charter outlines what the UNSC can and cannot do with respect to threats to peace and acts of aggression. Chapter VII states the UNSC will call for provisional measures first, then escalate to measures not involving armed forces, severing economic and diplomatic relations, before finally engaging in armed conflict against the violator [12]. Despite the threat of war, countries like Russia, Democratic People's Republic of Korea (DPRK), and Iran have continued to push forward with their violations. Russia violated the 1994 Budapest Memorandum on Security Assurances when they annexed Crimea from Ukraine in 2014 and began a land invasion in 2022. The memorandum states Russia, the US, and the United Kingdom will honor the sovereignty of Ukraine's borders in exchange for their nuclear disarmament after gaining independence from the USSR following the Cold War [13]. Russia's nuclear arsenal, military might, and global economic importance prevented any direct armed conflict against them, and sanctions have not weakened them as much as intended. Countries who wish to violate international law will do so despite the ramifications of their actions.

DPRK and Iran have a lower GDP than Russia and yet they continue to violate international law. DPRK was forced to sign the NPT and undergo IAEA inspections in 1985 by the Soviet Union in exchange for new light water reactors [22]. Despite being part of the non-proliferation regime, DPRK continued their work towards building a nuclear weapons program and became the only country to withdraw from the NPT in 2003 [15]. Sanctions and non-military actions have been used against DPRK, but they have been unsuccessful in stopping the sale of missile technology and nuclear weapon production. DPRK's economy has reached the point where their citizens are starving so the government can continue to show force with missile tests and threats of nuclear weapon use [16].

Likewise, Iran was one of the original signatories of the NPT in 1970, but secretly began a nuclear weapons program in the 1980s in response to the Iran-Iraq war. Iran had all necessary facilities and equipment to achieve a nuclear weapon until someone reported them to the IAEA. Their clandestine operation was discovered, and they paid a heavy financial toll. Despite that, Iran has continued to enrich uranium well past what is needed for their nuclear reactors. Israel and the US have engaged Iran in a series of attacks to mitigate their efforts. There has been no sanctioned military action by any UN country to stop DPRK and Iran from continuing their programs. This is a major vulnerability in the nuclear non-proliferation regime if violators can overcome their punishment and continue to have success. It sets a bad precedence for other countries to sacrifice international standing to achieve regional dominance if that is their desire.

The IAEA is also hindered by their lack of resources which are approved by the UNSC. Their budget is limited to zero real growth; meaning the budget cannot expand except for increases in statutory and unavoidable costs which was only 1.7% in 2023 [17]. This is not sufficient for the IAEA to perform their mission and turned them into a charity of sorts just so they can sustain their core capabilities and operations [20, p. 3.1]. Their 2023 annual budget at a glance shows 21%, or €149.5M, of the budget they require was unfunded. The largest unfunded area is their operational budget which is responsible for monitoring nuclear fuel cycle and power, nuclear safety and security, nuclear verification, and administration services. This is their core mission, and this will only get worse as more states gain access to nuclear technology and training. More contributions from member states are required but likely not forthcoming. The problem has become so dire that the IAEA Director has called upon private companies for assistance during times of crisis such as the COVID-19 pandemic. With the nuclear watchdog unable to perform their key functions, states are required to take actions into their own hands to prevent nuclear proliferation on a global scale. To do this, there must be some sort of risk assessment framework developed to monitor the various aspects of the nuclear fuel cycle in order to determine if it is being used for peaceful or military means.

2.4. Proliferation Resistance of Advanced Reactors

Many companies are moving away from the large light water reactors (LWRs) and turning to smaller, more efficient advanced reactors. Many of the concepts for advanced reactors have been around for decades, but never became operational. This is changing as many new nuclear companies are working to license and produce safer, more efficient, and more diverse reactors. Pebble bed reactors (PBRs), molten salt reactors (MSRs), and sodium cooled reactors are at the forefront of these designs. Part of the motivation to use these reactors is they are resistant to proliferation because they either make the desired fissile material difficult to obtain or they burn the same material as fuel. However, it is still possible for motivated actors to obtain the desired fissile material needed to create a weapon.

Pebble bed reactors, such as HTR-10 in China and Xe-100, are based on a concept for the 1960s and 1970s. The current reactors use 60 mm graphite spheres or pebbles to contain 7,000-15,000 tristructural isotropic (TRISO) microspheres containing high assay low enriched uranium (HALEU). The HTR-10 uses 17% enriched uranium coated in four layers of buffer and ceramic layers forming the microsphere. In total, each pebble only contains 5-9 g of uranium and there are approximately 29,000 pebbles in the core [19]. These pebbles are cooled with high temperature helium gas circulated through the core before heating water to generate steam. Dany Mulyana and Sunil Chirayath's paper examines the proliferation resistance of a pebble bed reactor for various refueling schemes. They used Monte Carlo N-Particle (MCNP) code to show using one-batch at 64 GWd/MTU yields the greatest amount of Pu-239 and U-235 per pebble. Increasing the burnup or the number of passes reduces the amount of Pu-239 in each pebble and increases the amount of undesirable plutonium isotopes [19]. A one-batch refueling scheme is estimated to produce 3.69E-02 g per pebble of Pu-239, which would yield about 1 kg of Pu-239 in the used fuel pebbles. The amount of fissile plutonium in a PBR core is 80% compared to a light water reactor core which produces 60% [5]. This means one would need to do this eight times to produce what the IAEA considers a significant quantity of 8 kg Pu-239 [20].

What makes TRISO fuel resistant to proliferation is accessing the fissile material in each pellet within the pebble. It is difficult to remove the four layers of material around each microsphere. A state would need the expertise to dissolve the ceramic coating and remote handling equipment to do it safely. The spent fuel will have a high radiation exposure rate immediately after being removed from the core. It will take time for these undesired fission products to decay [6]. Safeguards are needed to ensure the fuel pebbles are continuously moved through the core and attempts at diverting the pebbles are monitored. The difficulty at accessing the fissile material in each pebble makes them more resistant to proliferation than the next two reactor types.

Molten salt reactors were first designed to power an aircraft which could fly for longer hours without needing to refuel. The project began at Oak Ridge National Laboratory (ORNL) in the 1960s. The program was ultimately scrapped because of the size and weight needed to protect the flight crew from the radiation. MSRs offer the nuclear industry a way to deliver efficient power production and reduce nuclear waste. MSRs do this by creating a closed loop nuclear fuel cycle which can be refueled online instead of shutting down like a PWR. Fission products can also be removed while fissile materials remain in the molten salt allowing for greater burnup of fuel. The greater the burnup allows for increased quantities of undesirable uranium and plutonium isotopes.

As shown in the 1968 study from ORNL, Pa-233 can be removed from the fuel in the core so it does not capture additional neutrons. This is vital because the Pa-233 has a 27-day half-life and undergoes a beta decay creating U-233. In a normal system, the fluorination U-233 would be moved back into the core and used to generate more power. Proliferators can remove the Pa-233 and create U-233 which can be used for a nuclear weapon. A significant quantity of 8 kg U-233 is equal to Pu-239 at 8 kg. Thorium is more abundant than uranium on the earth. Steps are needed to reduce proliferation associated with the Th-U closed cycle as all processing is done within the same facility [22].

Like high temperature gas cooled reactors (HTGRs), many companies are exploring sodium-cooled fast reactors (SFR). This technology has existed for decades but met decreasing interest after the cold war [23]. Sodium has advantages over water because it can operate at higher temperatures and lower pressure than current PWRs creating a more efficient reactor. The neutrons in the core do not need to be slowed down to create fission as they do in water reactors. The disadvantage is introducing water into the sodium, such as during a loss of coolant accident, will create a violent reaction. Using fast neutrons allows the reactor to be a closed fuel cycle because it can generate power using mixed oxide fuel. This would drastically reduce nuclear waste as nuclear reprocessing and actinide incineration would occur within the power plant. Not separating the plutonium from uranium in the fuel would make this reactor more resistant to proliferation.

Using mixed oxide (MOX) fuel does reduce proliferation, but it does not completely prevent it. MOX fuel contains both uranium and plutonium oxides, making it more attractive to potential proliferators than spent nuclear fuel which still contains fissionable isotopes. Attempting to isolate fissile isotopes of plutonium from MOX is nearly impossible because mass separation between Pu-239 and Pu-240 is 1 AMU. Current methods for separating these isotopes do not exist, which means the primary target would be uranium. This would then require separating the uranium isotopes to collect U-235. Kumar, et. al., discuss adding thorium to the MOX fuel for SFR. Their estimate current uranium resources could be depleted as early as 2155 as demand for nuclear power increases [24]. As mentioned with MSRs, thorium is a fertile isotope which can be used in nuclear fuel to create fissile material. Using SERPENT2 reactor physics code, they determined the masses for various isotopes at the beginning and end of cycles for five continuous 285.5-day cycles. The results showed less than 1 kg of U-235 was produced and the ratio of Pu-239 to Pu-240 was undesirable. The fuel also contained significant quantities of U-233 and Np-237 which can be used as fissile material for nuclear weapons [23]. Both isotopes are under less stringent safeguards than uranium and plutonium isotopes [25]. Failure to account for these could allow a non-NWS to produce their own weapons.

The Generation IV International Forum identified six reactor types as the most fuel efficient, waste reduction, economically competitive, safe, and proliferation resistance ready for commercial development by 2030 [26]. Three of those reactor types were discussed above. The remaining three share a variety of similarities to others. These generation IV reactors will revolutionize industry, making nuclear power safer and more readily available to the world. This expansion comes at a cost. The desire to create or have nuclear weapons will not go away. There are flaws with the current nuclear non-proliferation regime which need to be revised to reduce this risk. This thesis will use PRA to show how a state could bypass current nuclear safeguards and develop their own weapons programs. This methodology can also be used by others to identify the areas of greatest risk and implement mitigation measures.

CHAPTER 3. Methodology

3.1. Overall Methodology

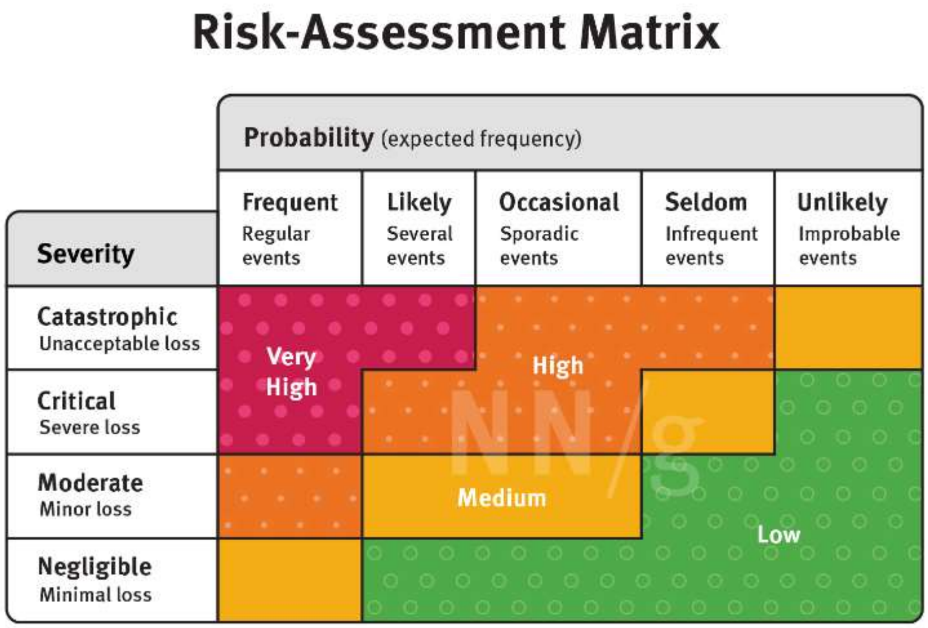
Probabilistic risk assessment (PRA) has been used to examine both pre-detonation and post-detonation decision making to mitigate risks. There have been no efforts taken to quantify the risk associated with a state developing a nuclear weapons program. States or actors could use a framework to determine the best way to deter or prevent the creation of a nuclear weapon. For this paper, the PRA method will be referred to as quantitative risk assessment or QRA. PRA and PSA (probabilistic safety assessment) generally refer to nuclear power plants. QRA is the same as PRA and is being used because this thesis does not examine the risk of nuclear reactors. This chapter includes a literature review, description of QRA, and developed event trees used to quantify risk. Bayesian networks are used to identify the initiating event for the three event trees resulting in success or failure to defeat the pathway. The methods and safeguards have already been identified by the IAEA and UN, but they have not been placed in a logic tree to quantify data which was previously only given qualitative values.

3.2. Literature Review

There have been large datasets used to tackle this problem by looking at political factors leading to the decision to begin a weapons program and the effects of what a new nuclear weapons state means for global power balance. Current research for the risk of weapons of mass destruction (WMDs) generally fall into two categories: pre- and post-detonation. The Department of Defense (DoD) uses a method which could encompass both categories if it is modified. Other articles surrounding pre-detonation activities attempt to create a tool to predict if and when a country will acquire nuclear weapons. They have also explored how to deter or detect potential terrorist attacks before they occur in major cities. Post-detonation articles and software have been used to monitor fallout or dispersal of WMDs. Decision makers can then use this data to apply appropriate mitigation measures to either reduce the spread of the hazard or reduce casualties. The fundamental problems with these methods are the lack of a proper definition of risk, the attempt to predict what a state will do, and it is assumed a weapon is ready for deployment.

3.2.1. Pre-Detonation Literature

The DoD developed the Joint Risk Analysis Methodology (JRAM) to identify and mitigate risks during an operation [27]. There is no defined guidance on when to use this reference. It could be used to quantify the risk of twisting an ankle walking on uneven terrain or assess the risk of going to war with a near peer adversary. The JRAM calculates risk by multiplying the probability by the consequence as shown in the matrix in Figure 5. Probability in this case is measured using qualitative labels such as frequent, likely, occasional, seldom, and unlikely. Consequence or severity is measured in a similar way with the four qualitative categories of catastrophic, critical, moderate, and negligible. Both measures for probability and consequences are subjective. Measuring risk in this manor means having a very likely probability with minor harm consequence is equal to a very unlikely event with severe consequences [11]. These two situations are not the same because this definition of risk is too broad. The user can define the percent range for very likely and identify what constitutes major harm [27]. These values can then be interpreted differently by someone else which could void the results. This methodology also omits rare events, such as an asteroid destroying the earth, which is where most WMD efforts flourish [27]. These events are unlikely and catastrophic, but applying mitigation actions does not qualitatively change this result. This method is used for the military to manage risks during operations, but it is not appropriate for all scenarios.



Risk-Assessment Matrix

Severity	**Probability** (expected frequency) **Frequent** Regular events	**Likely** Several events	**Occasional** Sporadic events	**Seldom** Infrequent events	**Unlikely** Improbable events
Catastrophic Unacceptable loss	Very High	Very High	High	High	Medium
Critical Severe loss	Very High	High	High	Medium	Low
Moderate Minor loss	High	Medium	Medium	Low	Low
Negligible Minimal loss	Medium	Low	Low	Low	Low

Figure 5. Qualitative Risk Assessment Matrix to Categorize Risk Levels [29]

Baum, et al., developed an expansive model which shows various initiating events which could lead to either an intentional first strike or retaliation strike [30]. The former scenario group consists of escalation of crisis or wars which result first use of weapons because of a perceived threat. The latter is a series of false alarms and human errors which lead the decision maker to believe they are under attack, and they must retaliate. Both groups of initiating events lead to nuclear war. The authors show 56 historical events from 1945 to 2018 which can be grouped into two categories. Baum uses qualitative analysis to form his conclusions about the threshold for countries to pursue nuclear war and identified several initiating events during the Cold War which almost led to nuclear action.

Dr. Diaconeasa, et al., advances this further during the Quantifying Global Catastrophic Risks Conference, sponsored by the B. John Garrick Institute for the Risk Sciences. They identify false alarms as a scenario of interest in Baum’s model and quantify the likelihood of inadvertent nuclear war [31]. A sequence of events shows where failures in decision making could occur from the initial false alarm to the launch of a nuclear weapon during the Cold War. The event tree examines the success or failure during each decision event in the process and its resulting end state. Fault trees were developed to determine human and equipment error. Lastly, Bayesian Networks were created with the influencing factors for each of the five decision makers. The results of their analysis estimate there was a 7.64E-4 per year probability of a nuclear attack from 1977-1984. Their studies show PRA can be used to quantify risk in national policy decision making.

Ezell, et al, argue to use PRA to thwart potential terrorist attacks. Many at the National Research Council's Committee on Methodological Improvements to the Department of Homeland Security's (DHS) Biological Agent Risk Analysis (NRC Committee), argue PRA is not capable of adapting to changing WMD threats [32]. The authors adapt a slightly modified equation from Garrick and Kaplan's risk definition [28, p. 12]. They define risk as the probability of attack multiplied by the probability of success given the attack occurs by the consequence of attack. They then develop event and decision trees with assuming the attack will happen [32, p. 583]. This means their equation is the same probability multiplied by consequence as discussed in the JRAM and is not a full scope risk model. These authors also discuss the challenges of using PRA for terrorist attacks. First, the data is gathered by intelligence and may have a high level of uncertainty associated with it. Second, the probability is not static, and the adversary is always searching for new methods of success. Bayesian inference or updating allows for adjustments to a model based on new evidence or data. This technique is used in the model proposed in this paper and will be discussed in chapter 3. The authors propose using PRA as a method to predict terrorist attacks, which is difficult to do.

Li, et al., use quantitative models to attempt to project a country's nuclear proliferation activities [33]. They build upon a paper written by Singh and Way which uses open-source data and weighted variables to predict if and when a country will acquire a nuclear weapon. Singh and Way's paper explores how technological determinism, external determinants, and internal determinants can lead to a country's decision to explore, pursue, or acquire a nuclear weapon. They assign values to 12 dependent variables for 149 countries, which are shown in Table 1 below. These values either increase or decrease the country's risk of nuclear proliferation. The results are distributed using both Weibull and Multinomial Logit Models. Their model does a good job or predicting when countries would seek to pursue nuclear weapons, but failed to predict countries with low economic and developed status, such as Pakistan and Libya, pursuing the bomb [34]. Singh and Way's model is incomplete because it fails to account nuclear infrastructure specific data. It only accounts for the country's overall technological and industrial capabilities, which is why it failed to detect Pakistan. It also fails because it is impossible to predict what a country will or won't do. One can collect information to make an estimation, but there are large uncertainties with this process.

Table 1: Singh and Way Theoretical Expectations and Measures for Proliferation [34, p. 868]

Explanatory Variable	**Operationalizations**
Level of Development	Gross domestic product (GDP) per capita; energy consumption per capita
Industrial Capacity	Index based on steel production and electrical generating capacity; aggregate and per capita electricity and steel production
Security Threat	Participation in enduring rivalry; frequency of militarized interstate dispute (MID) involvement
Security Guarantee	Alliance with Great Power (US, Russia, China)
Democracy	Current Democracy status
Democratization	Change in democracy scale (3-, 5-, and 10-year periods)
Global Democracy	Percentage of democracies among states in system
Exposure to Global Economy	(Exports and imports)/GDP
Economic Liberalization	Change in trade ratio (3-, 5-, and 10-year periods)
Dissatisfaction/Symbolic Motivations	Either global or regional hegemon

Li, et al., attempt to build on Singh and Way's shortcomings by examining nuclear technological capability profiles data from the IAEA for their models [33]. These authors also chose the Weibull distribution because the convergence characteristic is most favorable. They also chose a Cox model because it doesn't require parameterization of the baseline function. In total, 66 variables were chosen to project proliferation probability. The authors chose four anonymous countries and compared the historical data, multinomial logit data and either the Cox or Weibull distribution during the three phases of nuclear proliferation: explore, pursue, and acquire. Their results show the models failed to accurately predict if and when a country would explore, pursue, or acquire a nuclear weapon. The models would show low levels of proliferation risk prior to the historical point at which the country sought a bomb. This is promising, but some models also had falsely increased proliferation risk when a country had not attempted to develop a weapon. The results also highlighted several variables which had a 90% significance level for proliferation risk, such as: GDP per capita, enduring rivalries, IAEA membership, uranium enrichment capability, and more. These risk factors can be useful as researchers seek to build more accurate assessments. Li's model must be constantly updated based on observed data either by the IAEA or other intelligence agencies [33].

3.2.2. Post-Detonation Literature

Shifting to post-detonation analysis, the DHS is leading the effort to conduct risk assessments for potential terrorist threats. Their latest software is called the Probabilistic Analysis for National Threats Hazards and Risk (PANTHR). The purpose of PANTHR is to enable risk-informed decision making against WMD threat [35]. It does this by modeling WMD attacks in populated areas to give first responders an estimated casualty prediction and how to mitigate further spread of contamination. Modeling these situations can also provide policy makers with information to secure against potential attacks in the future. This software is only capable of understanding how the WMD will affect a population after release or detonation and not used to identify potential pathways.

Tang, et al., propose using Bayesian Networks (BN) to identify greatest risk during a dirty bomb attack in Beijing, China. The top level of their network focused on the time of day of radiation release and its location. The next two layers focused on mitigating factors such as police presence and emergency response and exacerbating factors such as bomb size and weather conditions. The results of this network were used to approximate the casualties from cancer or bomb blast [33]. Their results show the security checkpoints reduced the risk and the amount of radiation released from the bomb yielded the most casualties [33]. Using BNs is useful when looking at probability distribution of multiple variables such as deciding if creating a WMD program is viable or not.

There is not one approach that will fully encompass the decision-making process to start a weapons program and end with a weapon. This process is comparable to the procedures seen inside engineered systems. Each step has a probability of occurring or not, just as a pump will either function or not when triggered. The difference between the two is human decision making is complex and has a large amount of uncertainty associated with it. There needs to be a method which can combine several of the ideas discussed above into one so the risk can be quantified.

3.3. Quantitative Risk Assessment

3.3.1. Defining Risk

After the attacks on September 11, 2001, US President George W. Bush called for stronger safeguards to prevent WMD terrorism. The US focused their efforts to disrupt terrorist movement, deny access to materials, and deter states from using any stockpiled WMDs [37]. Today, many agencies are working towards this goal but are only using qualitative values to represent the risk. There needs to be an equation which allows the user to systematically quantify the risks so decision makers can make accurate decisions and assess if the mitigation measures, they are using are working or not.

Risk is commonly defined as "something that creates a hazard" and "the degree of probability of such loss [38]." Engineers use safeguards to mitigate the hazards by reducing the probability of the risk occurring. Risk can be defined as a hazard divided by the safeguard as shown in Equation 1 [26].

$$\text{Risk} = \frac{\text{hazard}}{\text{safeguard}} \tag{1}$$

This equation is still incomplete because both hazard and safeguard are not quantifiable. Quantitative risk assessment (QRA) uses a "set of triplets" definition of risk. The triplet definition of risk focuses on answering three questions:

1. What can go wrong? (scenario)
2. How likely is that to happen? (likelihood)
3. What are the consequences if it does happen? (consequence) [36]

This definition is broader than the one used by the DoD and the examples Ezell uses in their paper. This can also be written in a similar format shown in Equation 2 [26], [36].

$$R_i = \{(s_{€}, p_{€}, x_i)\}, \qquad i = 1,2,\dots,N \tag{2}$$

Where, s_i is the scenario, p_i is the likelihood of that scenario, and x_i is the consequence or the measure of damage for that scenario. The brackets denote a complete set for the definition event sequence i. Answering these questions provides a logical sequence of events starting with an initiating event and ending with the consequence over some amount of time [37]. This can be arranged in a qualitative event tree. The event tree is divided into three sections which mirror the risk triplet. The first is the initiating event which begins the sequence. Next, a series of fundamental events are modeled and can vary depending on the system. In PRA for a nuclear power plant, the initiating event is followed by a series of events which are designed to mitigate the risk of core damage. The last section is the end state or consequence of the sequence of events. This model can be used to create a logical series of events for almost any scenario to determine the end state.

3.3.2. Event and Fault Tree Development

Quantitative risk assessments use event and fault trees to graphically display the progression of a specific event for the system. Event trees begin with an initiating event and terminate with an end state. Between those states, are a series of system failure events which result in multiple event sequences with different consequences. These events are known as intermediate events, and they are binary: success or failure. The failure branch is on the bottom and is assigned a probability based on the failure data collected in the fault tree. The top success branch probability is the failure branch subtracted from 1. The sum of the two branches will always equal one. An example event tree for a pipe break in a nuclear reactor is displayed in Figure 6 below [40, p. 156].

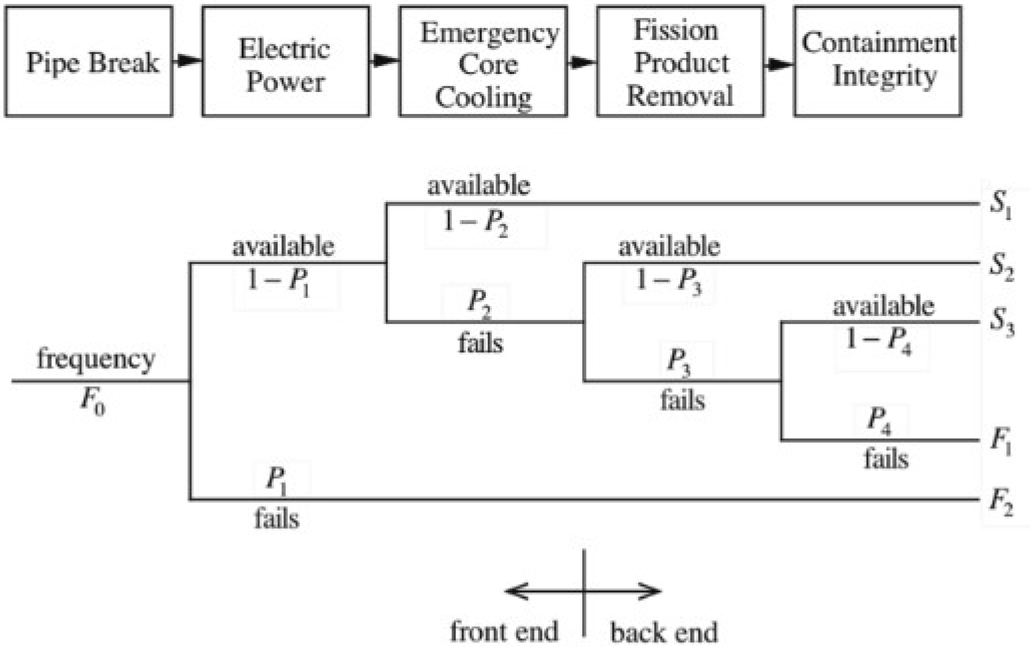
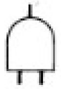
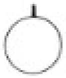
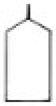


Figure 6. A Simplified Event Tree for a Loss-of-Coolant Accident

Fault trees are logical models. The undesired failure event is the top event. One then works downward by determining what could have caused the top event. This creates a series of subordinate fault trees which are connected by AND, OR, NOT AND, NOT OR, etc. gates. Once the causes can no longer be separated, they terminate in what is called a basic event. Failure data is then added to each basic event in the fault tree and quantified to determine the probability of the top event. Table 1 provides examples of the symbol associated with AND and OR gates and basic events. It also describes how the two different gates mathematically interpret the data [40, pp. 157–158].

Table 2. Fault Tree Symbols and Description

Symbol	**Name**	**Description**
	AND gate	The intersection of operation events; the output occurs if all inputs occur. $P(A \cap B) = P(A)xP(B)$
	OR gate	The union operations of events; the output occurs if one or more inputs occur $P(A \cup B) = P(A) + P(B) - P(A \cap B)$
	Basic Event	Primary fault event
	House Event	Normally occurring basic event; it is not a fault event

3.3.3. Initiating Event and Fundamental Event Derivation

Each event tree starts with an initiating event which is an internal or external hazard that challenges normal plant operation. Without mitigation, this event will likely result in negative outcomes, such as core damage to a nuclear reactor [21]. There are many techniques used to identify the initiating event like master logic diagrams (MLDs), Bayesian Networks (BN), and failure modes and effects analysis (FMEA). A MLD is a top-down analysis intended to document the hazards which could affect the system. It uses fault tree logic to identify different hazards and possibly group them with similar hazards [39]. A Bayesian Network is considered a reasoning model which shows cause-effect relationships [40]. These relationships show a joint probability density between multiple variables [33]. Lastly, failure mode and effect analysis (FMEA) analyze the effects of a single component or function failure on other systems. It is used for new reactors to determine initiating events for support systems and expected effects on the plant [21]. Bayesian networks were selected to identify the initiating event because of its ability to cause-effect relationship between multiple variables. This method is valuable when analyzing decision making with large amounts of uncertainty.

A BN is a type of directed acyclic graph (DAG) which account for joint probability of the problem [44]. A DAG is composed of nodes or variables which are connected by arrows or edges. The graphic depicts a relationship, whether it is known or unknown, between the nodes. A BN is different because it assigns conditional probability to the nodes because they are statistically dependent on each other. Using this method, a DAG example is constructed in Figure 7. It shows the linkage between factors which cause a country to modify their military arms and how they would decide to do so. Conditional probabilities will be added to this DAG in the case study portion of this paper to create a BN specific to example countries.

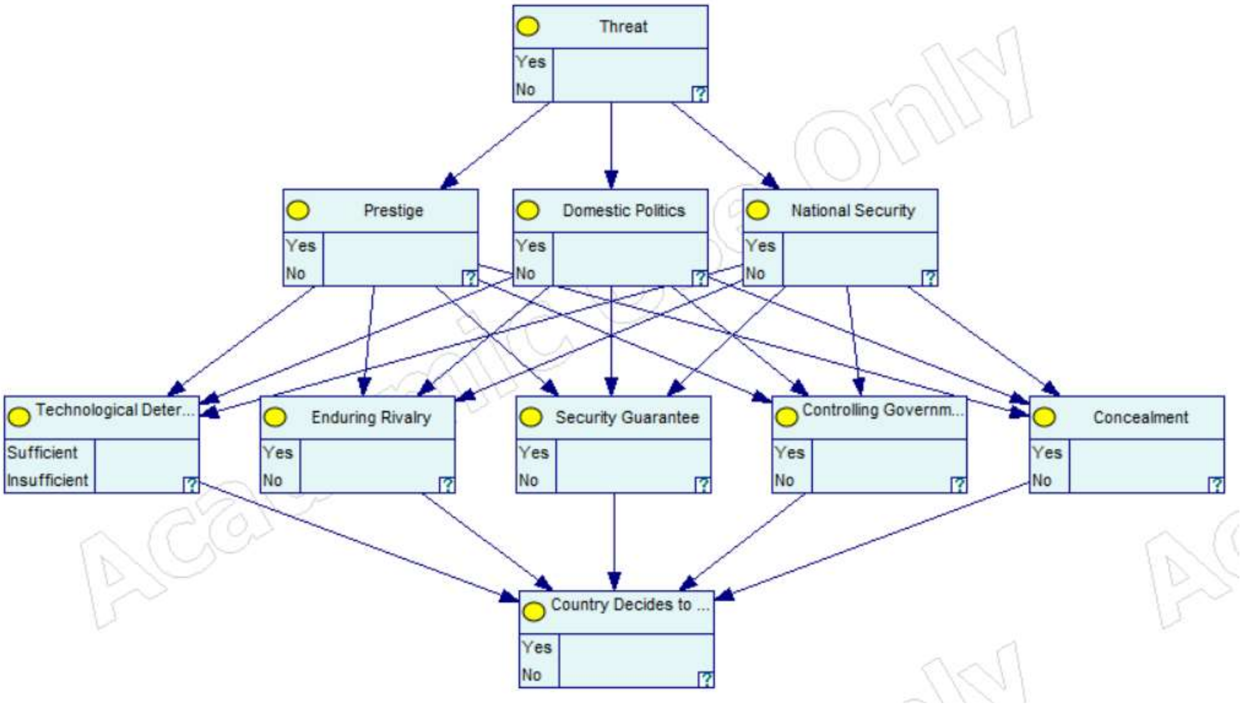


Figure 7. Bayesian Network Used to Determine Initiating Event Probability

The top event for this network is a threat. This threat can either be seen, such as an attack from another state, or it is perceived. In response to this threat, Scott Sagan argues there are three models which explain why a state would choose to build a nuclear weapons program: external threat, internal threat, or prestige [42]. External threats, also called the security model, says a state will build a nuclear weapons program to protect themselves against a foreign threat. This external threat will likely need to have nuclear weapons or have vastly superior military forces. This model explains the cascade of nuclear programs after World War II when Russia built their nuclear program to protect themselves from the US threat. Internal threat, or the domestic politics model, is a state's decision to pursue nuclear weapons to bolster their domestic or bureaucratic interests. This can be seen by South Africa as they developed a nuclear program to maintain control over the apartheid government. Prestige, or the norms model, refers to a state's decision to build a nuclear weapon to show their modernity or identity. Pakistan and North Korea are examples of this as the former wanted to have the first "Islamic bomb" and the latter wanted to increase their international status by having nuclear weapons. Every nuclear weapons program, regardless of if it was successful or not, can be placed into one or more of these categories. These threats and norms make up the top two layers of the Bayesian Network and can be applied to decision making to either pursue a WMD program or seek assistance from other foreign powers.

The third layer identifies several decision factors which will lead a country to pursue a specific military response to the above threats and norms. Technological determinants are those which measure the level of a country's development. This can be done by examining economic development and industrial capacity of a nation. Singh and Way did this by analyzing gross domestic product, energy consumption per capita, electrical generating capacity, etc. [31].

Enduring rivalries measure the state's frequent involvement in conflicts and their duration. Frequent and enduring conflicts increase the likelihood a country will develop WMDs to protect against their security threat [31]. In contrast, security guarantees reduce a state's desire to pursue more hazardous weapons. These security guarantees come in the form of alliances with nuclear-capable states, such as the nuclear umbrella, which can deter increased threats from other states [31]. The controlling government plays a role by assigning priority to items such as economic independence, democracy, liberalism, etc. These factors can sway a country to pursue stronger alliances or become more independent which requires strengthening their military power. A country's desire to conceal their weapon program is the last deciding factor of what pathway to choose. Overt WMD programs can lead to sanctions or military action against the violating country, but also could be completed faster than attempting to conceal one [6, p. 120]. These are key factors as part of the decision making a country does prior to pursuing a weapons pathway.

Because the focus of this paper is solely on nuclear weapons, the network terminates by calculating the likelihood a country would pursue a nuclear weapon or not. These nodes reflect the weapons pathways a country will choose when threatened or to challenge global norms. Determining the initiating event involved assigning probabilities ranging from 0 to 1 to each node of the BN based on the interpretation of each of the four countries current capabilities, political climate, and regional security. This resulted in a final probability of 20% which is demonstrated for Nigeria in Figure 8 below. This number was then multiplied by the probability of a country successfully developing a nuclear weapons program. As previously stated, there are only 10 countries out of 195 who have been successful. Multiplying 0.2 by 0.512 yields an initiating event probability of 1.03E-2. When examining historical examples later in this paper, not all these nodes will be applicable depending on the country and will have a conditional probability of zero. This

BN will determine the country's initiating event. Their success or failure is based on the responses of the international systems to their effort.

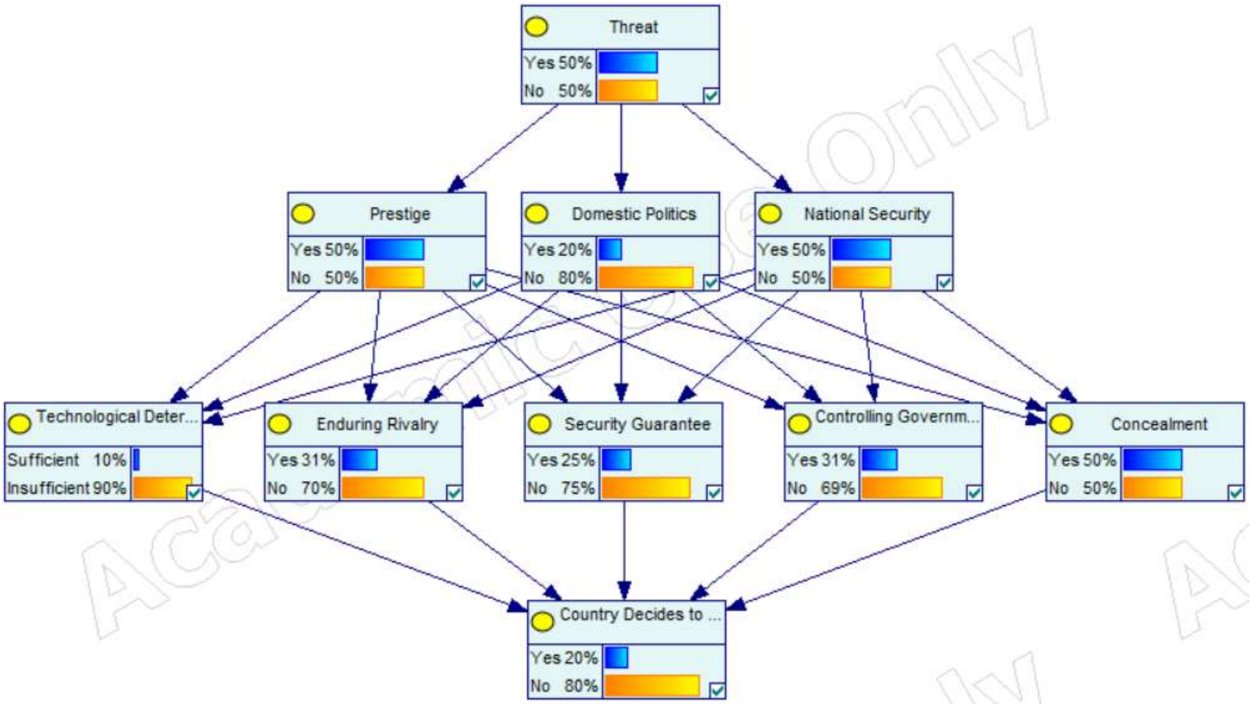


Figure 8. Initiating Event Quantification for Nigeria

3.3.4. Fundamental Events of Non-Proliferation Regime

Prior to developing an event tree, success and failure criteria must be defined. To prevent nuclear weapons, success would be preventing the weapon from being created and failure would result in a weapon. A premortem exercise was used to determine the fundamental events for the event tree. Premortem is an exercise developed by Gary Klein where a group is asked to identify why their project failed [46]. Using this method, a risk assessment of the international systems can be created with the initiating event set as a country is initiating a nuclear weapons program. The systems which can mitigate this effort are international laws, international safeguards, and export controls. This system is graphically displayed in Figure 9. If the systems are successful, then the country is deterred from acquiring nuclear weapons. Failure of at least two events results in a successful weapons program. Failed deterrence of international laws and export controls results in a program which attempts to operate undetected by the IAEA and other safeguard systems. Failed deterrence of international law and safeguards leads to a domestic weapons program. The country will need to acquire all equipment, expertise, and without major outside assistance. Failure of all mitigating events results in a country developing an overt weapons program.

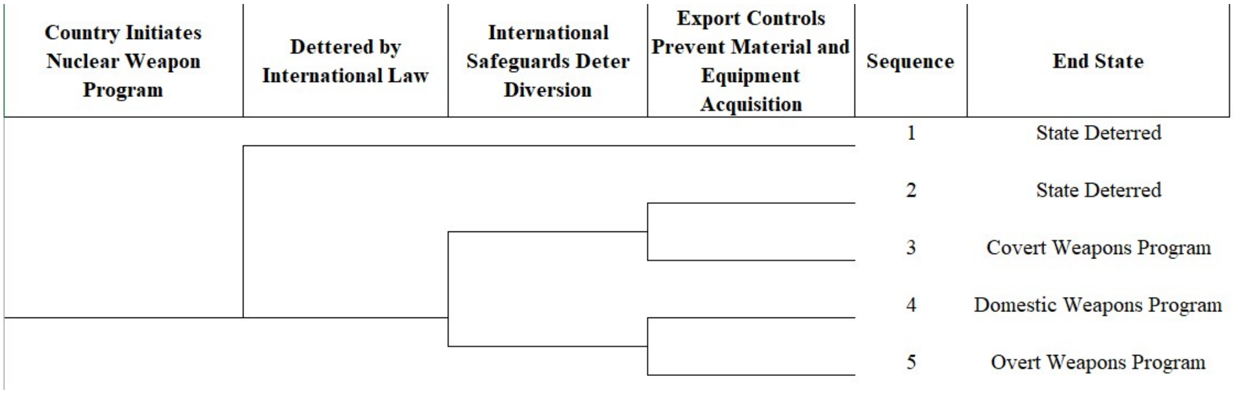


Figure 9. Event Tree Showing Possible Fundamental Event Mitigating Nuclear Weapon Development

International laws refer to the various treaties a country has approved, ratified, or accessed after it has been signed [47]. These treaties are legally binding, and countries can be punished for violating them. However, a country does not necessarily need to sign or ratify a treaty if they feel it violates their country's ideals. Failing to do either of these would result in failed deterrence of international law as shown in Figure 10. Punishment for treaty violations is difficult to model because there is no single international force which can prevent or detect a crime to maintain international order. Rather, the international organizations who back the treaty have the right to punish the violators. For the NPT, the responsible international organization is the UN Security Council (UNSC). Per Chapter VII of the UN Charter, violating the NPT can result in sanctions, military action, or nothing. The first response from the UNSC is to confront the violators and give them a chance to correct their failure. If that fails, then sanctions are levied against them. Military action is a last resort and is rarely used by the UN [48]. Similarly, individual countries can also levy sanctions or launch military attacks against the countries which violate the treaties even if they have not been detected by the international systems. Political actions are not straight forward and require long political negotiations to reach a conclusion.

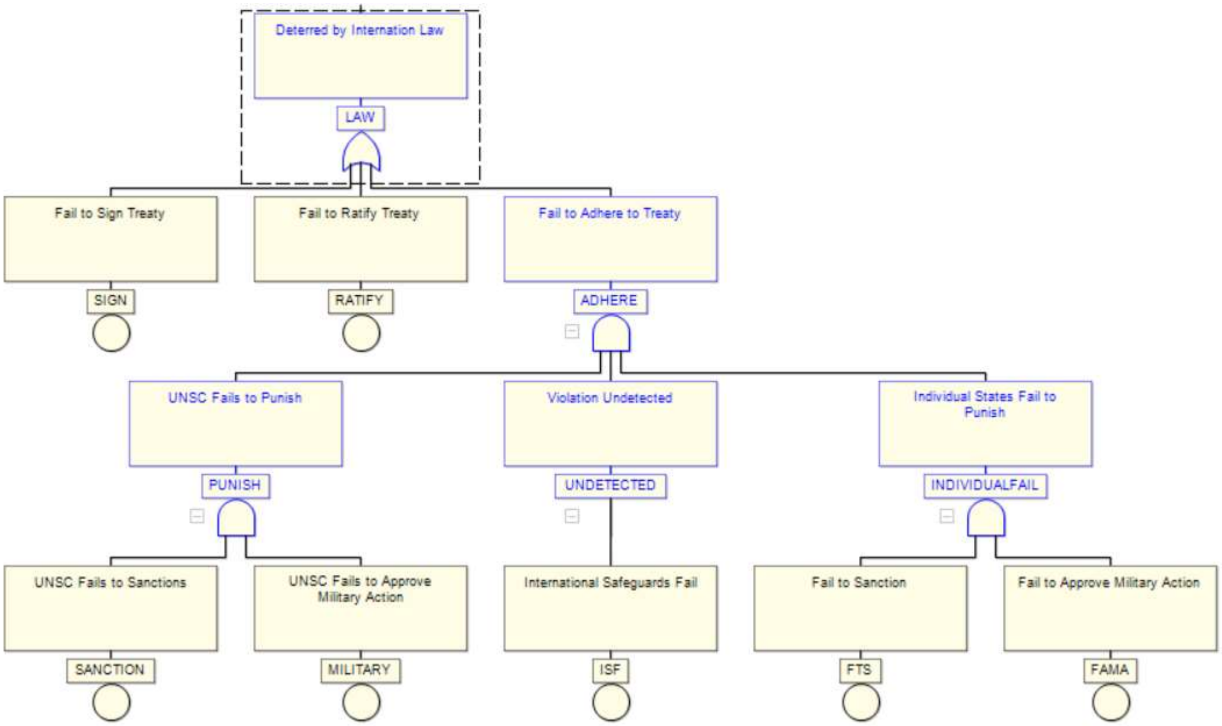


Figure 10. Fault Tree Displaying Failure Modes Associated with International Law Deterrence

Nuclear safeguards are how the IAEA monitors the peaceful use of nuclear material. Unless they volunteer, only non-NWS who have ratified the NPT are subject to IAEA safeguards. In 1997, the IAEA approved the Model Additional Protocols which expanded their rights to access information and inspect countries. These protocols were developed to correct the IAEA's failure to detect the Iraq's nuclear weapons program prior to 1990. As of November 2022, 140 states have ratified the additional protocols and an additional 13 have signed but not ratified them [49]. Many states have refused to sign the additional protocols because they only have small quantities of nuclear material and have instead signed the Small Quantities Protocols (SQP) [53]. Failing to sign any of the protocols in addition to the comprehensive safeguards agreement increases the likelihood of a state engaging in nuclear proliferation. Similarly, states could fail to volunteer their import and export information. This makes it challenging for the IAEA to verify the material which could have been moved between inspections. The Additional Protocols allow inspectors to have long-term visas and conduct short notice inspections of facilities.

Figure 11. lists the failures which can occur during the inspections or any of the additional monitoring systems the IAEA uses. The bulk of the IAEA's effort to prevent nuclear weapon proliferation are the inspections. As of 2021, the IAEA had around 280 inspectors who spent over 14,600 days in the field inspecting over a 1200 locations [51]. This is a huge undertaking, and it is possible for these inspectors to miss something. The inspector's failure to catch material diversion could come from the inspector's equipment failing due to malfunction or poor calibration. The inspectors could also make an error and the missing material isn't detected.

To prevent countries from diverting material when inspectors are not present, the IAEA has installed remote monitoring systems in many facilities. These systems collect and transmit data collected by nuclear infrastructure back to the IAEA. Remote data transmission (RDT) may also become more prevalent as the nuclear industry continues to expand globally and new reactor designs are incorporated in the power production. These systems sound good in theory but are challenged by countries refusing to implement these systems due to privacy concerns, inability to analyze the vast data the RDTs collect, site power failure, and incompatibility of systems because of the lack of standardization [55].

The IAEA also incorporates commercial satellite imagery as a means of nuclear site detection and monitoring. These satellites collect hundreds of photos a year which require analysis to determine if a new site is nuclear and what is going on there. Trying to find a new site can be like trying to find a needle in a haystack, especially if the facility is underground. The satellites are equipment with radar imagery, but these can only detect underground facilities to a certain depth. Many of the sites the IAEA has monitored come from open-source information or informants. Their analysis is also up for interpretation as seen by the IAEA's understanding of Pakistan's Khushab nuclear reactor. The reactors power was overestimated because it was equated to US nuclear reactors. After realizing the Pakistan is subject to export controls and reduced manufacturing capabilities the power estimate was reduced [53]. Satellite failure, underground facilities, or human error to detect or properly analyze a facility result in failed detection of nuclear proliferation.

The last method the IAEA uses for nuclear safeguards is environmental sampling. This could be taking swipes inside a facility or wide-area environmental sampling (WAES) to detect undeclared nuclear material or activity. These samples are required to be analyzed in clean labs by trained scientists to detect trace amounts of material. Environmental sampling has been successful at detecting violations in countries like Iran, though they cannot tell how much of the material is available [54]. These systems could fail if the country does not allow WAES, WAES fails to collect material, are tampered with, swipes are mislabeled, or contaminated. Similarly, environmental sampling could fail because of errors in the lab analysis phase such as equipment failure, human error, or lab contamination.

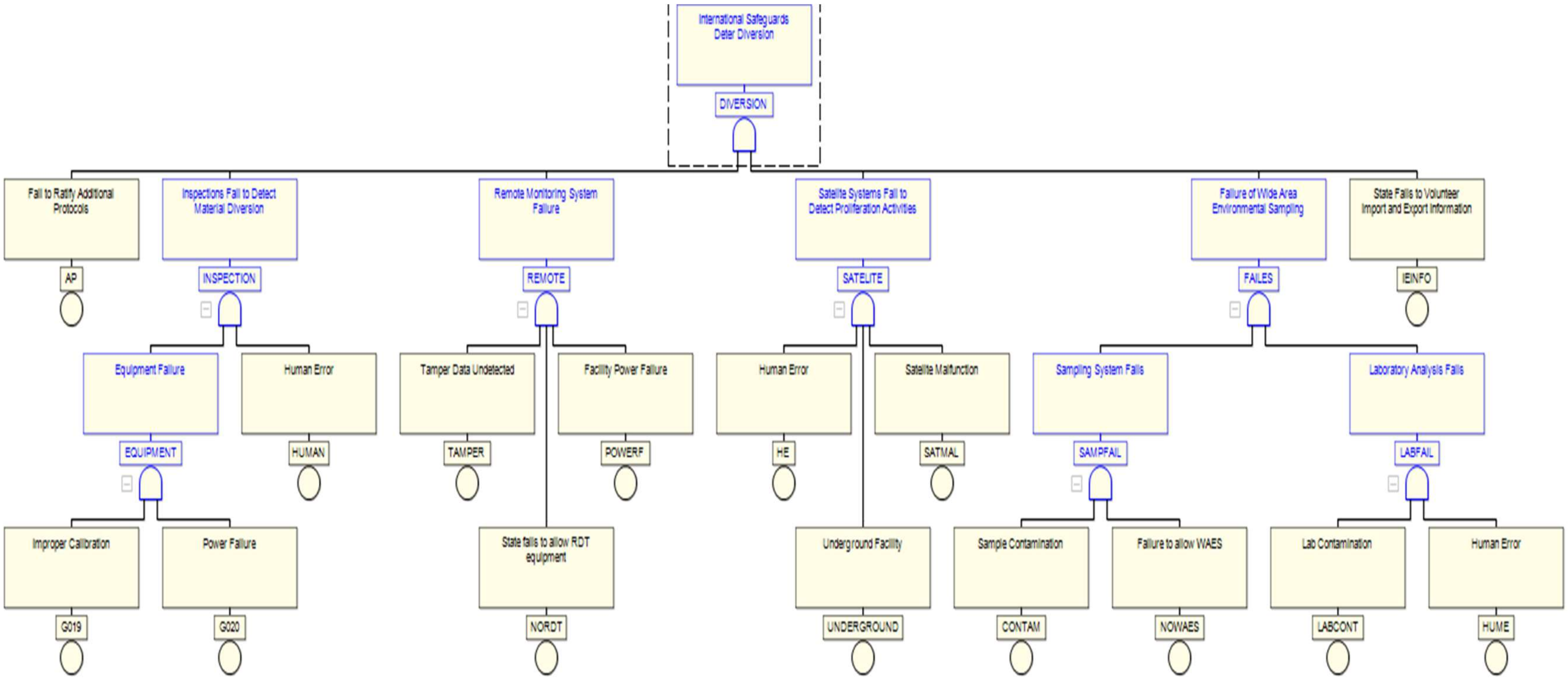


Figure 11. Fault Tree Displaying Failure Modes Associated with Internal Safeguards

Export controls are the last defensive measure which could deter a state from pursuing a weapons program. Attempting to control the import and export of sensitive material has been a key issue since India's nuclear test in 1974. India's test demonstrated how a country use a peaceful nuclear program to produce nuclear weapons. Each country has developed their own domestic system for monitoring their exports and four international groups have been created to also monitor exports which could be used for WMDs. An example of the US export control process and international export control groups are illustrated in Figure 12.

The US export verification process is controlled by the Department of Commerce's Bureau of Industry and Security. They lead several working groups which involve the Department of State and organizations knowledgeable about the equipment being exported. This working group screens recipients to ensure the equipment will be used for peaceful purposes, which could include pre-license and post shipment verification [55]. Nuclear exports are congressionally bound by the 123 Agreements. The 123 Agreements designate all nuclear fuel, reactors, and equipment exports can only be conducted with countries who have signed the agreement [56]. This process fails if the working group fails to detect the illicit use of the exports or if the equipment is illegally shipped and not detected by customs. Each state has a responsibility for their exports, but there are several international groups who identify the equipment or material which requires export controls.

Wassenaar Arrangement (WA), Nuclear Suppliers Group (NSG), Australia Group (AG), and the Missile Technology Control Regime (MTCR) are the four international organizations who restrict the proliferation of conventional weapons, WMDs, and their associated technology based on treaties. These groups do this by regularly exchanging information on denied export requests and emergent technology which should be added to their trigger lists. The WA consists of 42 members who monitor exports of conventional munitions and dual-use equipment to non-WA states. Their goal is to prevent a country from accumulating destabilizing amounts of munitions in their region [57]. The NSG is comprised of 48 member states who monitor the export of nuclear material and equipment which support nuclear weapons proliferation [58]. The AG is like the NSG, but the focus is on preventing the proliferation of chemical and biological weapons. The group consists of 43 states [59]. 35 states participate in the MTCR. These states are responsible for restricting the proliferation of missiles, complete rocket systems, unmanned air vehicles, and related technologies. Their work is important because these systems can be used to deliver WMDs [60]. Any of these groups could fail to prevent exports from occurring. Countries can also circumvent domestic and international export controls by manufacturing equipment or producing material from inside their borders.

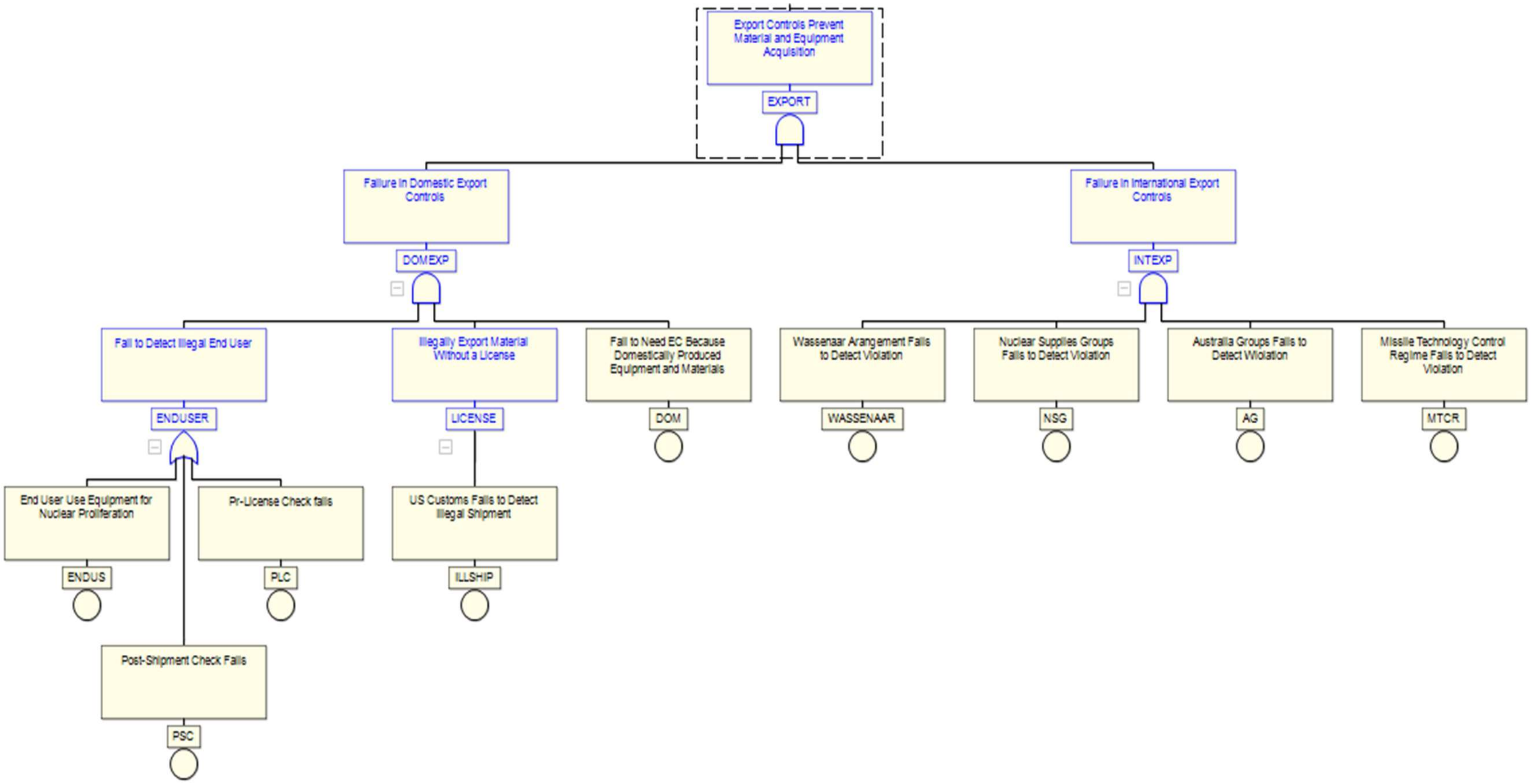


Figure 12. Fault Tree Displaying Export Controls for Material Acquisition

3.3.5. Top Events of Nuclear Weapons Components

In this scenario, the question of how a country would create a nuclear weapon was answered by identifying the three primary components of the weapon: delivery system, non-fissile components, and fissile material. In this paper, delivery system refers to any part of the nuclear triad: air dropped bombs via bomber or multirole fighter, intercontinental ballistic missiles (ICBM), and submarine-launched ballistic missiles (SLBM) [64]. Non-fissile components refers to any part of the weapon that initiates or boosts the nuclear explosion such as high explosives, detonators, reflectors, gas bottles, etc. [65]. This also refers to the expertise needed to assemble a weapon. Lastly, fissile material refers to material in the weapon which is used to generate a supercritical reaction. The IAEA defines a significant quantity as "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded [66]." These aspects of the weapon are subject to extreme scrutiny by international agencies who attempt to limit access to them. Figure 13 is an event tree which shows what could happen if a country succeeds or fails to develop any of the three components of a nuclear weapon. If the country succeeds, then they can create an implosion device. Failure to achieve sophisticated high explosive initiation would result in a gun-type nuclear weapon. No delivery system, but the country can acquire a significant quantity of fissile material and can acquire the non-fissile components they need results in a nuclear device like India's Smiling Buddha test in 1974. Failing to acquire enough fissile material results in the creation of a conventional weapon. Lastly, failing to acquire all three results in no weapon. The decision maker for each region is responsible for determining the end state probability where intervention is necessary. Using the below case studies as an example, countries with high nuclear latency show higher probability to create nuclear weapons. Therefore, there should be some sort of intervention to stop them from completing their program. Each system in the event tree is more complex than what is shown below.

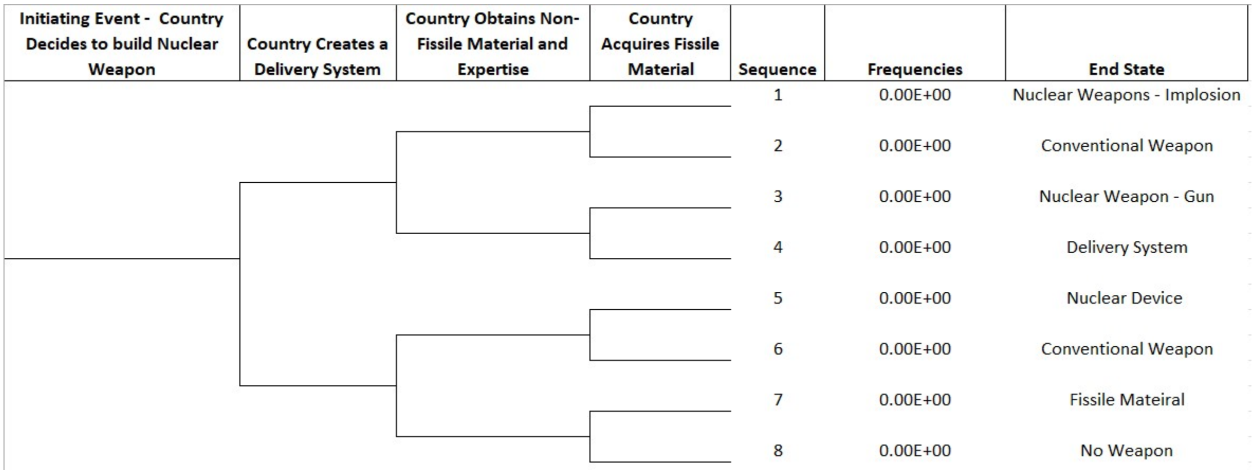


Figure 13. Event Tree for Country Deciding to Begin Nuclear Weapons Program

Fault trees were developed, which can be tailored to specific countries or regions, to examine the possible methods countries could take to acquiring delivery systems, non-fissile components, and fissile material. Creating these top-down models will assist in quantifying the likelihood of them occurring or not. The quantification of the model will either increase or decrease depending on the ability for a state to successfully achieve a pathway. The figures below denote example pathways for each of the fundamental events in the event tree. Identifying the key pieces of each pathway will allow a decision maker to understand where and how to implement mitigation measures to prevent them from occurring.

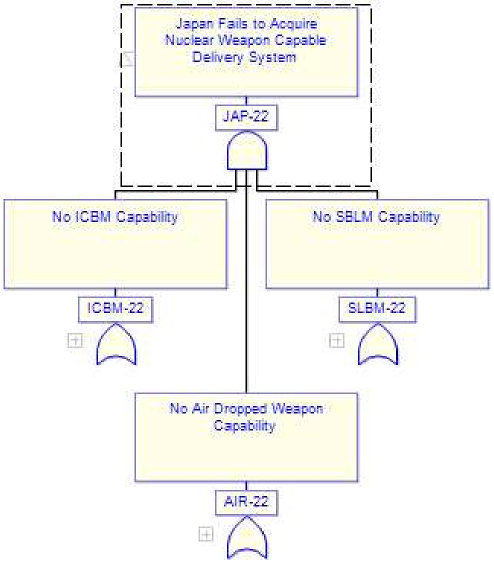


Figure 14. Delivery System Fault Tree With Focus on ICBM, SLBM, and Bomb Capabilities

Figure 14. shows what could lead to a country not being able to acquire a delivery system. This could be no ICBM capability, no SLBM capability, or no aircraft capability. Further analysis is done which results in a basic event for each of the primary failure events. For example, failing to acquire an ICBM could be a result of not having the correct solid or liquid rocket propellent components such as aluminum or liquid oxygen respectively [67], [68]. Lack of missiles could come from the failure to acquire or develop an operational guidance system, accuracy components, which requires specific batteries, diodes, and more [65]. The largest indicator for ICBMs is their delivery platform which can either be stationary, like a silo, or mobile.

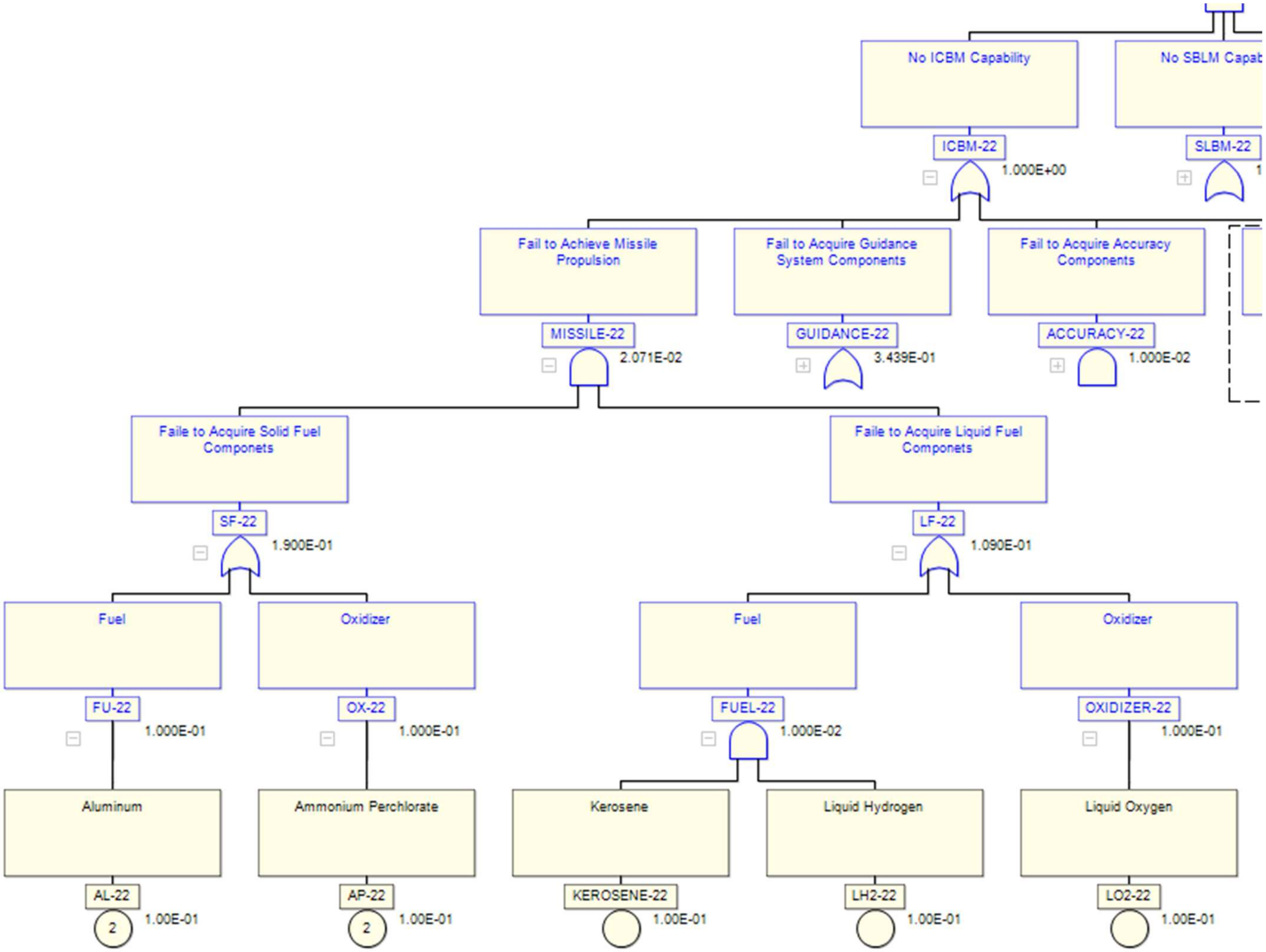


Figure 15. Country Fails to Achieve Missile Propulsion for ICBM

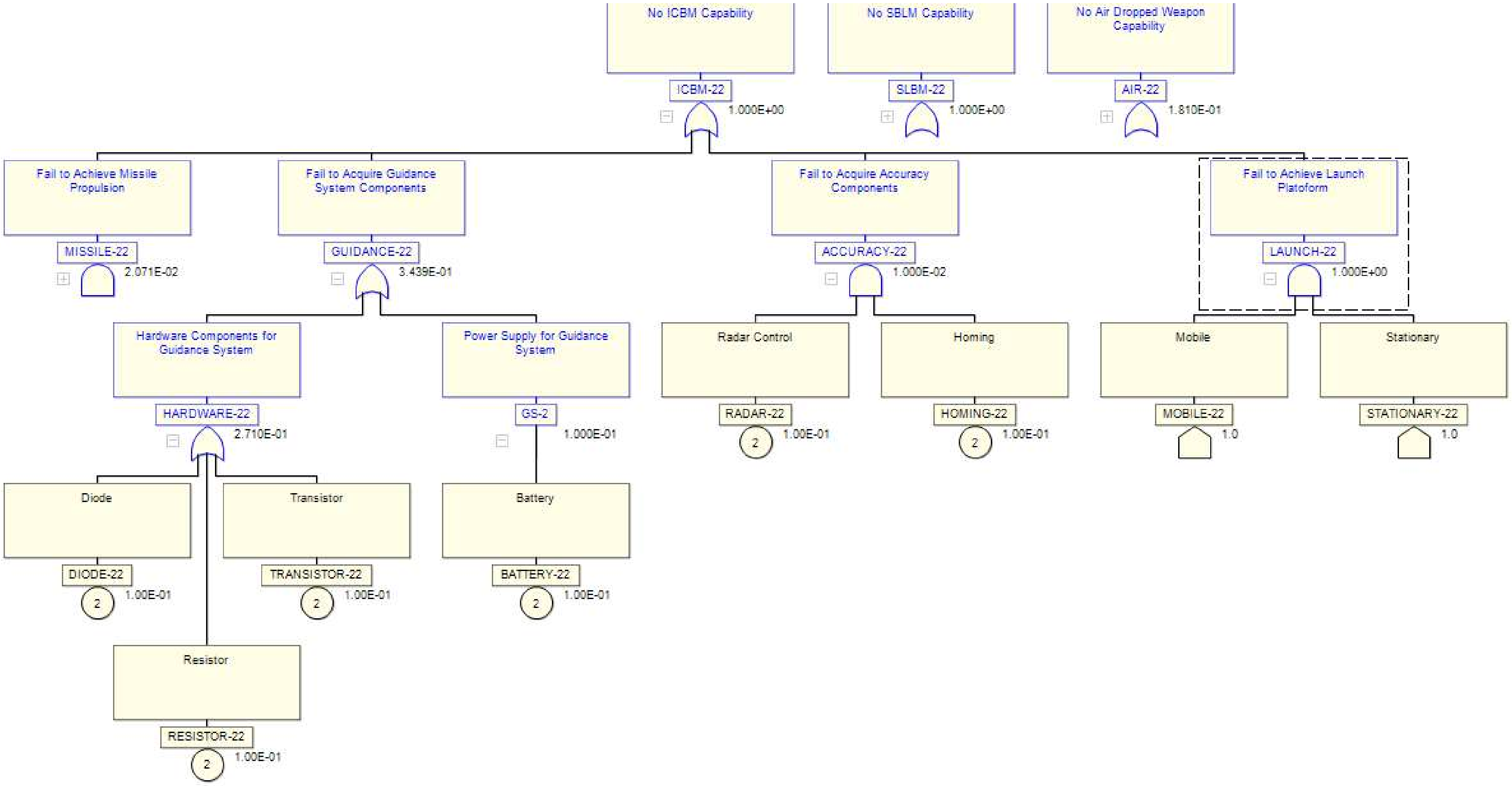


Figure 16. Country Fails to Acquire Components for Guidance System, Accuracy, and Launch Platform

The fault tree for a SLBM is similar to the ICBM except for two key pieces. The first is SLBMs do not use liquid propellent so this was removed from this subordinate fault tree. Second, the launch platform was replaced with a submarine instead of land-based systems. This is interesting because many countries in the world do not have submarines which are capable of launching nuclear missiles.

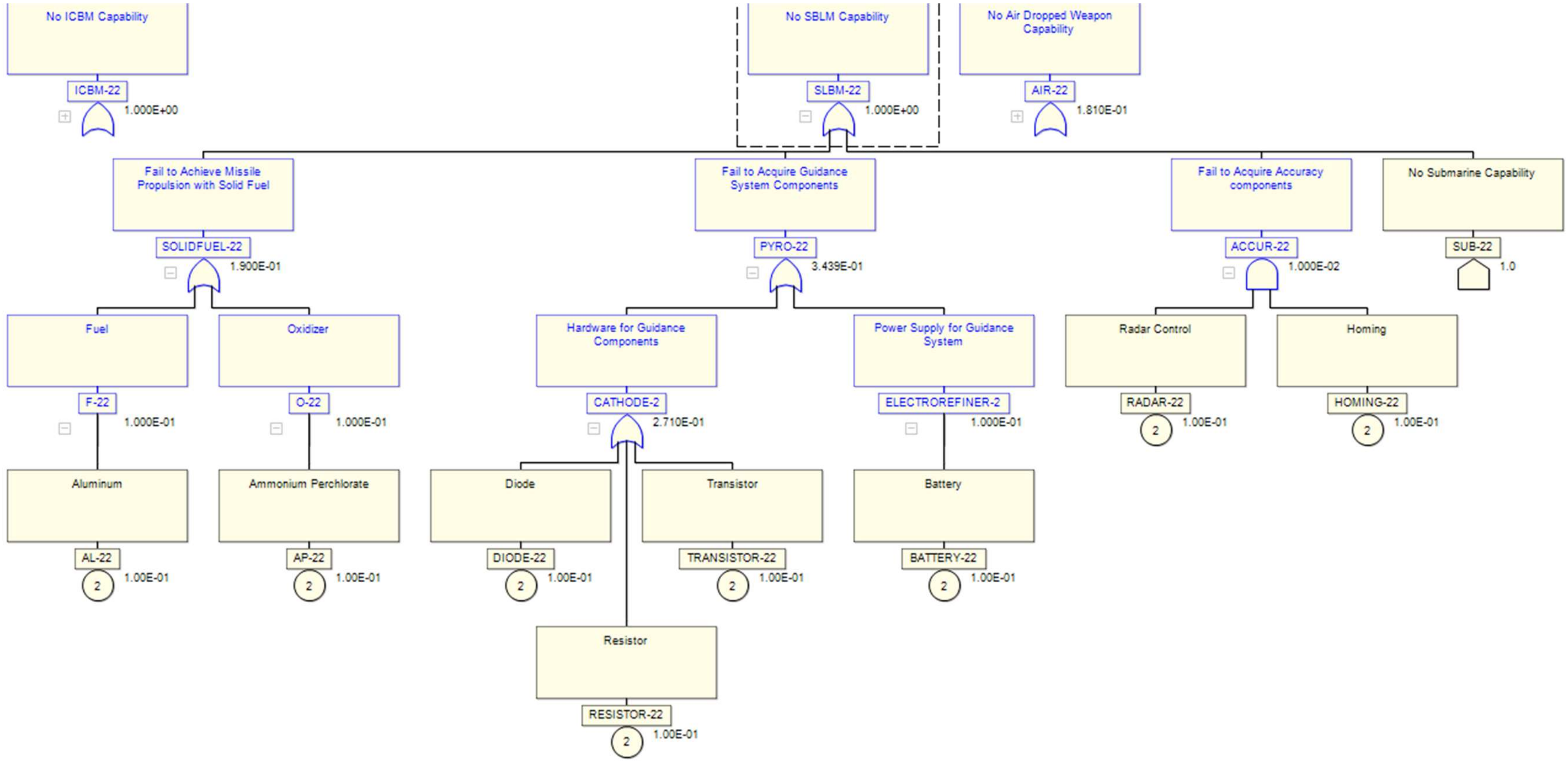


Figure 17. Country Fails to Acquire Submarine Launched Ballistic Missile Capabilities

Also, not all aircraft can carry a nuclear bomb. For simplicity, one aircraft which are designed to carry nuclear weapons were considered; cargo aircraft could possibly drop a nuclear weapon, but they were not included in this analysis. Examples of nuclear capable aircraft include US F-16, B-2, and F-15E or NATO's Tornado and Mirage aircraft. The US advertises their strategic bombs can be carried by two types of bomber aircraft, but their lower yield tactical bombs can be carried by a large variety of fighter aircraft [66]. The delivery system is only one piece needed to create a strategic nuclear weapon. The flight stabilizers allow for the bomb to fall in a controlled manner, usually nose down. This assists the fuzing and firing devices to work appropriately during operation. These fault trees can begin to resemble a supply chain for the various components required for each type of delivery system, non-fissile system, and fissile material.

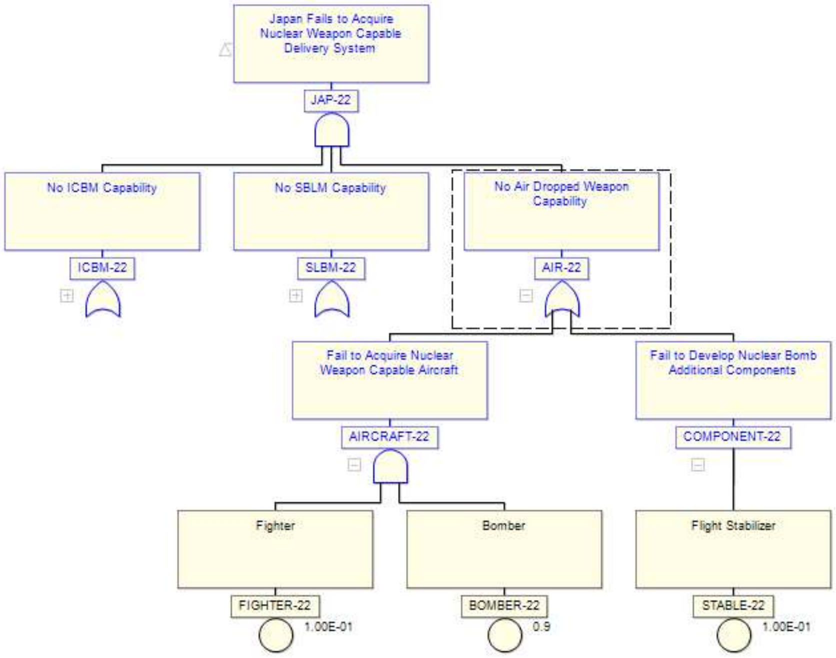


Figure 18. Country Fails to Develop Air-Dropped Bomb Capabilities

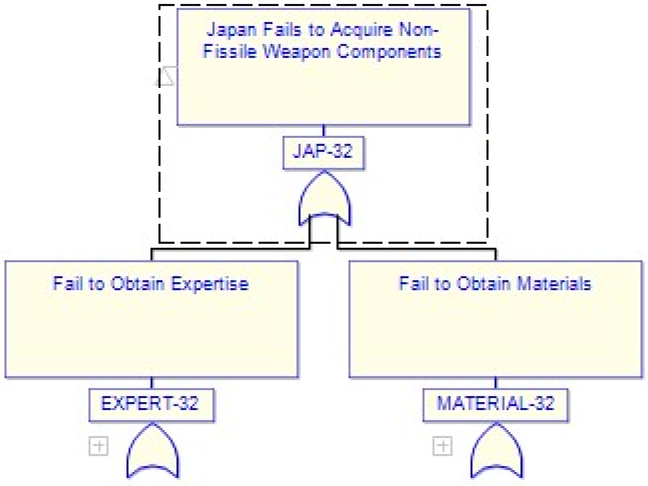


Figure 19. Fault Tree Illustrating a Country Failing to Acquire Non-Fissile Weapon Components

Figure 19. above describes what is required for non-fissile components of a nuclear. Failing to acquire these would result in the country failing to create an implosion nuclear weapon and would limit the development of a thermonuclear weapon. This fault tree not only encompasses non-fissile materials, it also includes the expertise needed to assemble and detonate a nuclear weapon. The most challenging aspect of an implosion nuclear weapon is the uniform, spherical blast wave which compresses the hollow subcritical core, creating prompt criticality which releases large amounts of energy. Failing to do this and not synchronizing the detonations would result in a detonation well below the estimated value or a fizzle. Creating a uniform shockwave requires expertise in simultaneous initiation of detonators and forms the high explosives in a way to create uniformity. The expertise can also come from metallurgists who form the other components such as tamper and reflector for more efficient neutron and x-ray use.

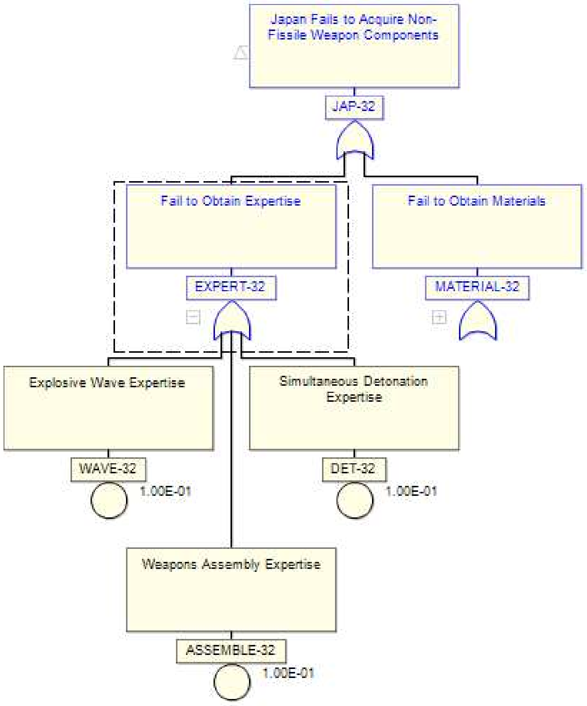


Figure 20. Fault Tree Showing the Country Fail to Obtain Necessary Types of Expertise

Non-fissile materials needed for a nuclear weapon range from explosives to neutron generators. The list for nuclear weapons components is long, but only a few items are listed here due to classification concerns. Both insensitive and sensitive explosives are needed to detonate a weapon. Sensitive explosives can be found in detonators to initiate the explosive train after the exploding bridge wire receives an electrical signal from the firing device. The detonator begins the explosive train which results in some variety of high explosives detonating. For example, composition B was using to detonate the Gadget device. Surrounding the explosives is a tamper material which reduces the number of neutrons which could escape the explosion. Adding a tamper around the core decreases the amount of fissile material needed, which decreases the weapon's weight. Historically, high-Z, or high atomic number, materials such as depleted uranium or gold has been used as a tamper.

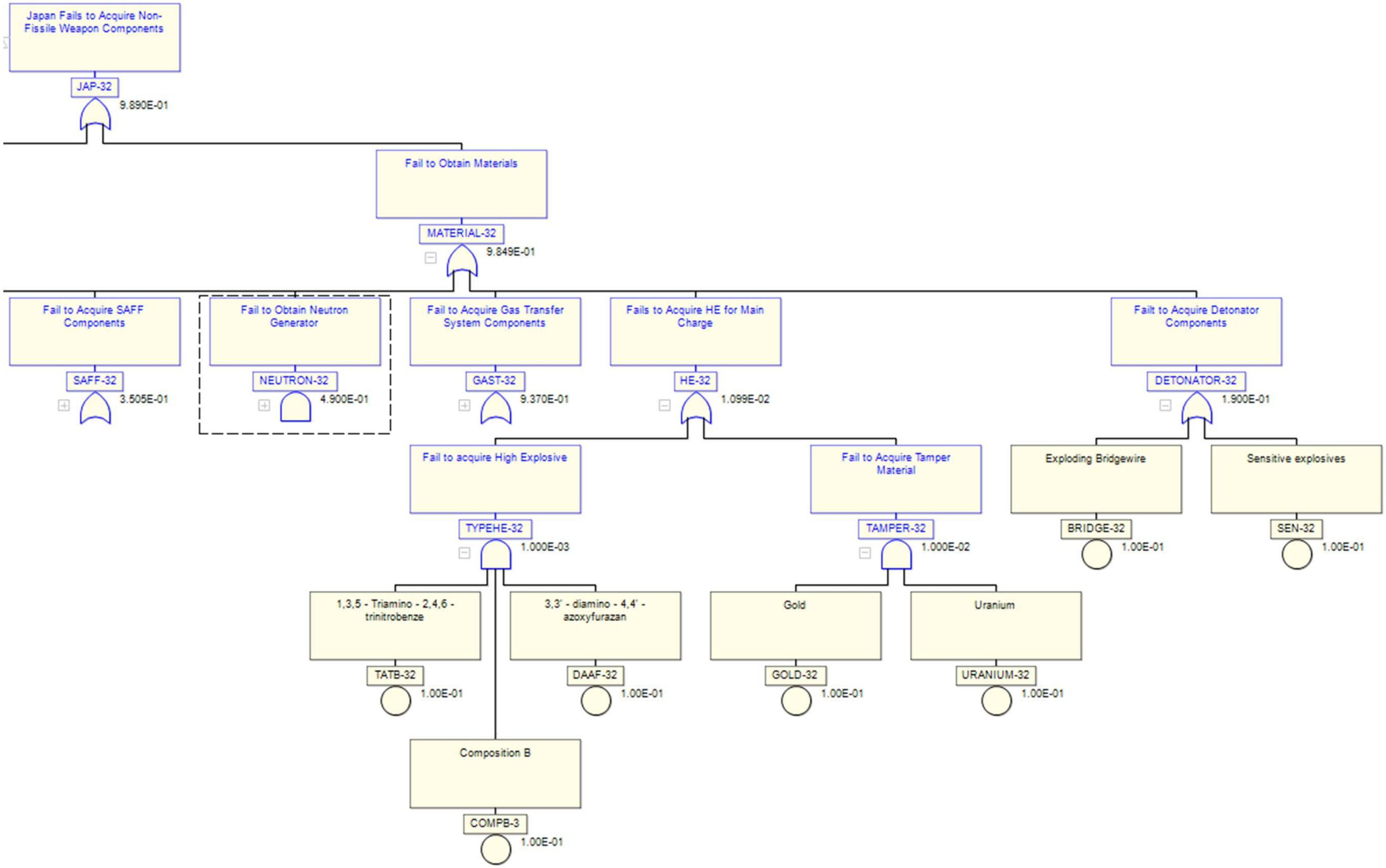


Figure 21. Country Fails to Acquire Detonator Components and High Explosives Necessary for a Nuclear Weapon

Neutron generators and gas transfer systems are required to initiate a nuclear chain reaction and boost it when desired. Neutron generators like polonium-210 in the first nuclear weapons and MC4380 in the W76 system are used to release neutrons as the detonation compresses the core [67]. Polonium was chosen for the Manhattan Project because it emits alpha particles during natural decay which release neutrons when they strike a reflector material. Reflectors are made of lighter elements such as beryllium [68]. Utilizing neutron generators allows for controlled nuclear chain reaction and the precise moment the fissile material is compressed enough to go supercritical. Gas transfer systems were introduced to supply high-energy neutrons to the fission chain reaction. This will increase the yield of the weapon compared to those which use no gas. Acorn reservoirs are components of a gas transfer system used by the US in the past [69]. Today's weapons can use lithium-6 hydride, which contains deuterium, to create tritium when bombarded by neutrons. Li-6 is not a common isotope of lithium; it must be enriched from natural lithium which consists primarily of Li-7. This is what assists the fusion reaction in thermonuclear warheads [70]. Without these components, it will be difficult for a country to create a high yield fission weapon.

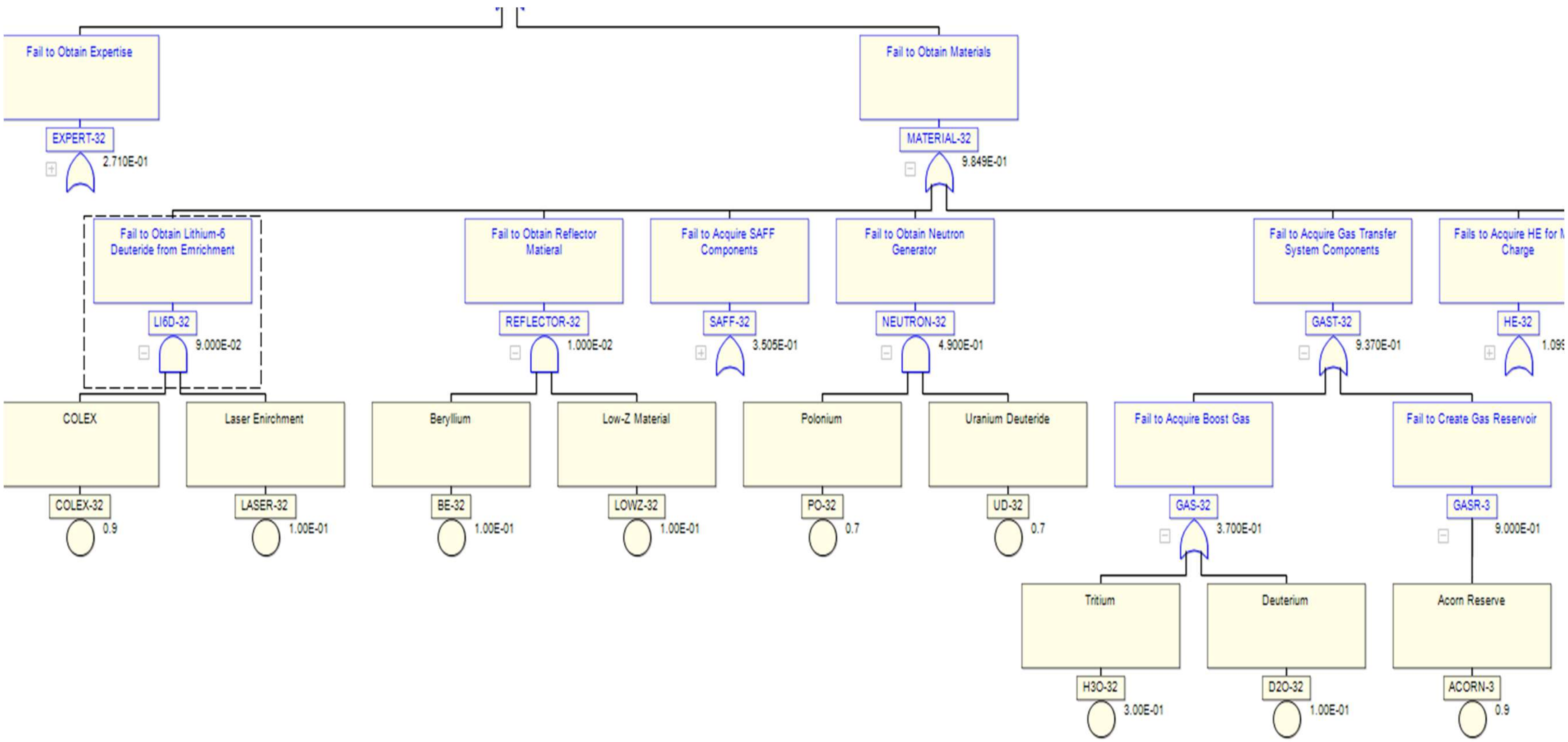


Figure 22. Country Fails to Develop Lithium-6 Enrichment, Boost Gas, Neutron Generator, and Reflector Material Capabilities

Safing, arming, fuzing, and firing (SAFF) systems are required for the bomb to detonate at the desired time and be safe in all other conditions. Safing systems help prevent detonations during accident scenarios such as a plane crash or a weapon catching fire in a missile silo. This component is not necessarily needed but does help to prevent unintentional detonations. Arming components which remove any positive blocks in the explosive train. The bombs dropped in WWII had arming plugs installed during the flight. Fuzing mechanisms are used to provide a signal to the firing set when the weapon is at the appropriate location. These were the barometric and radar sensors on Fat Man and Little Boy. The firing set is what triggers the detonators to fire. Safing and arming systems are used for safety considerations, but failing to have a fuzing and firing mechanism will prevent a detonation [71].

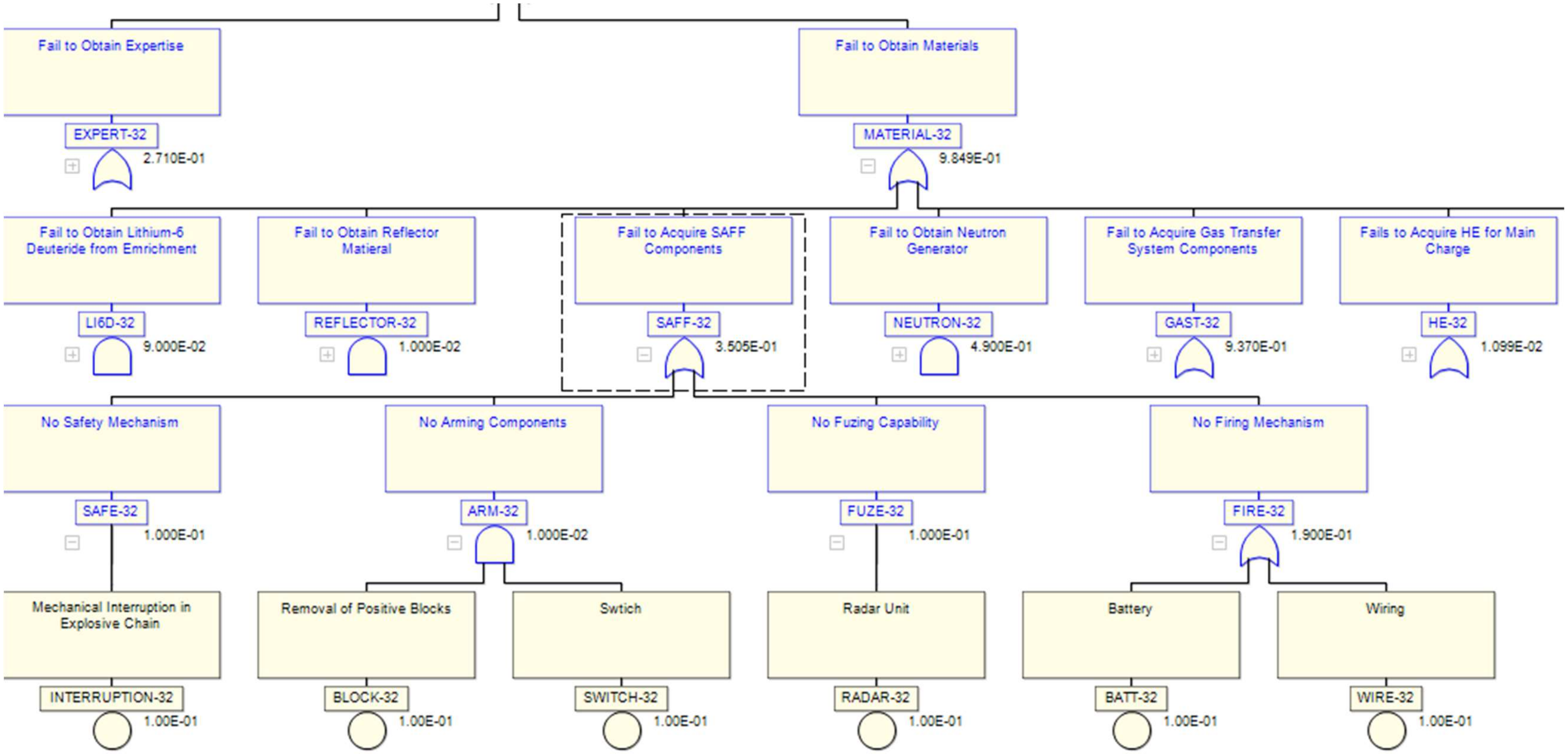


Figure 23. Country Fails to Acquire Safing, Arming, Fuzing, and Firing Components

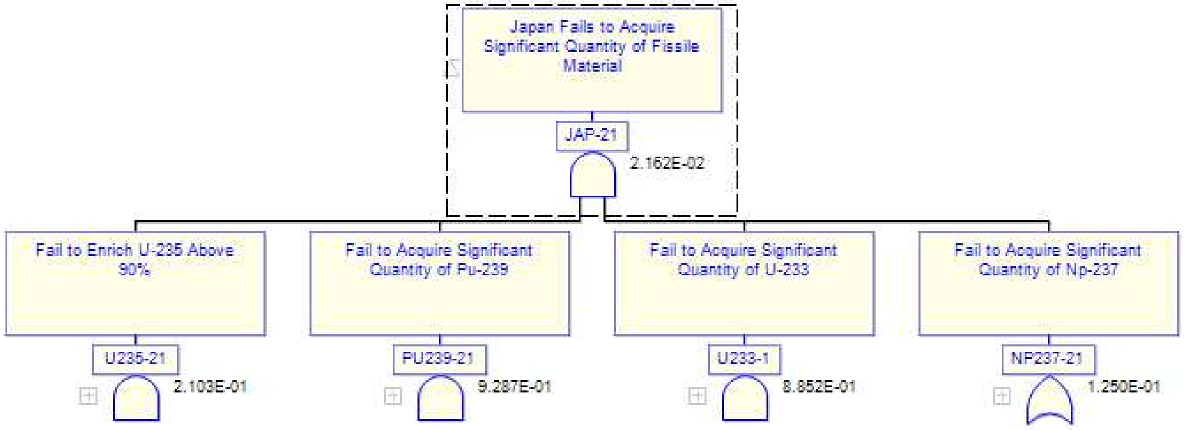


Figure 24. Fissile Material Acquisition Fault Tree

Figure 24. describes the pathways to create fissile material necessary for a nuclear weapon. The primary pathways to create fissile material are enriching U-235 from natural uranium and separating Pu-239 from spent nuclear fuel. Enriching natural uranium means increasing the amount of U-235 which makes up only 0.72% of natural uranium, primarily U-238. Various techniques have been used to do this, but currently over 50% of the world currently enriches uranium utilizing gaseous centrifuges [72]. Electromagnetic isotope separation, gaseous diffusion, and laser enrichment are other methods to enrich U-235. All four methods require the gaseous form of uranium called UF6 and a large and constant electrical input. UF6 is created once the mined ore has been milled and gone through the conversion process. Each method requires different levels of electrical input. Gaseous diffusion requires several gigawatts of electricity, whereas gaseous centrifuges only require a few hundred megawatts [73]. This is still more than would normally be seen in a standard facility or warehouse.

Centrifuges use a rotor spinning at a high rate of speed to separate the two isotopes of uranium. The material continuously moves through different stages of a cascade until the product contains more than 90% U-235. These rotors are made of carbon fiber because it is both strong and lightweight. Magnets, maraging steel, electric motor, and vacuum pumps are also key elements of a centrifuge.

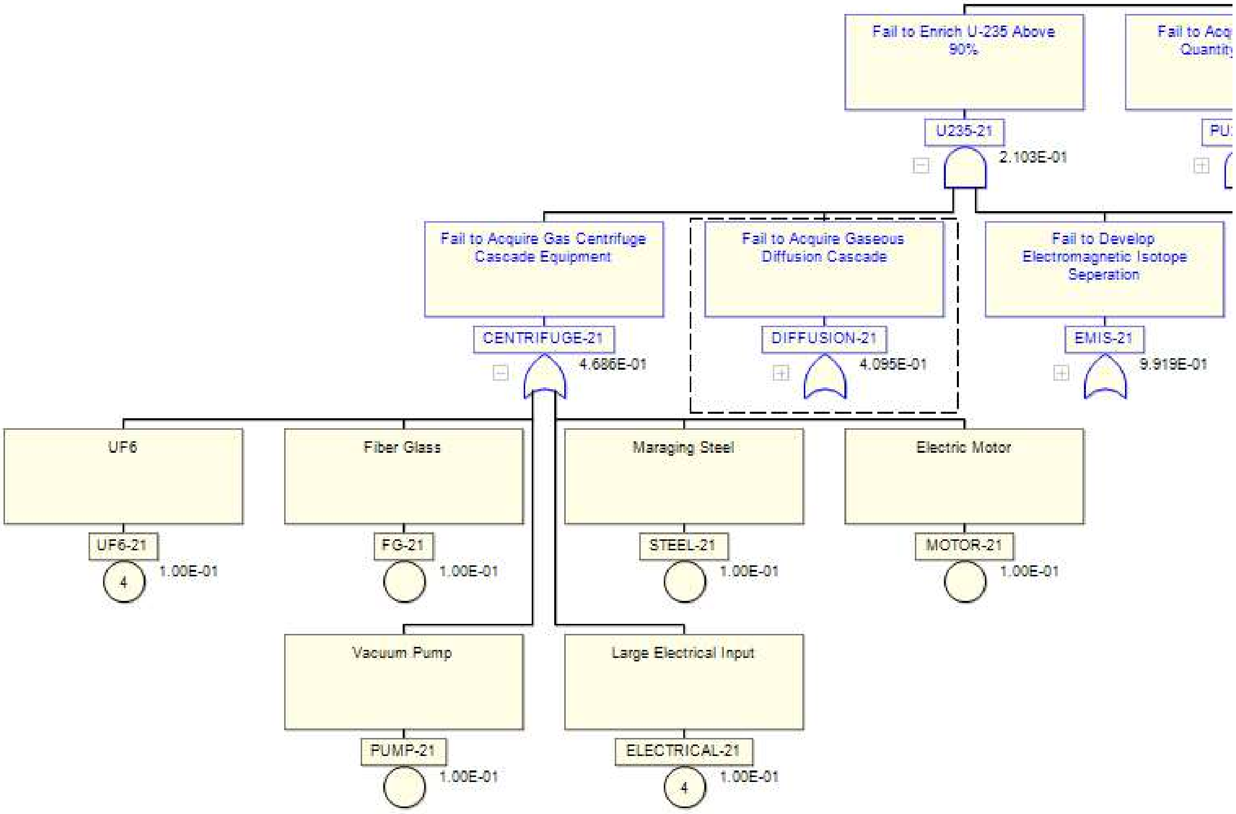


Figure 25. Country Fails to Acquire Gaseous Centrifuge Cascade Equipment

Electromagnetic isotope separation (EMIS) and gaseous diffusion are not as widely used as they were during the years after WWII. EMIS separates the two uranium isotopes by moving the uranium gas through a magnetic field. Because of the different weights of the isotopes, their trajectory is different. The U-235 pulled closer to the magnet than U-238 is so they are collected in separate systems. Large magnets and several thousand tons of silver were used during the Manhattan Project to create the Electromagnetic Plant at Oak Ridge. Gaseous diffusion plants force uranium hexafluoride through porous membranes which only the U-235 can pass through.

Both processes require large amounts of energy, huge facilities, and are not efficient. The porous membrane, heat exchanger, and compressors required for this process are key identification features of a diffusion plant.

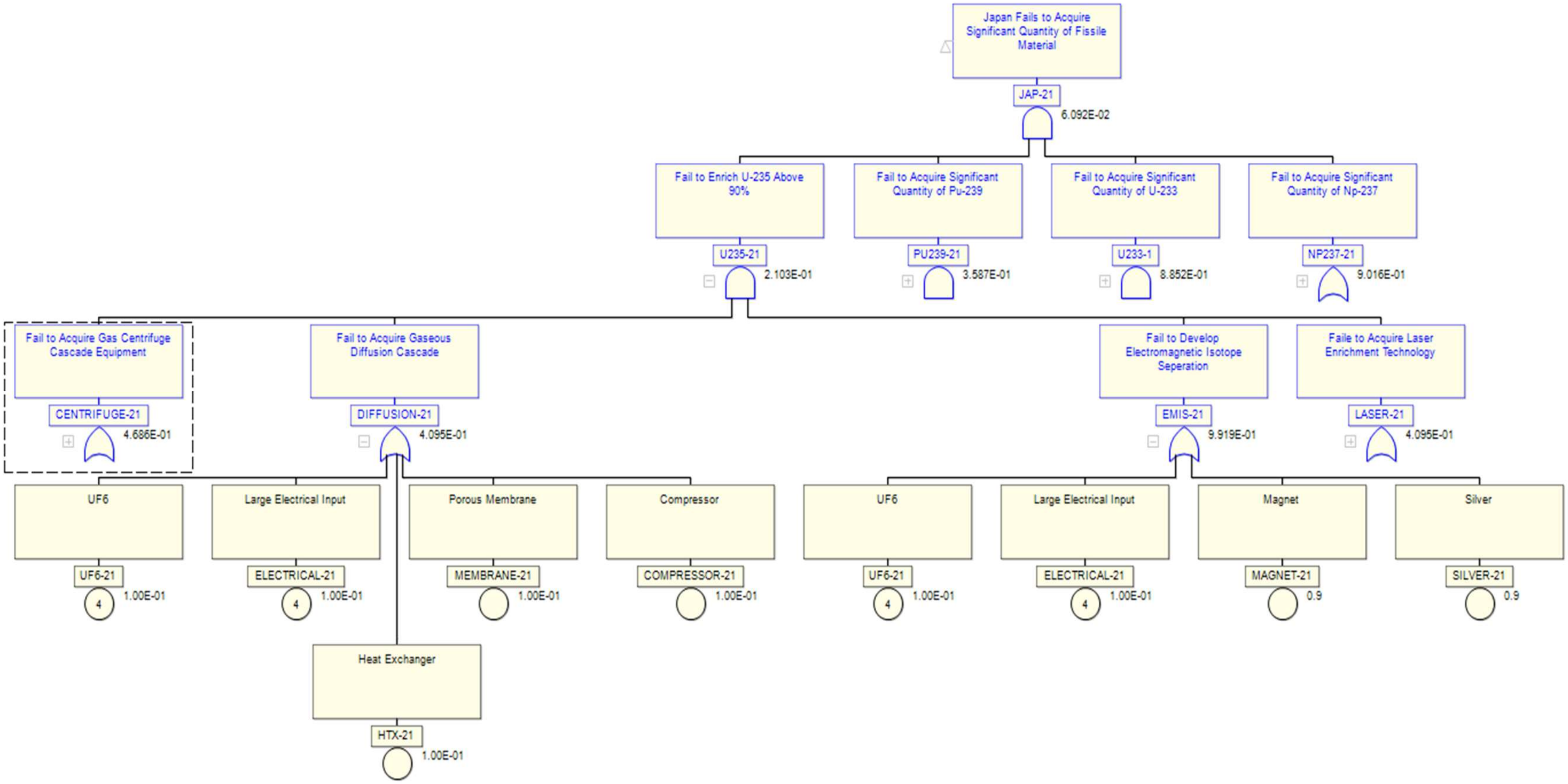


Figure 26. Country Fails to Acquire Materials Necessary for Gaseous Diffusion and EMIS Enrichment

Lastly, laser separation is an emerging technology by exciting the molecules by photoexcitation. This process has a higher separation capacity than the other methods and is easier to conceal [74]. Countries could also reprocess spent nuclear fuel to retrieve partially enriched uranium using the same process to acquire plutonium. This technique is still being developed for large scale purposes and many countries do not have this capability. It requires liquid uranium handling equipment, tunable lasers, and a scanning electron beam to add with a large electrical input and converted uranium.

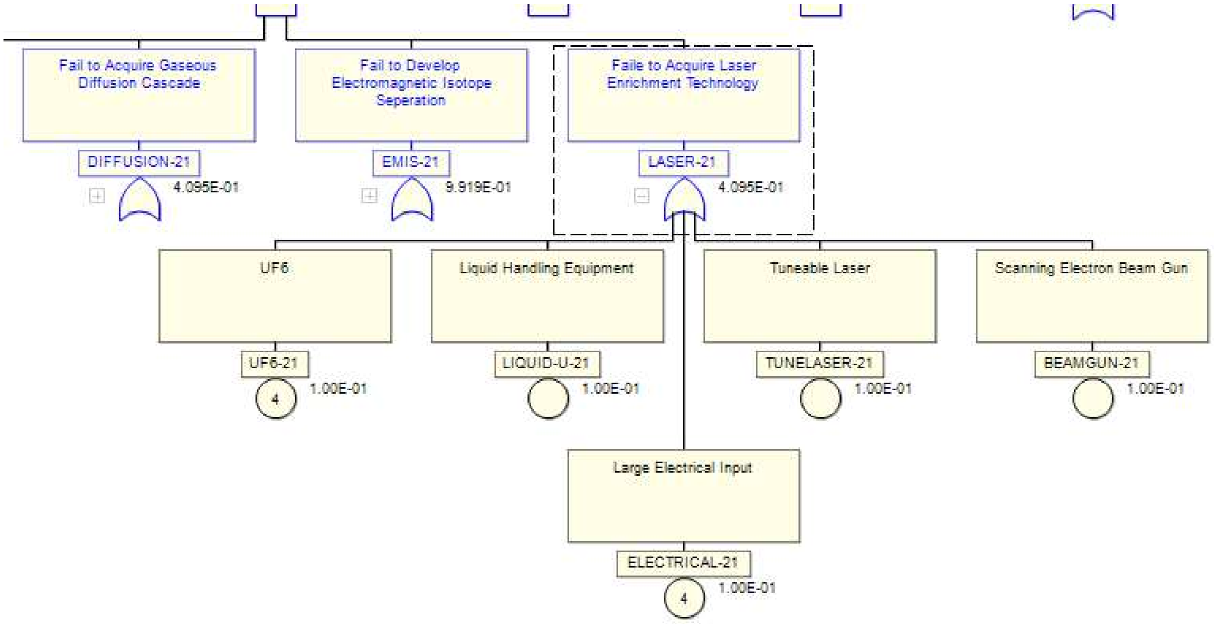


Figure 27. Country Fails to Develop Laser Enrichment Technology

Pu-239 is generated when U-238 captures a neutron and undergoes two beta decays with Np-239 as the intermediary with a half-life of 2.4 days. This primarily occurs while fuel is in a reactor. The fuel must have a shorter core life cycle than normal or the Pu-239 will begin capturing neutrons creating undesired plutonium isotopes such as Pu-240 which has a high spontaneous fission rate. Weapons grade plutonium contains around 93% Pu-239 compared to the other isotopes. It is possible to use plutonium with less than 93% Pu-239, but the probability of success and yield both decrease the greater the quantity of Pu-240. The two primary methods for plutonium separation are plutonium uranium extraction (PUREX) and pyroprocessing.

PUREX process starts with decladding the fuel rods which separates the fuel pellets from the outer zirconium alloy shell. This is done inside of a hot cell because of the radioactivity of the spent nuclear fuel. The fuel pellets are then dissolved in around 7 molar nitic acid. This solution is mixed with tributyl phosphate (TBP) in either a mixer settler or pulse column. During this step the uranium and plutonium bind to the TBP and are separated from the other fission isotopes. The TBP mixture is then combined with other chemicals which reduces the metals so they precipitate out of the solution and are then collected [75].

Pyroprocessing is another method of reprocessing spent nuclear fuel for a closed loop fuel cycle. The first step is to reduce the oxide fuel to metal. This can be done in an electro-reduction process with molten LiCl salt at 650°C as the metal is converted into an anode. This anode is then placed onto a liquid cadmium cathode which separates it from the fission products. A cathode processor removes the salt and cadmium at 1200°C. The product is now ready to be converted into mix oxide fuel pellets for a fast fission reactor. Since this process does not directly result in significant quantities of pure plutonium, it is thought to be proliferation resistant [76]. The problem is, the fuel can then be run through a PUREX process which would separate the plutonium from the uranium. In both cases, the purified plutonium is then made into subcritical spheres ready for a nuclear weapon.

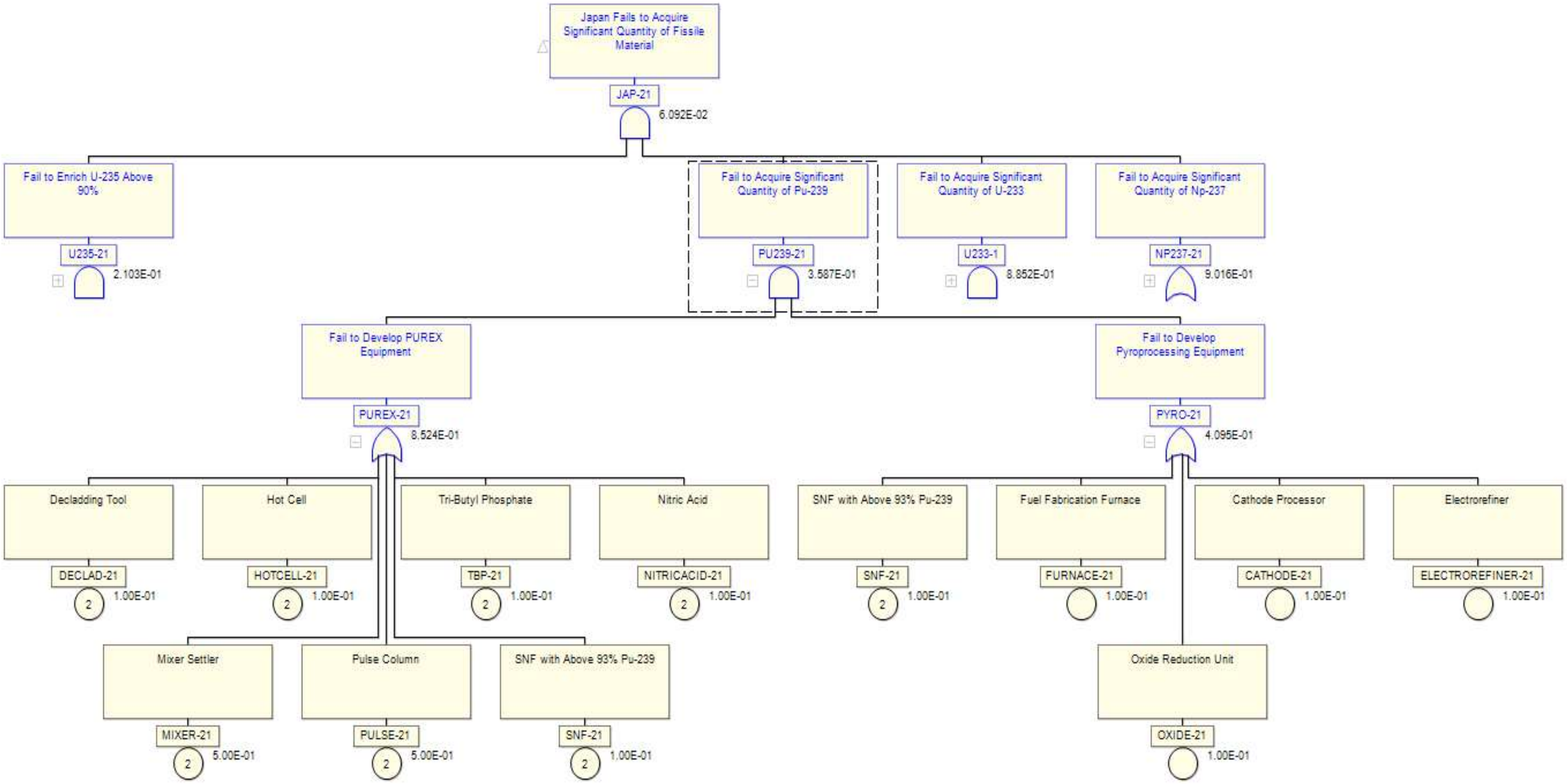


Figure 28. Country Fails to Develop Both PUREX and Pyroprocessing Techniques to Isolate Pu-239 From Spent Nuclear Fuel

U-233 and Np-237 are two other fissile isotopes which have been used to create nuclear weapons in the past. It is possible U-233 could become a more primary fissile material for countries who have large amounts of thorium deposits. If Th-232 is irradiated, then it creates Th-233 which goes through two beta decays to create U-233 [77]. This can be done by separating U-233 from spent nuclear fuel in a process like PUREX, or Pa-233 can be isolated from thorium fueled MSRs while the reactor is running. Pa-233 has a half-life of 27 days and beta decays into U-233. Isolating Pa-233 is more desirable than chemical separation because it reduces U-232 contamination [78].

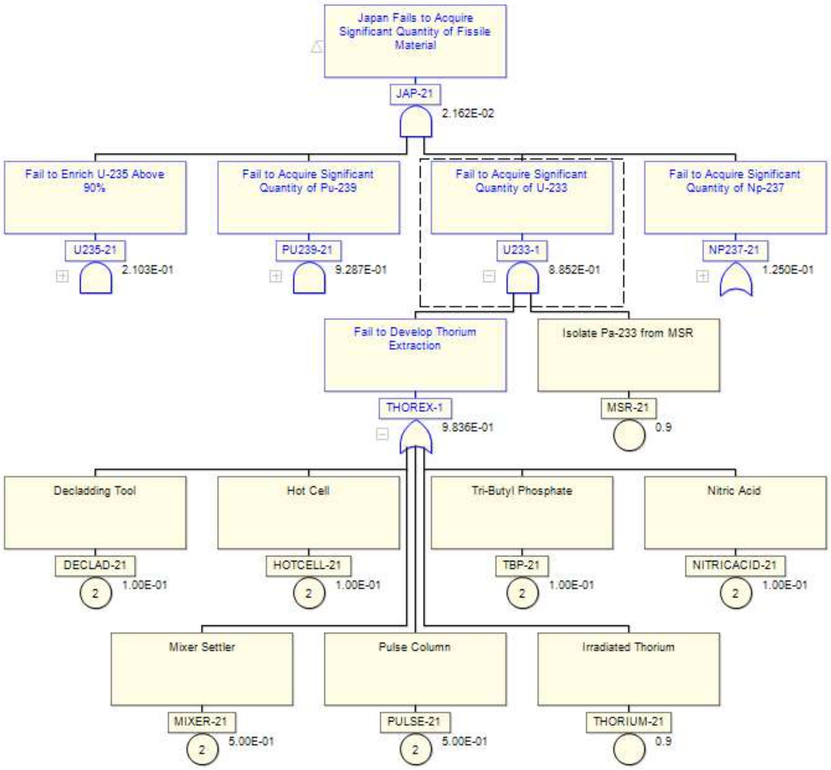


Figure 29. Country Fails to Develop Processes to Isolate U-233

The last fissile material analyzed here is Np-237. It was first discovered in Japan shortly before World War II. Yoshio Nishina and Kenjiro Kimura exposed purified natural uranium oxide to fast neutrons for more than 50 hours. The fast neutrons were produced by bombarding lithium with 3MeV deuterons in a cyclotron. They discovered U-237 is the result of an (n, 2n) reaction with U-238. U-237 has a half life on 6.75 days then beta decays to create Np-237 [79]. Np-237 is also commonly found in spent nuclear fuel. A 1 GWe PWR may produce around 10 kg of Np-237. The Np-237 is separated from irradiated nuclear fuel as part of the aqueous solution during PUREX or another extraction process. Depending on the extraction method determines if the Np-237 is precipitated with the plutonium or kept with the other fission products [25]. While in the aqueous solution, Np-237 can be removed via coprecipitation using 1M hydrochloric acid, potassium iodide, and thenoyl-trifluoracetone (TTA) in xylene [80]. The country would need to either divert nuclear material or build a program without being detected by the IAEA or others to be successful.

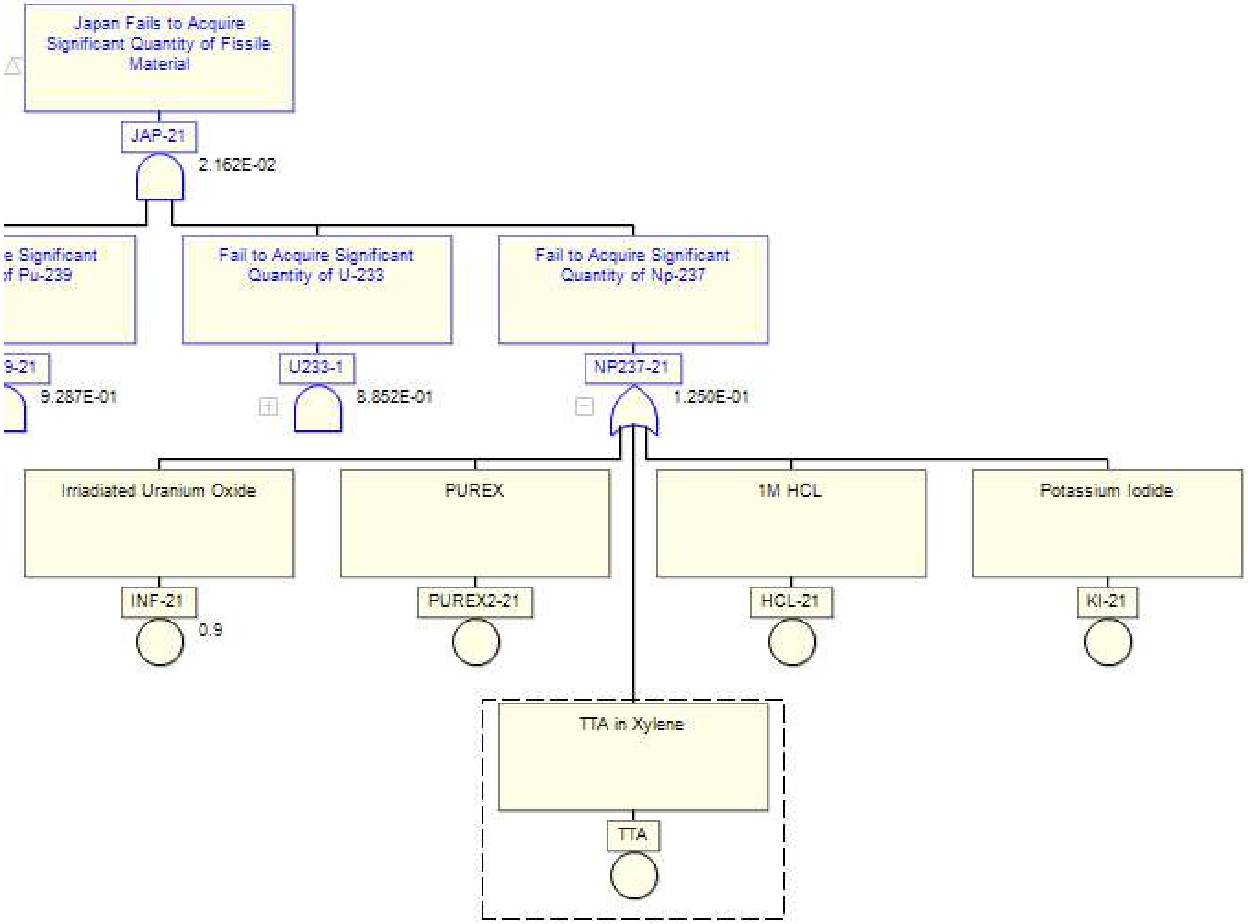


Figure 30. Country Fails to Isolate Np-237 from Irradiated Uranium Oxide

3.3.6. Uncertainty

As Ezell, et al., mentions in his paper, there is a large amount of uncertainty in this analysis. They argue uncertainty comes from two reasons. The first is the incompleteness associated with intelligence data prevents probability estimates. Similarly, expert opinion may be biased or inexperienced when examining the intelligence data. Second, the probabilities are constantly changing over time because the perpetrators will likely change their tactics once they have been discovered [32, p. 578]. There is no way to prevent using expert opinion while gathering data for non-proliferation. Mosleh, et al., demonstrates how expert opinion can incorrectly estimate component maintenance durations at a nuclear power plant. Experts were asked to estimate how long the maintenance of pumps, valves, heat exchanges, etc. should take. The results showed the experts were usually off by a factor of 3 for their estimates [81, p. 70]. This failure can be seen when asking both single and multiple experts to formulate an opinion. Bayes' theorem provides the framework necessary to reduce uncertainty as more data is accumulated over time.

Bayesian inference uses the theorem in equation 3 to update prior opinions as new data is observed. This would allow analysts to update their reports as new information is received. Miniscule data can prove to be useful in updating the prior probability and yielding better results. [83].

$$\mathrm{P(H|E)} = \frac{\mathrm{P(E|H)} * \mathrm{P(H)}}{\mathrm{P(E)}} \tag{3}$$

In this equation, $\mathrm{P(H|E)}$ is the new probability of the hypothesis given the new evidence or posterior, $\mathrm{P(E|H)}$ is the probability of observing the evidence given the hypothesis or the likelihood, P(H) is the probability of the hypothesis before the new evidence or prior, and P€ is the marginal likelihood which will not change as new evidence is discovered. Looking at this equation, the posterior will increase as hypothesis supporting evidence, or the likelihood, is found because the denominator will not change [36]. This will create a higher peak for the posterior as shown in Figure 31. It will decrease if the evidence found does not support the hypothesis. From there, standard deviation can be used to assess variations in the hypothesis and rule out low likelihood events for that scenario. A decision maker will also weigh the analysis of an expert's estimate in a similar fashion. The decision maker will accept the expert's estimate for the likelihood term if it is believed they are accurate most of the time. In contrast, the decision maker will favor the prior if they do not have confidence in the expert.

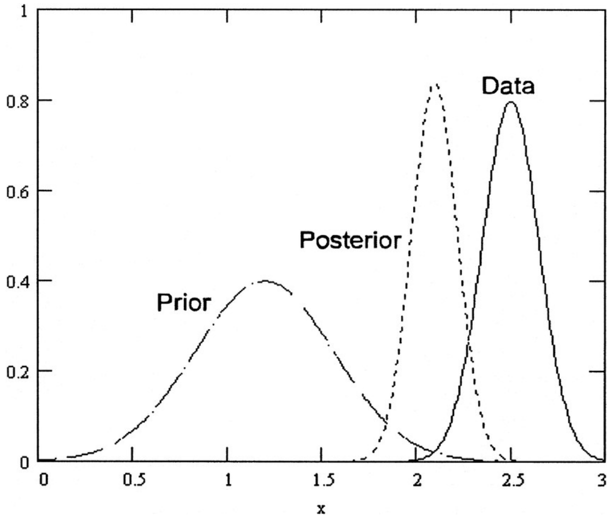


Figure 31. Bayesian Updating Prior Distribution with Addition of New Data

Bayesian inference can also be used to weigh the opinions of multiple experts. Analyzing intelligence leads to subjective opinions by the experts. Experts can either over or underestimate the importance of an adversarial action which means the decision maker must act on inaccurate data. This can be corrected by assuming the experts' opinions are normally distributed [82].

Equation 4 shows how Bayes Theorem can be written when multiple experts are used. This error is can also come from the subjective opinion of the decision maker in which they base the error on its variance to their beliefs [83]. The error in this equation can then be modeled using either the additive or multiplicative error models in equations 6 and 8.

$$\mathrm{P}(\mathrm{H^t}|\mathrm{E_1},\ldots,\mathrm{E_N}) = \frac{\mathrm{P}(\mathrm{E_1},\ldots,\mathrm{E_N}|\mathrm{H^t})\mathrm{P}(\mathrm{H^t})}{\mathrm{P€}} \tag{4}$$

The basis of the additive model is shown by equation 5. $\mathrm{X_1}$ is the experts estimate as a variable, x^t is the true value, and ξ_1 is the error term. This can be substituted back into equation 4 to create the additive model equation [85].

$$\mathrm{X_1} = x^t + \xi_1 \tag{5}$$

$$\mathrm{P}(\mathrm{E_1}|H^t) = \frac{1}{\sqrt{2\pi}\sigma_1}\exp\{-\frac{1}{2}\left[\frac{\mathrm{E_1} - (H^t + < \xi_1 >}{\sigma_1}\right]^2\} \tag{6}$$

Where $< \xi_1 >$ is the mean of the error term and σ_1 is the standard deviation of the error distribution [85]. The multiplicative error is similar but instead of adding the true value and the error terms together, they are multiplied. Dalkey observed individual responses to a series of Delphi experiments. The results showed the density of the standardized estimates to follow a lognormal curve. The experts' opinions in this case are multiplicative instead of additive [83]. By taking the logarithms of equation 7, the additive model can be used to derive equation 8.

$$\mathrm{X_1} = x^t\, \xi_1 \tag{7}$$

$$\mathrm{P}(\mathrm{E_1}|H^t) = \frac{1}{\sqrt{2\pi}\sigma_1 \mathrm{E_1}}\exp\{-\frac{1}{2}\left[\frac{\ln(\mathrm{E_1}) - (\ln(H^t) + \ln(< \xi_1 >)}{\sigma_1}\right]^2\} \tag{8}$$

Where $\ln(<\xi_1>)$ is defined as the median of the error term [85].

WMD analysis will be inherently flawed because the data will have high uncertainty compared to reliability of machines. Assuming the error in the expert's bias or decision maker's opinion is normally distributed, the additive or multiplicative models can be used to identify the standard error. One method of correcting this is to provide historical examples which demonstrate how states have pursued and acquired WMDs. This could reduce bias and train new intelligence analysts by standardizing information interpretation. Training the data standardization will only help if the model uncertainty is reduced, which could prove difficult in an ever-changing environment.

One of the greatest challenges with creating a model for nuclear weapon proliferation is the dynamic relationship between friend and foe. As the foe circumvents the rules established by the friend, the friend will then attempt to thwart the foe's new strategy. This becomes a continuous loop as one tries to get the upper hand over the other. It has been shown by the establishment of new international safeguards to mitigate the nuclear proliferation by India prior to 1974 and Iraq in the 1980s. This dynamic environment leads to greater model uncertainty as the initial basic events of the assessment are no longer significant and must be adjusted to new attempts to acquire nuclear weapons. This data suffers from epistemic uncertainty. Epistemic uncertainty is incompleteness in how to represent new nuclear infrastructure and the safeguards required to prevent proliferation in the QRA model. Li, et al., and Singh, et al., both struggle to interpret the data and attempt to correct this by using Weibull and Cox distributions to correct for the uncertainty error. This leads to inability to accurately predict if and when a country explores or acquires nuclear weapons. These situations lead to completeness uncertainty of the model by adding new basic events to the logic model [85].

Uncertainty in this model was determined using beta distribution. It was chosen because it is a generalization of binomial distribution. The difference being the failure on demand is replaced with a continuous random variable between 0 and 1. There are two positive parameters within the equation which are a complement to 1 and control the shape of the distribution: alpha and beta. The mean of the probabilities for the basic events was calculated. A simplified constrained noninformative distribution was used which sets the alpha parameter to 0.5. Setting the parameter equal to 0.5 was done because of the large uncertainty with open-source literature in regard to nuclear weapons programs. Solving for the beta variable was done using equation 9. Equation 10 calculates the variance of the beta distribution which is needed for uncertainty quantification using CAFTA tools [86].

$$\beta = \frac{\alpha}{\bar{x}} - \alpha \tag{9}$$

$$\sigma^2 = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)} \tag{10}$$

$\bar{X}$ represents the mean and σ^2 represents the variance in equations 9 and 10 respectively.

Completeness uncertainty is the failure to account for risk contributors in the model. This could include leaving out basic events, initiating events, or the methods for analysis have not been developed yet. NUREG-1855 recommends using a consensus model to combat uncertainty. For WMDs, a consensus model would be routinely published and peer-reviewed by those who work to counter WMD acquisition. This could be by any of the four export control groups or experts within the government to identify proliferent activity [85]. Doing this will result in refining the model by eliminating hazards which cannot occur in the region or adding emergent technology. This can be done during a qualitative or quantitative analysis of the model to determine the significance of the non-modeled scope items. The quantitative analysis is done by setting an upper limit, such as the 95th percentile. The realistic data should lie within this best estimate. Setting upper limits are used to analyze the case studies in Chapter 4 using the programs GeNIE 4.0 and SAPHIRE 8.0 to test the model's applicability.

3.3.7. QRA Software

In this study, GeNIE 4.0 is used to create the Bayesian Network to identify the frequency of initiating events and CAFTA was used to create the event tree. GeNIE 4.0 is developed by BayesFusion. The GeNIE Modeler utilizes artificial intelligence modelling and machine learning for Bayesian Networks. This program will determine the joint probability of occurrence for the initiating events [87].

The Computer Aided Fault Analysis System (CAFTA) version 11 was used to build and quantify the fault and event trees. CAFTA is a computer software program developed by the Electric Power Research Institute, EPRI. The probability for the top event of each fault trees was determined using the direct probability calculator (DPC). The truncation for DPC was set to 1E-20 to capture the greatest amount of cut sets. These values were plugged into an event tree created using Microsoft Excel to generate sequence probabilities shown in Chapter 5. The software includes a PRAQuant and UNCERT tool which were used to quantify the sequences of the CAFTA model and determine the uncertainty. UNCERT used Monte Carlo random sampling method for 100,000 samples to determine the uncertainty. These results were collected and Python was used to plot then with a boxplot to visually see the 5th and 95th percentiles, mean, and median of the data [88].

CHAPTER 4. Nuclear Proliferation Case Studies

4.1. Overview

The nuclear programs for Nigeria, Saudi Arabia, Japan, and Pakistan were selected for analysis using this method. The combination of these four countries shows a wide array of nuclear and country capabilities. Nigeria is one of the greatest economic and military powers in Africa but has almost no nuclear infrastructure to speak of. Similarly, Saudi Arabia has little nuclear capability but has enough money and territorial power to rapidly build a nuclear weapons program if desired. Japan has the largest peaceful nuclear capability of the four countries. If they felt threatened and lacked protection, then they could easily begin creating nuclear weapons. Lastly, Pakistan was broken into two time periods: 1968 and 1998. The government in both time periods wanted a nuclear weapons program but Pakistan lacked the resources in 1968 and tested their first weapons in 1998. This broad-spectrum analysis will show the utility of using QRA to analyze breakout periods for nuclear weapons.

The case study for each country will include a brief background highlighting the economic, internal struggles, national security threats, technological determinants, and more which either help or hinder their nuclear program. Open-source data will be used to complete the fault and event trees which will quantify the end states for the country’s nuclear weapons program. The results will show which country has the greatest risk of creating a nuclear weapons program and what is limiting them from doing so.

4.2. Nigeria

Located on the western coast of Africa, Nigeria is the most populous country in the continent. They gained independence from Britain in 1960 and became a federal presidential republic in 1999 [89]. Despite having the largest market economy in Africa, their gross domestic product (GDP) ranks 39th of the 213 countries in the world [90]. Nigeria struggles with maintaining electricity for 60% of their population. They also have the largest military in Sub-Saharan Africa but are focused on fighting against insurgent organizations Boko Haram and the Islamic State within their own borders [89]. Despite these struggles, Nigeria wants to expand their nuclear energy capacity to gain more economic and domestic stability.

Militarily, Nigeria is focused on defeating an internal threat which threatens to destabilize them. There has been no need to escalate their military to focus on strategic weapons such as ICBMs or large, air-dropped weapons. Their industrial complex is centered around the export of crude oil. This could be transitioned to make fuel for liquid-fueled short, medium, or long-range missiles, but there are no developments at this time. Nigeria's Navy has no submarine capability, which negates any potential threat of a SBLM. They are currently pursuing a diesel-electric submarine from China, but it does not have the capability to launch ballistic missiles [91]. To support troops on the ground, the Nigerian Air Force employs a series of fighter and close-air support aircraft. These aircraft are capable of dropping bombs on targets but are not capable of carrying a nuclear weapon. It is possible for them to utilize a cargo aircraft to drop a weapon, but there is no evidence to support this option. Currently, the only component of a delivery system Nigeria has is a guidance system which could be retrofitted from their other munitions. It is unlikely they are reverse engineering equipment from munitions to create new ones. For these reasons, a failure rate of 0.999 is assessed for Nigeria's strategic delivery systems. This does not mean they cannot create a nuclear device; it just means it is improbable they can create a nuclear weapon capable of attacking or deterring other countries.

Nigeria has a many munitions which could serve as a model for the non-fissile components of a nuclear weapon. Though they could use these components to initiate an explosion, it is assessed Nigeria lacks the expertise needed to simultaneously initiate an explosion and create a uniform shockwave need for an implosion weapon. It is possible they could create a gun-type using the materials they currently have, but they lack other resources needed to enhance the weapon yield. Nigeria is not currently using or developing a need for tritium and deuterium to improve the yield. Nor do they have a need for a neutron generator to initiate a chain reaction at a desired time. Failing to add these components as well as Li-6, reflector material, and the desired expertise causes the success rate for Nigeria's non-fissile material to be 1.0E-6. This is in line with current thinking that which Nigeria is not currently working to manufacture their own munitions because it is more cost effective to purchase them from other countries as they have down with all other military equipment.

Despite not needing material to boost a supercritical fission reaction, Nigeria still has a need for fissile material. They operate a 30-kW thermal power miniature neutron source reactor (MNSR) called the Nigeria Research Reactor (NIRR-1). Originally, this Chinese supplied reactor operated on 1 kg of 90% enriched HEU but was modified to use LEU in 2018 [92]. Nigeria is working with Russia to finance and build a 4000 MW nuclear power plant. There is not yet a timeline for this project apart from both countries have agreed to work together towards this goal [93]. Because there is not a significant quantity of enriched uranium in Nigeria, there are no IAEA safeguards for the material in the country. There are some uranium ore reserves in Nigeria, but there is no effort to mine and process this ore into usable material [94]. At this time, Nigeria does not have the resources or the desire to generate significant quantities of fissile material. This could change in the future once their nuclear power plants come online, but for now the failure of fissile material acquisition is calculated at 0.9741.

The success and failure rates were populated in an event tree to calculate the sequences for Each end state which is shown in Figure 32. The lack of resources and desire to build a nuclear weapons program means the no weapon end state has the greatest frequency of occurring. Followed by fissile material which could be used for their nuclear energy program once started. The lowest frequency is an implosion type nuclear weapons because of the complex nature of the weapon and the substantial resources required. This could change as Nigeria gains more stability and change their industrial complex. For now, evidence suggests there is no weapons program in Nigeria.

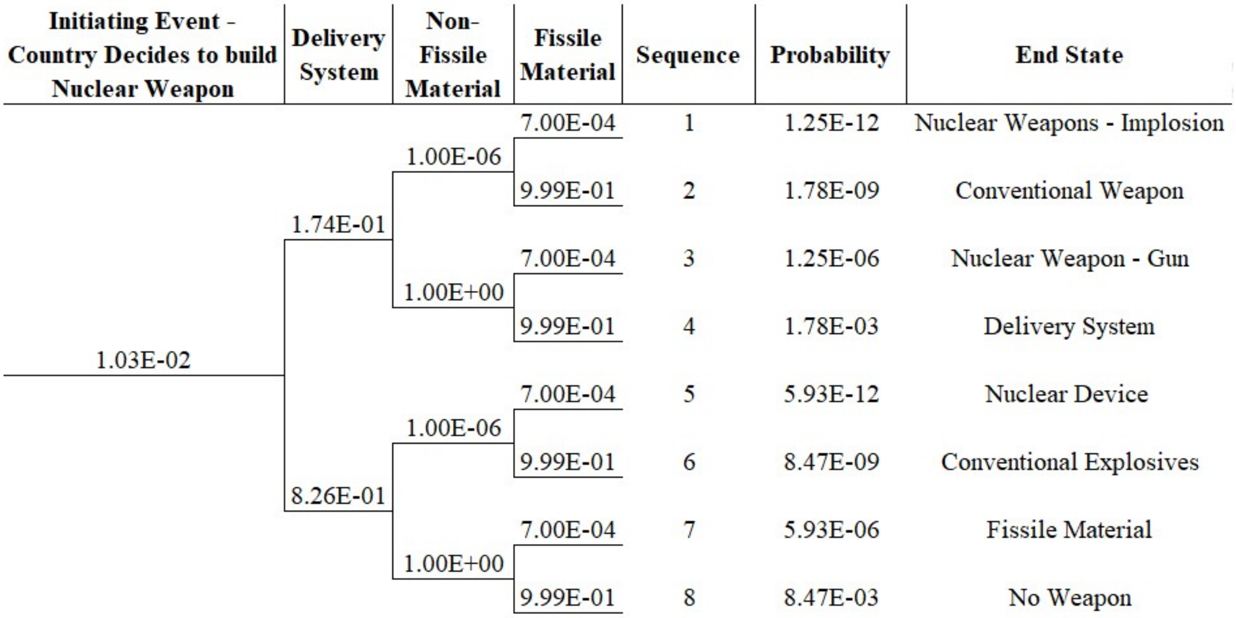


Figure 32. Event Tree for Nigeria Showing Little Probability of Nuclear Weapons Production

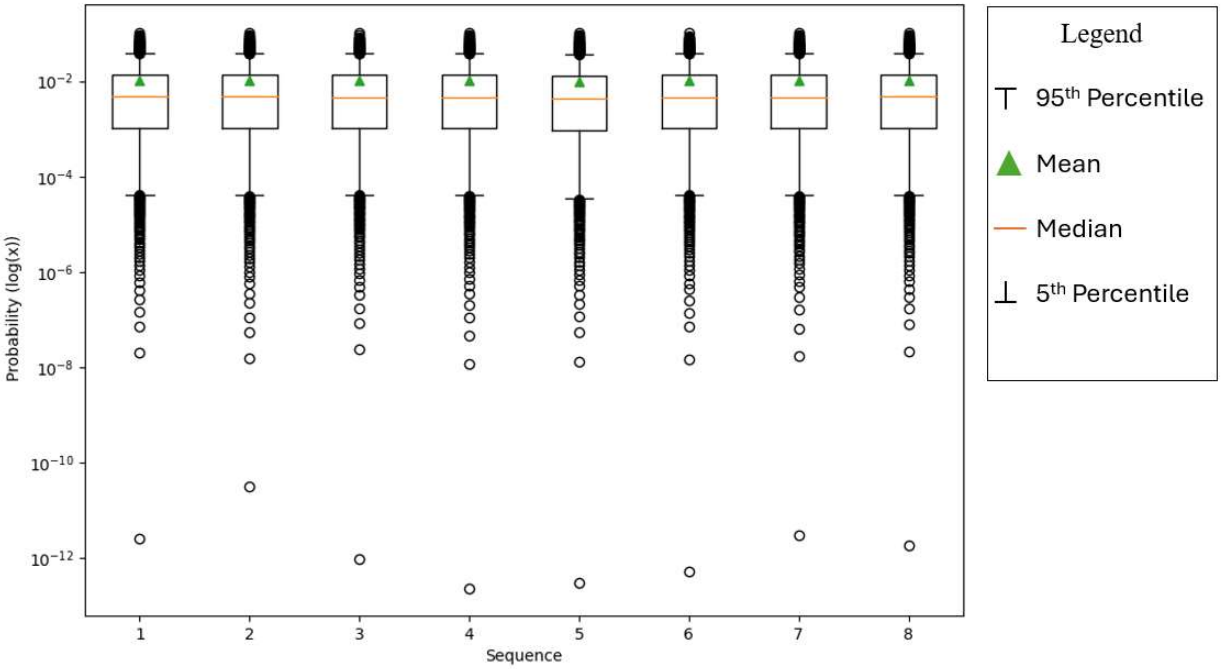


Figure 33. Uncertainty for Each Sequence in Nigeria Event Tree

4.3. Saudi Arabia

Saudi Arabia is in the middle of one of the geographically most turbulent areas in the world. It is hard for them to make extreme changes to their government without their neighbors viewing it as a threat. This becomes a challenge as they begin their major government reform called Vision 2030. This project seeks to boost Saudi Arabia's standing in the world and make them the greatest country in the Middle East [95]. Part of this new vision is to reduce their economy's reliance on the exports of oil and natural gas, which they are the world's leading supplier of [96]. Another pillar of their reformation is the increased reliability on renewable resources. As of now, this does not include nuclear because of Israel but this could change as time goes on. Though they lack peaceful nuclear capabilities now, they have the money and inexpensive manpower to quickly build nuclear power plants or purchase nuclear weapons. It is yet to be seen if they would do something like this, but they are increasing the range of their delivery systems.

Saudi Arabia's military is comprised of mostly European and US funded equipment, but they have been receiving help from China to develop their ballistic missile program. Their military is focused on defending their borders from other powers in the Middle East. In 2015, they deployed forces to Yemen for military intervention against the Iranian backed Huthis and tensions between the two groups have increased in 2024. Saudi Arabia's navy is focused on defending the Saudi territorial waters and trade routes around the country [96]. They do not currently have any submarines which gives them an SBLM failure rate of 1. Of the approximately 380 fighter aircraft in their Air Force, 81 of German supplied Tornado IDS multirole aircraft which are used by Germany to carry B61-Mod 3 and 4 nuclear bombs [97]. If Saudi Arabia, used a similarly designed bomb, then they could load it onto this aircraft. The greatest delivery system threat from Saudi Arabia comes from their manufacturing of ICBMs. In the 1980s, Saudi Arabia purchased dozens of liquid-fueled DF-3 missiles from China. More recently, they purchased and began manufacturing solid-fueled DF-21 from China [98]. Currently, it is assessed these missiles have been modified so they cannot hold nuclear warheads. These missiles can travel over 1000km carrying thousands of kilograms of explosives. Though it does not appear Saudi Arabia is working towards a nuclear program, they have the resources to hold more than just Israel and Iran at risk if they build nuclear warheads [99]. This creates a delivery system failure rate of .1401. A key indicator Saudi Arabia is looking to create a nuclear warhead is if they begin testing non-fissile components used to create an implosion.

Saudi Arabia has the financial capital to purchase anything they desire, including the technical expertise and material needed to create a nuclear armed ICBM. It is unknown if they have explored this option to the point of hiring or training scientists in simultaneous detonation and uniform shockwave development needed to create a nuclear explosion. This yields a failure rate of 0.875. Conversely, Saudi Arabia expertise with ICBM technology can directly translate to their ability to manufacture impurity free high explosives, detonators, SAFF, tamper, and reflector materials. There is no evidence to suggest they are producing the two key items for initiating and boosting nuclear detonations: neutron generator and tritium-deuterium gas transfer systems. It is possible they are purchasing these components instead of manufacturing them, but this information is not available through open-source literature. The high success rate of obtaining non-fissile materials coupled with the failure of obtaining nuclear explosives expertise yields a success rate of about 1.0. This means they could develop a nuclear weapon if they obtained the appropriate fissile material. Fortunately, Saudi Arabia has only threatened this to prevent Iran from finishing their nuclear weapons program.

Saudi Arabia currently has no power or research reactors and is not a signatory of the Additional Protocol. The Argentinian company Invap has built a 30kW reactor in Riyadh but it still does not have any fuel as Saudi Arabia continues to negotiate IAEA safeguard inspections. It is unknown when the fuel will be loaded, and the reactor will go critical. Part of their long-term strategy is for Saudi Arabia to create their own nuclear fuel cycle; powering and supplying their nuclear program with resources for their country. They have only taken steps to begin exploratory mining for uranium, which holds slightly over 1% of the world's reserves. Saudi Arabia does have five hot cells which they use for medical isotope research. This could be used for the PUREX process, but there is no indication they are being used for nefarious purposes because of the lack of spent fuel or irradiated thorium. With the current lack of fissile material resources, the failure rate to obtain fissile material is 1. Saudi Arabia does not appear to be working towards a nuclear weapon, but this could change as the regional politics change.

Their fissile material acquisition is likely to increase in the coming years to meet their Vision 2030 goals, but it is unclear how regional rivals Israel and Iran will react. Israel has purposely sabotaged and attack other nation’s nuclear infrastructure and could do so again. As of now, Saudi Arabia is working towards a peaceful nuclear solution, but it could become a weapons program if other Middle East States initiate their own programs. Currently, the results in Figure 34 show Saudi Arabia will continue to produce conventional weapons and explosives. This will change if and when Saudi Arabia completes their research reactor and begins their own fuel cycle.

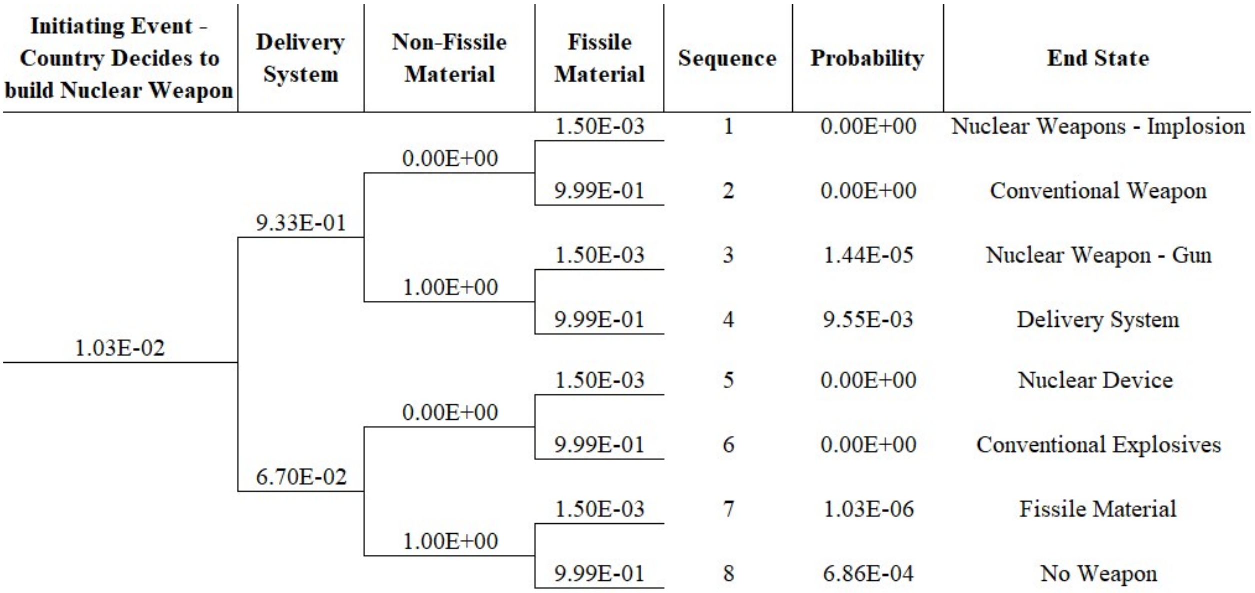


Figure 34. Event Tree for Saudi Arabia Showing High Probability of Conventional Weapon Production

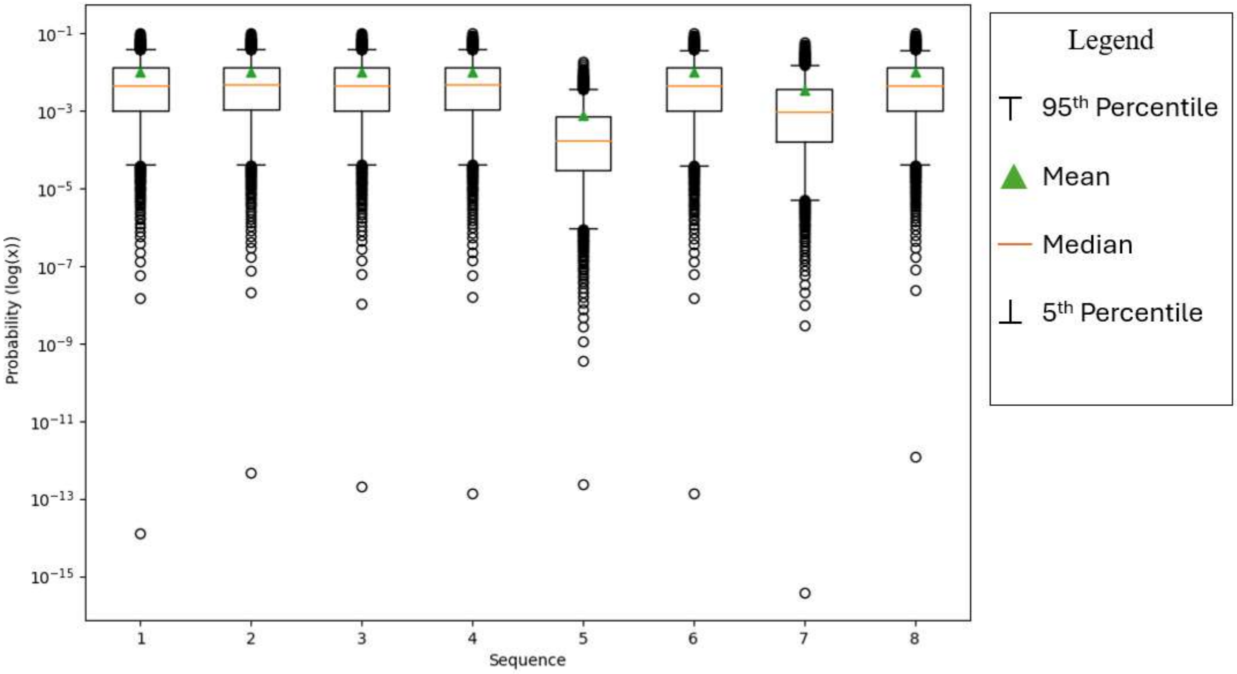


Figure 35. Uncertainty for Each Sequence in Saudi Arabia Event Tree

4.4. Japan

Japan is the most technologically advanced and has the highest GDP of the four countries being analyzed. Located on an island with little in the way of natural resources which can be used to create electricity, they built 12 nuclear power plants which can produce over 11 GW of electricity [100]. They are miles ahead of Nigeria, Saudi Arabia, and Pakistan in most categories, but they still have not built nuclear weapons. This is partly due to their history as the only country to have been targeted by nuclear weapons during war. They have seen the destruction and lived with the residual affects of nuclear weapons. They also have a strong alliance with the US which covers them under their nuclear umbrella. The relationship has strained in recent years as North Korea continues to demonstrate their military prowess and China advances in the East China Sea. This has led to Japan’s leadership to question if they should continue to support their non-nuclear stance. A change of leadership or treat to their homeland could cause them to rethink their stance on nuclear weapons. If they do, then they have the capability to create a physics package but lack the resources to hold other countries at risk with strategic delivery systems.

The greatest shortfall in Japan's potential nuclear weapons program is their lack of delivery systems. Currently, Japan does not have any ballistic missile capabilities. They are looking to change this shortfall with the purchase of 400 Tomahawk cruise missiles from the US. These missiles can be launched from surface or naval platforms and have a range of around 1,000 miles [101]. These cruise missiles can be armed with nuclear warheads, but it is unlikely any of these 400 missiles will be modified for this capability. Japan also maintains a fleet of 22 diesel electric and no nuclear-powered submarines. None of these diesel electric vessels can store or fire ballistic missiles. Lastly, Japan's Air Force maintains a fleet of Japan and US produced aircraft. None of these aircraft are designated as bombers with the closest coming in the form of multirole aircraft. None of these aircraft are known to be modified to carry nuclear weapons. This makes sense with the US' strong stance to defend Japan with their nuclear weapon. Because of their current lack of delivery systems, the failure rate is 1. Once Japan receives the cruise missiles from the US, the failure rate will drop to 0.079. Until then, Japan will not have a strategic nuclear weapon capability despite the ability to supply non-fissile material.

Japan has the third highest GDP in the world and ranks number 1 in educated population. With this prowess, it is assumed Japan has the explosives expertise needed to create a uniform shockwave which could compress a subcritical mass to a supercritical mass. Similarly, they have the knowledge to reverse engineer capabilities from the other weapons in their arsenal to produce SAFF components, multiple types of high explosives, and other non-fissile material. They do not have a need to large quantities of tritium or neutron generators such as polonium. Tritium is produced in nuclear reactors, but it can be difficult to remove such large quantities from the treated water which leaves the reactor. Tritium can be created by neutron interaction with Li-6, but there is little evidence to show Japan taking these steps. Japan also has little need for material which can produce neutrons during an explosion. They have three neutron scattering laboratories which they use for experimentation and do not show any intention to weaponize this capability. Lack of tritium and neutron generators does little to cause Japan to fail to acquire non-fissile material leading to a failure rate of 4.032E-9. As previously mentioned, Japan has a comprehensive fuel cycle and has the ability to create their own fissile material.

Japan is the only non-NWS to create their own closed-loop fuel cycle. Because of their lack of uranium deposits, they import refined uranium ore from Australia, Kazakhstan, and other countries into their fuel cycle. Japan has the ability to enrich some of their fuel at Rokkasho, but still imports the majority of their fuel [102]. Before the Fukushima-Daiichi accident, Japan also maintained some reprocessing capabilities. Now, France and the UK reprocess their spent nuclear fuel converting it into mixed-oxide fuel which can be used by several of the nuclear reactors. They are working to reclaim domestic enrichment and reprocessing capabilities with new facilities at Rokkasho, but these facilities have faced opposition and delay. This facility will hopefully be operational in 2024. Japan has taken steps to use thorium in molten salt reactors, but no such reactor was ever built. The failure rate associated with their current capability is 1.011E-4. They continue to advance their fuel cycle capabilities and could make small modifications from peaceful nuclear use to weapon production.

Japan attempted to develop a nuclear weapon prior to World War II but failed as laboratories and facilities were destroyed by bombing raids. After the war, Japan has held a strong anti-nuclear weapon stance and has called for global disarmament. Despite their stance, Japan has become one of the leading countries in nuclear research and uses nuclear energy meet some of their energy needs. They have most of the tools necessary to create a weapons program if there is ever a change in their political stance. With their lack of delivery systems, Figure 36 shows there is a 0.05 possibility they create a nuclear device and a 4.56E-6 to develop conventional weapons. They will not create a nuclear device without the ability to hold their regional rivals at risk. There is also no need to produce their own conventional weapons when they have demonstrated a desire to purchase such weapons from the US and other allies. As long as Japan is protected by US nuclear deterrence, there is no need for them to take steps towards developing more destructive capabilities such as nuclear weapons.

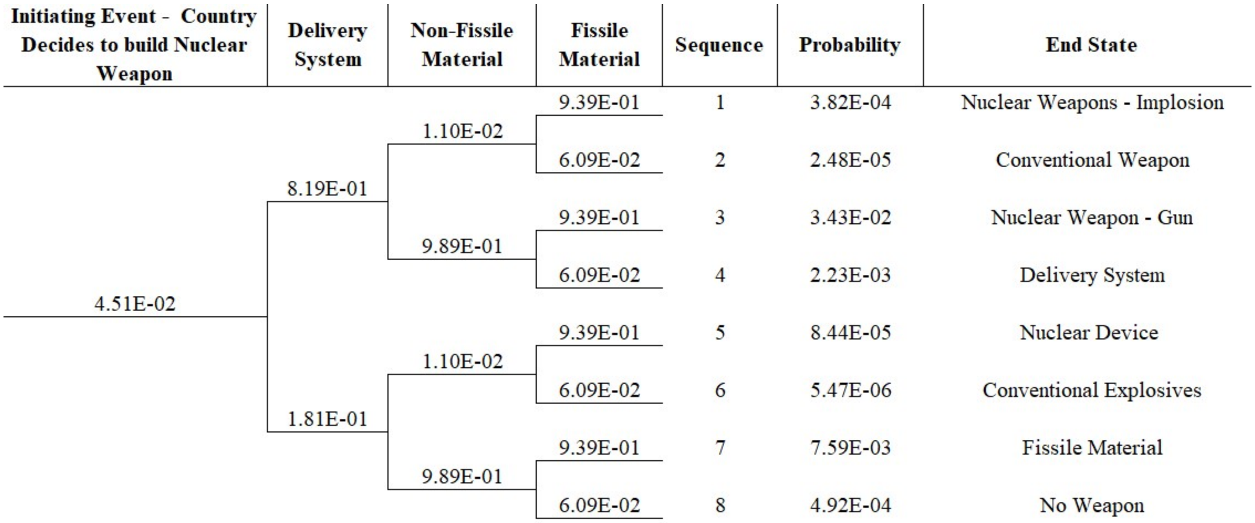


Figure 36. Japan Event Tree Showing Ability to Create Nuclear Device

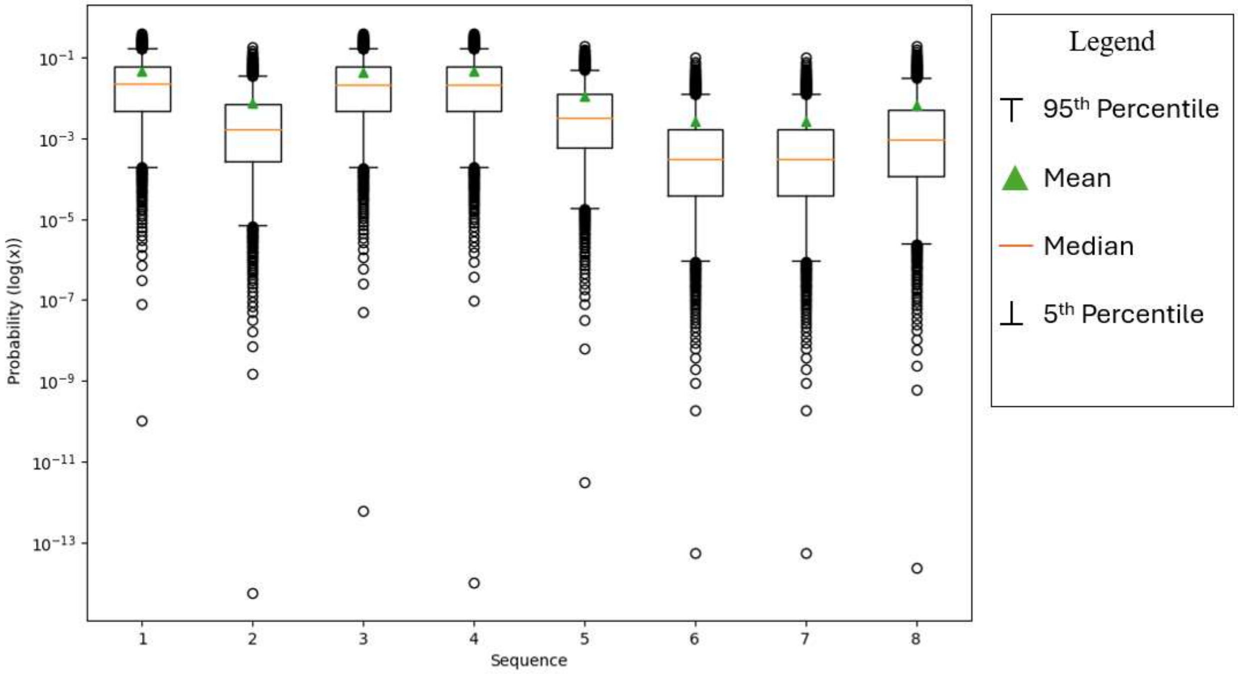


Figure 37. Uncertainty of Each Sequence in Event Tree

4.5. Pakistan

Pakistan is the most notorious nuclear weapon state to date. Their ability to build a nuclear program despite overwhelming odds from their regional military rivals, the new non-proliferation regime, and lack of domestic resources. Their program started under President Zulfikar Ali Bhutto who saw India's push for nuclear weapons as a direct threat to Pakistan's sovereignty since the two countries split in 1947. In 1965, President Bhutto proclaimed Pakistan would eat grass, leaves, or go hungry to build a nuclear weapon if India succeeded. India succeeded in 1974 and Pakistan escalated their efforts equalize their capabilities. Because Pakistan was successful in creating a nuclear weapons program, their case study is broken into two time periods: 1965 and 1990. The former is the start of Pakistan's nuclear ambition before they had any nuclear infrastructure. The latter is their first successful series of nuclear tests as they developed both uranium and plutonium pathways towards their weapons. The delineation between the results of the two time periods will demonstrate the model's ability to adapt to changing nuclear landscape for a country.

4.5.1. 1965

After China tested their first nuclear weapons in 1964, the US assumed India would follow because of their peaceful nuclear program and the recent clashes with China. Since US intelligence strongly believed India was moving towards a nuclear weapon, it can only be assumed Pakistan came to the same conclusions [103]. This led to President Bhutto declaring Pakistan would build a nuclear weapon at all costs. Unfortunately, Pakistan did not have any of the nuclear infrastructure India had. 1965 is when Bhutto rallied his leaders together to take the appropriate steps to match India. It took them decades to reach the same level of nuclear prowess.

In the early stages of Pakistan's program, they clashed with India over the disputed region of Kashmir. Pakistan's military equipment was largely procured from the US. This equipment primarily consisted of materiel used for conventional warfare, such as tanks, aircraft, and other armaments. Like their Army, Pakistan's Navy procured a series of vessels from the US and some from the UK. They attempted to procure a submarine, but the transaction fell through because of various internal and external political disputes. Interestingly, Pakistani scientists did train with the US National Aeronautics and Space Administration (NASA) resulting in the successful launch of a two-stage solid fuel rocket called the Rehbar-1 in 1962. This rocket was based off the unguided Nike-Cajun rocket used in the US at the time. Pakistan performed two more successful launches before 1964 for sub-orbital scientific experiments. They had no ability to weaponize these rockets at the time and their rocket program made little progress prior to 1981. The failure rate for Pakistan's delivery systems is 1because they lacked the aircraft, submarines, and their missiles were used for nothing more than for experiments.

Pakistan had little in the ways of non-fissile material which could be used to create a nuclear explosion. The only real material they had was explosives and SAFF mechanisms which they could use from their conventional weapons. Expertise, tamper material, and boosting gas would come later as Pakistan advanced their capabilities. At this period in history, Pakistan only has the capability to safe, arm, and detonate high explosives. This would not create any nuclear yield, so the failure rate is again 1.

As with most countries, Pakistan started their nuclear program without any infrastructure or a way to create a nuclear weapon. They needed to develop their nuclear expertise, build nuclear reactors for plutonium production, and create a pathway for uranium enrichment. Pakistan didn't even open their first uranium mine pilot plant until the 1970s [70, p. 313]. The failure rate of 1 for both non-fissile and fissile materials means Pakistan would never create a nuclear weapons program without strengthening these areas.

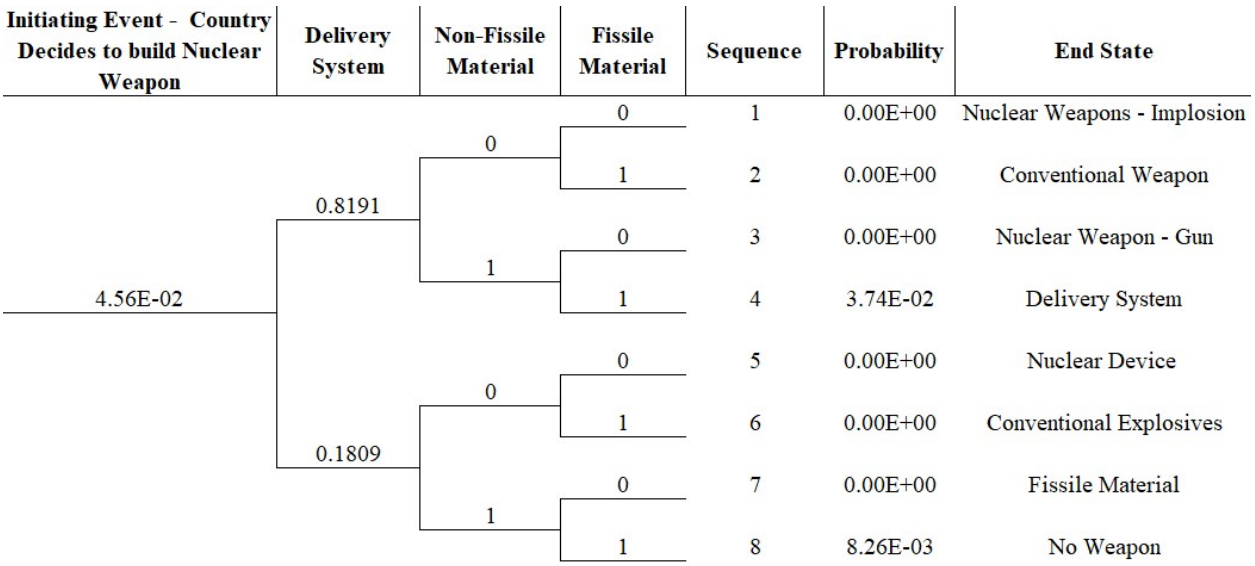


Figure 38. Event Tree For Pakistan in 1965 Showing High Probability of Pakistan Unsuccessful Development of Nuclear Weapon

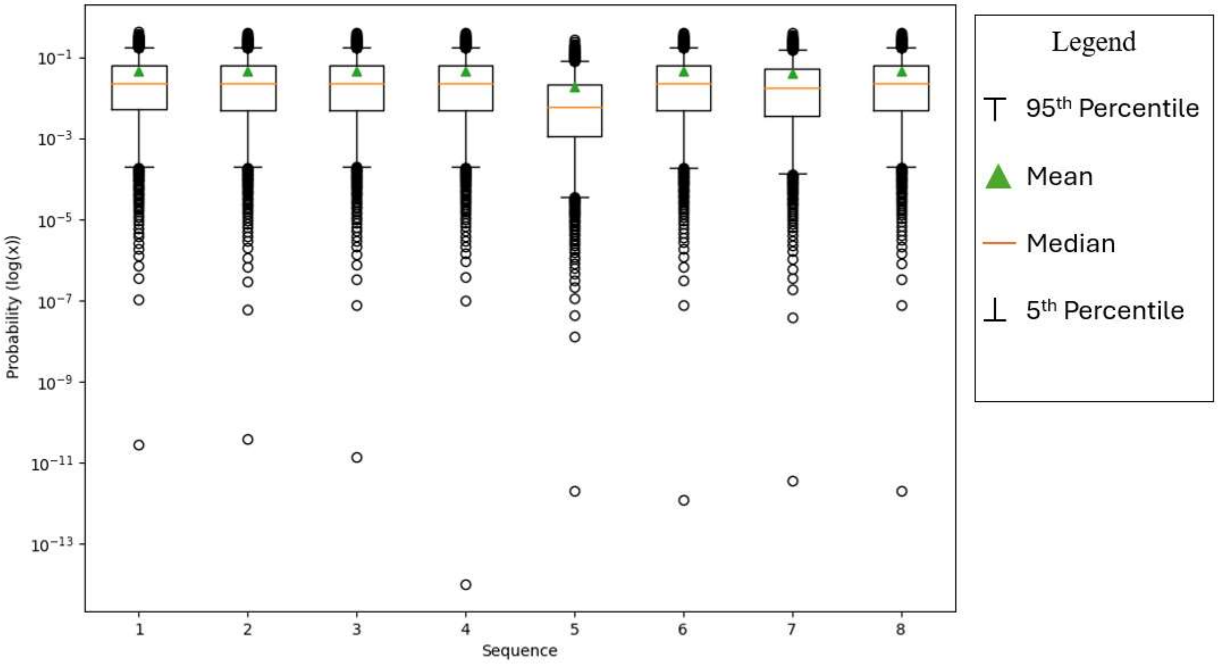


Figure 39. Uncertainty for Each Sequence of Event Tree

Looking at the evidence provided, Pakistan was not going to build their own weapons, let alone a nuclear weapon. They would need outside help from civilian nuclear programs, metallurgists, and other countries to be successful. Until they received this help, they would continue to procure weapons from the US or other suppliers to fight India and other regional rivals. Ultimately, this expertise and help would come culminating in the successful detonation of five nuclear weapons in 1998.

4.5.2. 1990

By 1990, Pakistan's dream of the first Islamic atomic bomb was coming to fruition. Their motivation for building a weapon had not changed since 1965 and now they have the infrastructure in place to create fissile material and hold regional rivals at risk with their own delivery systems. To overcome many of the afore mentioned hurdles, Pakistan received external assistance from countries like Saudi Arabia and China. The former provided hundreds of millions of dollars to fund their program. The latter provided technical expertise, such as reverse engineering, so Pakistan could avoid developing domestic products which would delay the process further. Abdul Qadeer Khan helped Pakistan navigate the nonproliferation regime by leveraging contacts to provide materials used for uranium enrichment which was not export controlled at the time [104]. This domestic and international assistance allowed Pakistan to build their atomic bomb.

Pakistan's delivery system program made leaps and bounds in the 1980s. They began to weaponize the sounding rockets they had developed with the assistance from NASA and France. These missiles were not accurate, but China aided increase accuracy, even offering their own ballistic missiles in exchange for access to western conventional and nuclear technology. This relationship flourished and Pakistan's solid and liquid fueled ballistic missiles became more accurate and their range increased [105]. North Korea would also trade ballistic missile technology for uranium enrichment expertise later. Pakistan has not now or ever had ballistic missile capable submarines, but they are currently building new submarines which could house eight ballistic missiles [106]. Pakistan's Air Force contains a mixture of aircraft from various nations such as the US, France, and China. In 1990, Pakistan purchased used Mirage aircraft from Australia and had F-16s from the US. Though both aircraft can be modified to accommodate nuclear bombs, the Mirage aircraft variants are the primary platform Pakistan would use [107]. With Pakistan having two of the triad of nuclear delivery systems, their failure rate in 1990 is assessed at 8.86E-3.

The weakest area in Pakistan's nuclear weapons program in the 1990s was their non-fissile component acquisition. China supplied them with the blueprints for a nuclear bomb in the 1980s and sent scientists to Pakistan to train their scientists. The blueprints, coupled with their scientists, helped Pakistan develop their explosives to create implosion devices [108]. Pakistan successfully cold tested several devices in the early 1980s and demonstrated they could create an implosion reaction by 1985 [109]. Open-source estimates claim Pakistan's ability to produce tritium is new and was not advanced in the 1990s. Pakistan's nuclear test used boosted weapons, but it is unclear what material was used. Kristensen et al. argues Pakistan should have more nuclear weapons if they had greater tritium production because it would reduce the fissile material needed [107]. It is possible Pakistan used a uranium deuteride (UD3) initiator for their designs because it was Iran is believed to have received from Pakistan [110]. The UD3 would serve as neutron generator. For this reason, the fault tree was modified to create a more accurate picture of what a 1990 nuclear device would look like in Pakistan. The neutron generator and lithium-6 deuteride branches were removed and replaced with "fail to obtain neutron initiator." With this adjusted fault tree, the failure rate is 1.6E-9.

Though it was stated Pakistan's nuclear program was started in 1965, others argue it didn't start until 1972 when they began to take steps towards an atomic bomb. It was more than a concept at that point, they began laying the foundation. Just like the Manhattan Project, Pakistan pursued both uranium enrichment and plutonium pathways. A.Q. Khan, nicknamed the father of Pakistan's bomb, ran the Khan Research Laboratories which headed the uranium enrichment pathway. Khan used the knowledge he gained from working at Urenco. He leveraged his global contacts to supply Pakistan with gaseous centrifuge equipment. China again played a major role by providing equipment, such as magnets, and highly enrichment uranium to Pakistan. His competition was the former chairman of Pakistan Atomic Energy Commission, Munir Khan. Munir Khan began Pakistan's plutonium production. He ran into severe roadblocks many plutonium reactors and reprocessing facilities were cancelled due to heavy pressure by the US. Their first heavy water, natural uranium reactor wouldn't be constructed until 1996 in the Khushab District. This reactor is completely indigenous and designed after the Karachi Nuclear Power Plant (KANUPP-1) which was supplied by Canada. Again, the fault tree can be modified to resemble the fissile material pathway they chose. For the purposes of this paper, only uranium enrichment via gaseous centrifuge cascades and plutonium reprocessing are considered for Pakistan's fissile material production. There is no evidence to support that Pakistan pursued Np237 or U-233 pathways. The results of this adjusted fault tree yield a failure rate of 1.563E-2. This would have been lower if Pakistan had completed their plutonium pathway by 1990.

Pakistan is one of the least likely countries to create a nuclear weapons program. They had to overcome economic, industrial, and political challenges to build and maintain a nuclear power plant. Peaceful nuclear practices were supposed to be rewarded, not prevented under Atoms for Peace. With the challenges they faced with peaceful nuclear energy, there is no way there should have advanced to nuclear weapons, but they did. They were successful because of their desire to maintain equality with their regional rival, India, at all costs. They fostered relationships with other countries to provide gain and expert assistance by trading or promising nuclear technology once successful. Though they didn't test their first nuclear weapon until 1998, they likely had some nuclear weapons by 1990 if not sooner. Their likelihood of achieving implosion type nuclear weapons is assessed at 4.45E-2. The only reason the likelihood is that low is the frequency of Pakistan starting a nuclear program is 4.56E-2 per year. In succeeding, Pakistan established themselves as a nuclear power despite a great power controlled nuclear proliferation regime.

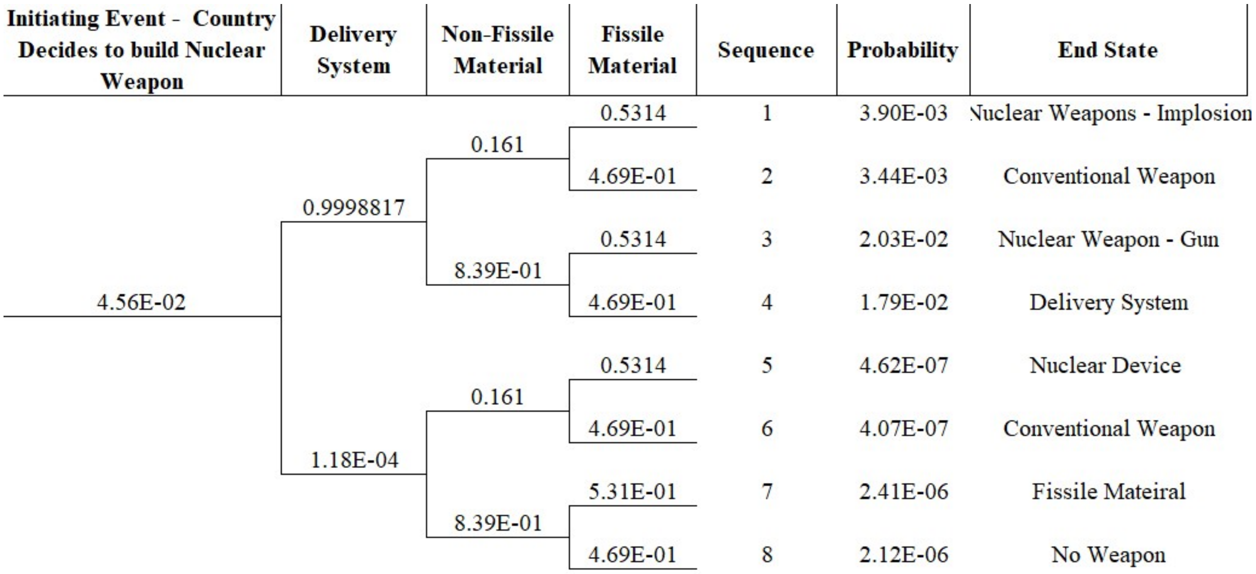


Figure 40. Event Tree Showing the Success of Pakistan's Nuclear Weapons Program After 25 Years

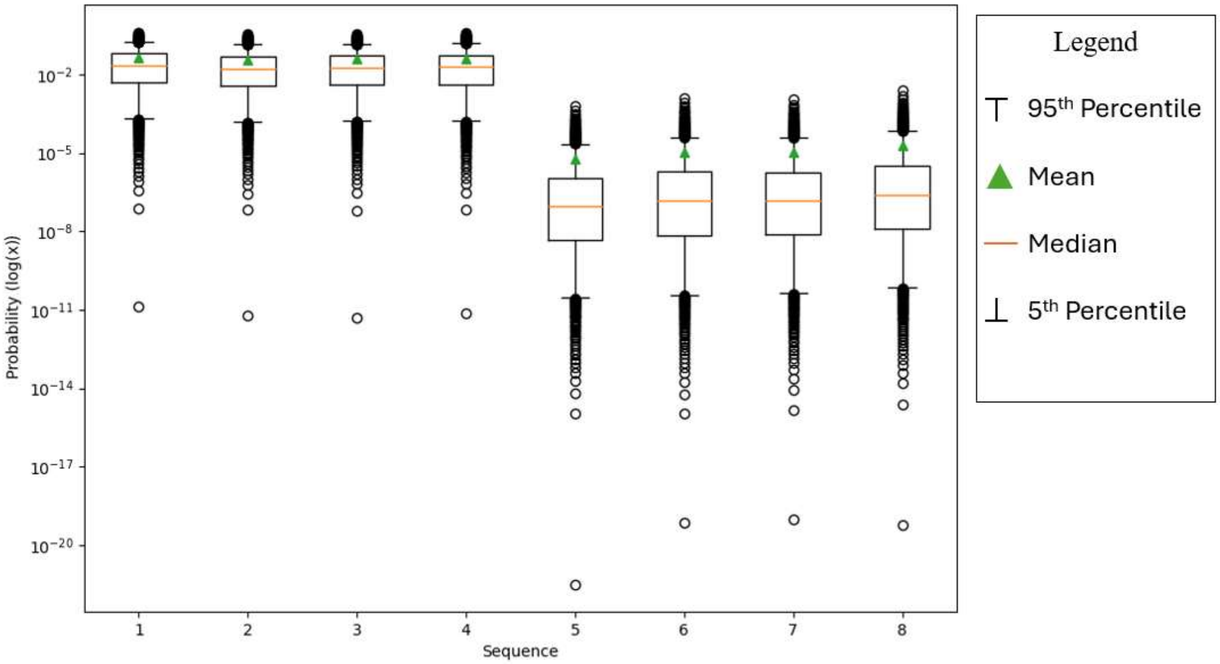


Figure 41. Uncertainty for Each Sequence in Pakistan 1990 Event Tree

CHAPTER 5. Discussion

The results of this paper demonstrate a basic analysis of Nigeria, Saudi Arabia, Japan, and Pakistan's nuclear programs at a point in time. This assessment will change as a country's political agenda, perceived threats, and technological advancements continue throughout time. The use of quantitative risk assessment for this paper is not and cannot be dynamic due to the large uncertainty of the political considerations in international relations. It will need constant updating from nonproliferation experts and country specific intelligence analysts to determine the success or failure of control mechanisms in the system. This method is not ideal because of the large uncertainty associated with human error, but it is better than the examples shown in Chapter 3 which attempt to use stochastic methods to predict when a country will develop a nuclear weapon. The strength of using QRA for this method is Bayesian updating which allows for changes based upon new information.

As expected, Nigeria and Saudi Arabia do not currently pose the capability to build a nuclear weapons program. Though both countries are considered wealthy compared to their respective regions, neither have the technical ability to achieve a weapon. Nigeria has no regional rivals which necessitate the need to pursue nuclear weapons. Similarly, they do not have domestic resources, such as stable electricity, to facilitate a program. Saudi Arabia has the financial resources to purchase any necessary equipment needed for a weapons program, though they will face challenges from export controls and the nonproliferation regime. They lack the technical knowledge to create a program because of their lack of nuclear facilities and infrastructure. Like Nigeria, their regional rivals, except Israel, do not have nuclear weapons which challenge them. Israel has nuclear weapons but is likely not to use them against Saudi Arabia at this time. Saudi

Arabia's decision to remain free of nuclear weapons could change if regional security threats change. An example of this would be Iran completing their bomb program.

The results of Japan and Pakistan's assessment demonstrated both programs could develop nuclear weapons for the time periods chosen. Japan is the most known example of nuclear latency and has all domestic infrastructure and resources to have a weapons program. This would increase as they restart their enrichment and reprocessing efforts and receive cruise missiles from the US. Adding delivery systems which can hold rival states at risk is missing element for Japan's strategic nuclear program.

A surprising response from the data shows Japan as having a higher-than-expected failure probability for their non-fissile weapons components. This is a failure in CAFTA. It uses the rare event approximation which removes intersection events when quantifying the OR gate and adds the basic events together. This results in probabilities greater than 1 which is not possible. This was checked with PRA software tools resulting in similar probability calculations. Pakistan is known to possess nuclear weapons so two time periods prior to their test date in 1998 were chosen for this assessment. When President Bhutto made the decision for a nuclear Pakistan in 1965, it seemed completely unlikely. The assessment showed they could indigenously create no weapon but to failures in every category. This changed in the years prior to 1990 when Pakistan developed uranium enrichment methods and began working on plutonium production. This effort was facilitated by assistance from other countries such as China, North Korea, and Saudi Arabia. By 1990, the assessment tool estimates Pakistan had a nuclear weapon capable of attacking India if desired. This wasn't confirmed until 1998.

The proposed method is a demonstrates how a country's non-proliferation system can be assessed as changes to the system occur. Though this is dynamic in nature, it is not possible to create dynamic event trees for this problem because of the human element associated with it. Dynamic QRA analyses the driving forces of a system and the reaction of these forces over time. The system is considered deterministic and transient [111]. The psychology surrounding the reactions of government leaders to setbacks in their nuclear aspirations is difficult to quantify. Perceived reactions could be estimated, but this would not give accurate answers. An example of this is shown in Israel's attack on Osirak, Iraq in 1981. The effectiveness of this attack is still debated by many scholars, but it did force Iraq to make a greater effort to conceal their uranium enrichment program. So much so, the US and the rest of the world had little knowledge of Iraq's nuclear weapons program until the two invasions by the US. Israel's decision to attack, slowed Iraq's nuclear weapons development, but the political fallout surrounding the attack made it a poor choice.

Using QRA as a tool to view a country's proliferation network is similar to the research done by Tang. This assessment explores what steps can be taken to inhibit a weapons program by outlining the methods a country would take then developing steps to prevent those methods. This paper uses some of the variables from Li et. al and the Singh and Way papers. Those variables are essential for analyzing a country's nuclear weapons program. This method does vary from those papers because it is not used to predict when a country should have a weapon. As previously discussed, it is impossible to know at what point in a time a country will have a nuclear weapon because of the many political factors and nonproliferation regime. An example of this is their analysis on Pakistan which showed they would never create a nuclear weapon. The research did not take foreign assistance into account which is what resulted in Pakistan's success.

The results of the event trees shown for each case study and the mean for each uncertainty quantification are different because of the way CAFTA calculates the results. To build the event tree, each top event was quantified individually and inputted into the excel file. These results were propagated across resulting in the final sequence probability. This is different from the mean values generated using the UNCERT tool of CAFTA because CAFTA is using rare event estimation. Rare event estimation assigns a 0 to any probability intersection in the OR gate quantification. It only adds the primary probabilities together and negates everything else. This leads to larger probabilities than anticipated. These values were checked with other PRA tools and those generated similar results. CAFTA also assigns a 1 to the success branches of the event tree when it quantifies the end states. This results in the top end state equaling the initiating event in sequence 1 and causes differences in the remaining sequences. However, Nigeria's event tree sequences were all calculated to equal the initiating event because of the large failure rates associated with each top event. Though there is a discrepancy, the probabilities were correctly captured in the excel histograms above. The greatest issue with the data is the uncertainty associated with each assigned value.

In its current form, this research suffers from limitations in the data. The data collected is based on the interpretations of one person and not the collective of a group of experts. Each variable should be understood by all readers, but it is possible this will change because of the subjective views of the person doing the analysis. The initiating events analysis suffers from the addition of psychological aspects of decision making based on either a political leader or a state's government. It is difficult to ascertain what these people would really do because analysis can only be done on what they say to the public. Public speeches do not necessarily equate to the discussions made behind closed doors. This paper was written without access to that material. Similarly, this paper did not have access to more technical equipment needed to create fissile material. This data is heavily classified, and variables were chosen based upon open-source information as being key to the process. This is why there is little information for producing significant quantities of Np-237. The high uncertainty associated with the assigned probabilities to each basic event is modeled using beta constrained noninformative distribution. Some values are known, like lack of nuclear capable submarines for all four countries, but others are estimated based on available data. This is the reason for assigning a value of 0.5 for the alpha parameter in the model. This value would decrease as more intelligence is collected to determine a better probability using Bayesian updating.

The proposed model successfully demonstrates a tool which can be used to analyze a country's nuclear weapons program. The results of this risk assessment show the current status, or previous status in the case of Pakistan, of the nuclear latency for each country in the case studies. This model combines both aspects of supply and demand of proliferation material in a quantitative way. This is important for decision makers to use when selecting the appropriate actions to take to counter adversarial efforts. The difficulty associated with using qualitative information alone for decision making is challenging. This method mitigates this problem and provides quantitative date which can be tracked throughout time.

CHAPTER 6. Conclusion

Quantitative risk assessment offers a unique way to both qualitatively and quantitatively analyze the risks associated with proliferation of nuclear material by a non-Nuclear Weapon States. Developing a qualitative outline allows the user to see how the country is investing in nuclear research and technology towards peaceful or military applications. The quantitative aspect shows how a country is progressing towards a nuclear weapon and evaluates the speed they are getting there. The speed is calculated by assessing the rate of change over time as the program is continuously reevaluated at some time interval. This shows if any external influences are having a positive or negative affect. Access to classified research and future work to analyze other WMD programs will continue to make this method more well-rounded. Doing so will better either state or agency intelligence to examine a country's program to make the best decision for how to respond to this emerging threat.

Though the method was demonstrated to show how the reassessment aspect can be used when looking at Pakistan and Japan, it is limited by open-source information. The data used for this evaluation is based on interpretation of facts surrounding each portion of a country's nuclear weapon program at a set point in time. It was limited to the information available to the public. More specific information or analysis is classified and could not be accessed for this paper. Having access to more classified data would help to develop better fault trees by increasing the amount of material for each gate. Gaseous centrifuges are more complex than the seven highlighted items show. Access to classified material will create more robust systems which in turn will yield better results. Improved analysis from country specific experts would reduce the uncertainty of this process, yielding better results. As mentioned, expert judgement can be skewed, but it is more accurate than what this author is capable of because of various nuances in global power dynamics.

The military can apply this as they examine threats across all domains in the geographically aligned commands by determining how close a country is to successfully starting or completing a program. This is based on changes in external posture to regional actors and changes in democratic practices such as trade. The application for this tool is vast and can apply to more areas as future research is conducted.

Future research is needed to develop risk assessments for the other types of weapons of mass destruction and for non-state actors acquiring these weapons. Developing fault trees for these two categories would allow authorities to better defend themselves transporting nuclear weapons or identifying future threats against the United States. Examining how non-state actors acquire nuclear weapons leads to better security measures being emplaced by states who do not secure their stockpile as well as the US. Developing fault trees for chemical, biological, radiological, or cyber threats will be challenging because there are so many possibilities, and many can be done at a small scale which are difficult to detect. Access to those materials is widely available and restriction only occurs on industrial scale equipment. Further advancing these risk assessments is a way to take preventative measures against future threats.

Future work should also be undertaken to examine the effects of retaliatory action on a weapons program. The Israeli attack on the Iraq Osirak nuclear reactor in the 1980s demonstrates the need for a model on risk in decision making. The Osirak reactor was still being built and not a viable option for weapons grade plutonium production for the weapons program. Israel took it upon themselves to launch a strike against Iraq, with hopes of facing no international backlash. Israel suffered major criticism from many nations, but faced no retaliation or reprimand. Using QRA to analyze the possible responses, such as sanctions, military response, etc., will yield to better decision making in the future. Humans naturally perform decision matrices like this already, but having a form which measures the success or failure of such responses in terms of human error could yield more informed actions.

Quantitative risk assessments can be used to evaluate a country's nuclear programs to determine if illicit practices are taking place. By examining each of the three parts of a nuclear weapon as a supply system, one can determine if a country is hedging or pursuing this technology and what method they are using. More research and analysis must be done to examine if international safeguards are the leading cause of deterring proliferation efforts or if it is global stability. Either way, QRA provides a framework to analyze these efforts for better decision making to maintain global stability.

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