Increasing Proliferation Resistance of Sodium Fast Reactor Fuel Cycle Through Use of a Nuclear Resonance Fluorescence Detector

by

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ABSTRACT

The proliferation resistance of a reprocessing facility can be improved by using a novel detection system that utilizes the nuclear resonance fluorescence (NRF) phenomenon to determine the isotopic composition of materials flowing through the plant. In an aqueous reprocessing facility, the waste stream was identified as a weak point for proliferation resistance. By identifying the isotopic composition of the waste stream and monitoring levels of plutonium and uranium, greater accountancy can be maintained. After the detection system was designed, a probabilistic risk assessment method was used to evaluate the added proliferation resistance afforded by the NRF detection system and the overall proliferation resistance of the reprocessing facility to a diversion of a small quantity of material from the waste stream by two individuals. The overall probability of success for a proliferator to divert materials from a reprocessing facility utilizing an NRF detection system is $8.73*10^{-5}$. This is a decrease, from $3.39*10^{-4}$, over the probability of success for the proliferator if the NRF detection system is not present. This decrease in proliferator success probability demonstrates and increased proliferation resistance of the reprocessing facility. The NRF detection system is shown to increase the proliferation resistance of the reprocessing facility.

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Introduction

In twenty years the world demand for electricity will be twice as great as the demand in 2000. To meet the increased demand, it must look to alternative forms of energy production ranging from renewables like wind or solar, to base load producers like nuclear power. For nuclear power to play a larger role in energy production, new reactors must be built. Reprocessing facilities must be built to provide a steady supply of nuclear fuel to these reactors. As nuclear power is extended to developing countries, great care must be taken to ensure the proper use of nuclear technologies and materials. The proliferation of nuclear materials has the potential to have dire consequences if placed in the wrong hands. While security measures exist currently to reduce the likelihood of proliferation, improvements can be made to bolster resistance. A nuclear resonance fluorescence (NRF) detection system has the potential to measure the isotopic composition of nuclear material to provide better material accountancy and in turn, to increase the proliferation resistance at a nuclear facility. A probabilistic approach will provide the basis for quantitatively determining the proliferation resistance of a facility which will identify weak security areas that must be strengthened[1].

One type of reactor that may be used in the future is the sodium fast reactor (SFR). These reactors have the potential to close the nuclear fuel cycle and in so doing, decrease the amount of uranium that is required to be extracted from the earth. SFRs can be used to produce energy while also burning excess transuranics that are produced during regular power production. These two attributes combine to make SFRs a very attractive option in the future. One component of the SFR fuel cycle is the reprocessing facility where spent fuel is reprocessed to be fabricated back into fuel. While the reprocessing facility plays a pivotal role in the fuel cycle, it is also a critical point in the cycle where proliferation can occur. In the reprocessing facility, the spent fuel is separated into three main streams: uranium, plutonium, and the transuranics. This is necessary to allow for fuel fabrication, but it also provides an attractive material for agents who would attempt to proliferate. It is during this phase of the fuel cycle that extra attention must be devoted to ensure that proliferation does not occur. The NRF detection system can provide this extra accountancy.

Nuclear resonance fluorescence describes the phenomenon that occurs in a nucleus when a photon with a specific energy is absorbed by a nucleus. When the photon is absorbed, a second, resonance photon is emitted with an energy slightly lower than the incident photon. If these resonance photons are measured, the composition of a material can be determined by using known resonance energies for various isotopes. Using NRF technology, it is possible to design a detection device that can be used within nuclear power plants and reprocessing facilities to add additional monitoring activities within the facility. An NRF detector can reduce the time to adequately test the composition of materials moving through the facility. Current methods to determine the composition of nuclear materials require chemical testing that can take weeks to complete. The NRF detector has the potential to do the same testing in a matter of minutes.

While an NRF detector appears to improve the proliferation resistance of a reprocessing facility by monitoring the streams of nuclear material as it passes through the facility, the true resistance added by the detection system can be measured quantitatively by using a probabilistic approach. Adopting methods from probabilistic risk analysis, an event tree can be made that identifies the tactics that a proliferator would use in acquiring material, and tracks his use of those tactics against a second actor, the safeguarder. This competition based model can then be populated with probabilities to reflect each action's likelihood of success. Finally, using success tree logic, the overall probability of a successful proliferation attempt can be calculated to determine the overall proliferation resistance of the reprocessing facility.

By integrating the NRF detector into the success tree, the added proliferation resistance provided by the detector can be determined in addition to the total proliferation resistance of the reprocessing facility. This information can be used to improve security in specific areas of the facility and can help provide information to regulators and inspectors like the IAEA to assist in making regulations for developing countries who seek to use nuclear power.

The Sodium Fast Reactor and Aqueous Reprocessing Facility

Sodium Fast Reactors (SFR) have the ability to close the nuclear fuel cycle. A SFR uses a fast neutron flux to burn off transuranics (TrU) and reuse the spent uranium that comes from light water reactors (LWR)[2]. The spent fuel from an SFR can then be reprocessed and used over again, increasing the efficiency of the entire cycle. One disadvantage inherent with the SFR is the creation and separation of plutonium. Fast reactors can easily be converted from burner reactors to breeder reactors which will increase the amount of nuclear material in the world stockpile[2]. This occurring at the reactor itself isn't necessarily an issue because a proliferator must still get the weapons usable material (WUM) out of the reactor. Weapons usable material consists of any material that can be used to produce a nuclear weapon. The primary WUM of concern is plutonium. Diverting WUM from a reactor provides a major challenge due to the nature of the material. At the reactor, the fuel is kept in fuel assemblies which are difficult to divert due to the size and radioactivity of each assembly. Once spent however, fuel assemblies are transported to a reprocessing facility where the fuel is separated into aqueous streams to allow for new fuel fabrication. It is in this section of the fuel cycle that the risk of proliferation is the greatest.

In an aqueous reprocessing facility (ARF), spent fuel is sent through an aqueous solvent process that separates the fuel into four components: uranium, plutonium and other minor actinides, and fission products[2]. This separation represents a potential proliferation weakness for the SFR fuel cycle. Whereas the SNM was in large, cumbersome fuel assemblies in the SFR, fuel in a reprocessing facility is separated into an aqueous stream that is easier for a proliferator to handle. Additionally, a single diversion in a SFR results in stealing an entire assembly, a diversion attempt in a reprocessing facility could result in as little as a few grams of plutonium being taken. This small amount is more difficult to recognize by standard accountancy measures. The nature of the material being diverted and the amount of material that can be diverted necessitates a new accountancy method that is able to recognize even slight fluctuations in the material passing through the facility's sub-systems. While diverting five grams of plutonium isn't enough to create a weapon, the success rate for that type of diversion makes it an area of weakness. Many diversion attempts can be made that will result in a significant quantity (SQ) of material that is required to produce a bomb.

The ARF has a number of distinct sections that each represents a material balance area (MBA) in which material entering the area can be compared with material exiting the area to ensure accountancy[3]. The primary area of interest is the waste stream. In a reprocessing plant, the fuel is separated into the streams that are very attractive to a proliferator. Ensuring that the same amount of material that is coming into the plant is also leaving the plant will ensure that the reprocessing facility isn't be operated in a way to steal materials, and will also protect the facility from an individual that attempts to divert a small quantity.

There currently exist a number of safeguards, or defenses against proliferation, that provide resistance against diversion attempts. Surveillance and portal control are two standard methods of providing proliferation resistance on the short term scale. In general, the feedback for these systems is immediate. If someone is caught on camera moving through an area that they are not allowed in, the alarms are raised immediately. Beyond this, there are no consistent security measures that can provide immediate protection against a diversion attempt. In the longer term, there are additional security measures that can ensure operations are running normally. Sampling and comparing can be done to inspect the material leaving the plant. In this process, samples are taken and compared to the results given via burn-up code simulations. This has been done in the past but can take weeks or more to complete. Further this type of analysis destroys the material. In the event that a proliferator is diverting small quantities on a regular basis, this type of accountancy will potentially detect the diversion attempt. For attempts that involve the diversion of a larger quantity of material, this type of measure may detect the diversion but may do so too late to have any positive effect. Finally, there are other systems in place, like satellite surveillance and International Atomic Energy Agency (IAEA) inspections that can also detect anomalies in facility operations. While these security systems have appeared to provide adequate protection against proliferation, as the nuclear industry changes, and experiences the need to move to fuel cycles like the SFR fuel cycle, additional systems will be necessary to ensure nuclear accountancy. Nuclear resonance fluorescence has the ability to provide the additional proliferation resistance to meet this demand.

Forms of Proliferation

Nuclear proliferation can be carried out by a variety of agents, and encompasses a variety of strategies. There are two primary forms that a proliferator, an agent attempting to divert nuclear materials, can take. Firstly, a proliferator can be an individual or group acting on their own accord. In this case, a proliferation attempt could involve only one person, but could also involve a group of individuals attempting to divert. This scenario implies that the proliferator will have fewer resources than the second form of actor. The second form that a proliferator can take is that of the state. In this scenario, a country is attempting to build up its nuclear program and does so by stealing nuclear materials. It is assumed that the state has more resources than an individual but this may not always be the case. When the state is attempting to proliferate, the entire facility may be working to divert materials. Even in this case, the state must hide its actions from international agencies like the IAEA. Additionally, if a state is attempting to create a nuclear weapon, additional steps aside from diverting materials must be taken. A clandestine facility must be built, tested, and operated to modify WUM and to build a bomb. While it may seem a state actor is more able to divert materials, it is also difficult to hide a clandestine facility. This provides safeguarders, people attempting to protect the WUM, with further opportunities to catch the state.

Proliferators have two ways of obtaining WUM. The first method of obtaining WUM is through a diversion of material. In this scenario, an actor, state or individual, attempts to steal materials by entering a location and leaving with WUM. This scenario assumes that the proliferator takes materials in a way that does not raise the alarm. In this scenario, a proliferator can take any amount of material. An individual could sneak into a section of the reprocessing facility and take a small quantity of Pu, or alternatively, a group could fool cameras, and steal an entire fuel assembly from a storage rack within the reactor. During the diversion of these materials, the proliferator must not be detected for it to be "successful." To evade detection, he will have to evade security cameras, and other detection systems. While the overall goal of a proliferator is to steal a significant quantity (SQ) of WUM, this goal could be met in any number of diversion attempts. An extension of proliferation via the diversion method is the act of misusing a facility. A proliferator may have the ability to misuse a facility in a way that helps them obtain more WUM. For example, fuel assemblies and blanket assemblies could be swapped in a way that produces more plutonium. The reprocessing facility could be altered in a way that modifies the chemical process for separating materials to be less efficient. The waste could then be used to extract extra Pu. The bottom line with the misuse scenario is that it does not result in the proliferator actually getting material. The proliferator must still divert material to actually obtain it.

An alternative to the diversion scenario is the abrogation scenario. In the abrogation scenario, a state announces that it will no longer follow the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). By doing this, a state is admitting to attempting to create nuclear weapons, but if it is far enough along in the process that it is testing, there is little that the world can do to stop the process. This is one of the hardest scenarios to protect against. The main strategies of a state attempting to abrogate is to amass a stockpile of material (can be spent fuel) and to build a clandestine reprocessing facility. A misuse strategy could also be used in this scenario. Changing core characteristics could create a stockpile that has more Pu than would be expected. This means the state can abrogate earlier than anticipated.

Nuclear Resonance Fluorescence

Nuclear resonance fluorescence (NRF) is a phenomenon that describes the process that nuclei go through when interrogated by photons of very specific energies. Just like atoms and compounds, nuclei also fluoresce when they have been excited by photons[4]. Regularly monitored photon absorption processes govern absorption in the majority of energies, but each isotope absorbs photons at an increased rate within specific energies. Normally the photoelectric, Compton, and pair production cross-sections dominate absorption of photons. At the resonance energy however, NRF dominates absorption processes. When a resonance photon is absorbed by the nucleus, a corresponding fluoresced photon is emitted at an energy that is slightly lower than the resonance energy. It is through these emitted, characteristic photons that the isotopic composition of a material can be determined. The isotopic composition of the fuel could be compared with the expected composition found via burn-up simulations. Any variation would raise an alarm, and it would do so in real time.

Detectors have been created using the NRF technology to identify hazardous materials in sea ports and airports[5]. Extending this detection system to a reprocessing facility creates difficulties due to the nature of the materials being detected and the environment in which the detection is taking place. Professor Bertozzi created a detection system to be used at sea ports to investigate cargo containers. The application of NRF to detect the isotopic composition of nuclear material is fundamentally different. One main difference is the knowledge of the material being scanned[5]. In the cargo application, the composition of the cargo container is not known. Fortunately, the content of the material being scanned in the reprocessing facility is known. The material is expected to have a certain isotopic composition based on the burning profiles of the plant and the fuel that was initially put into the core. Another difference between the two applications is the nature of the sample itself. In the cargo application, it is expected that cargo containers will contain mostly low Z material. In the reprocessing facility, the detection system will be inspecting primarily high Z materials and potentially fission products which can be considered medium Z materials. This will affect the amount of time necessary to obtain an accurate measurement. The final main difference has to do with the environment of the scan being done. In the cargo application, the sample will be in air and it is expected that there is no radiation. In the reprocessing facility, the operating atmosphere could be air, argon, or inert gas. There is also a high level of background radiation.

Due to the differences between the cargo application and the reprocessing facility application, modifications to the cargo detection system are necessary to create an effective detection system in an ARF. The background radiation has a large effect on the detection system. In the cargo application, back scattering NRF photons are detected and measured. In the reprocessing facility however, these photons would be masked by the large background radiation. This has pushed the detector to utilize the transmission method for measuring isotopic composition. In the transmission method, photons are interrogated on the sample[5]. The photons in beam that are in the NRF energies are more absorbed than the other photons. All photons will experience some absorption, but as previously stated, a greater number of photons will be absorbed in the resonance ranges of the isotopes in the sample. This will leave holes in the beam of photons that passes through the material[5]. If a rough composition of the sample is known (as in the case of the reprocessing facility), the same material can be placed in the beam behind the material being sampled. When the beam hits this reference scatterer, there will be back scattered photons in the resonance energies. By using this method, it is possible to negate the large background radiation from the sample, and focus on a few key isotopes. Without the transmission method, the detectors would be overwhelmed and render the detection system useless.

Experiment for NRF Detection System

An initial design has been created for the detection system that utilizes the NRF transmission method. This design is based on the design by Bertozzi, and is currently being tested by Bertozzi at Passport Systems[4]. There are five main components in the detector. The accelerator produces a constant stream of 8MeV photons so that photons are above all of the resonance energies of the sample. This beam then hits a metal target that emits photons via bremsstahlung. The resulting beam of photons is collimated into a narrow beam that passes through the sample and then through another collimator. This second collimator not only collimates the beam, but also provides space to properly shield the detectors from background radiation. Finally the beam hits the reference scatterer and then back-scatters photons into the detectors. This detection system is able to work because, unlike the cargo application, the composition of the sample is known. Any variation from the expected values is a sign that clandestine strategies are being used.

Every place in the detection system's photon beam has a specific shape. Knowing the geometry of the detection system and the characteristics of the fuel makes it possible to calculate the characteristics of the photons at every point in the detection system. What follows is a step-by-step walkthrough of the detection system and the characteristics of the photon beam at each location. Figure 1 shows the experimental setup of the NRF detector.

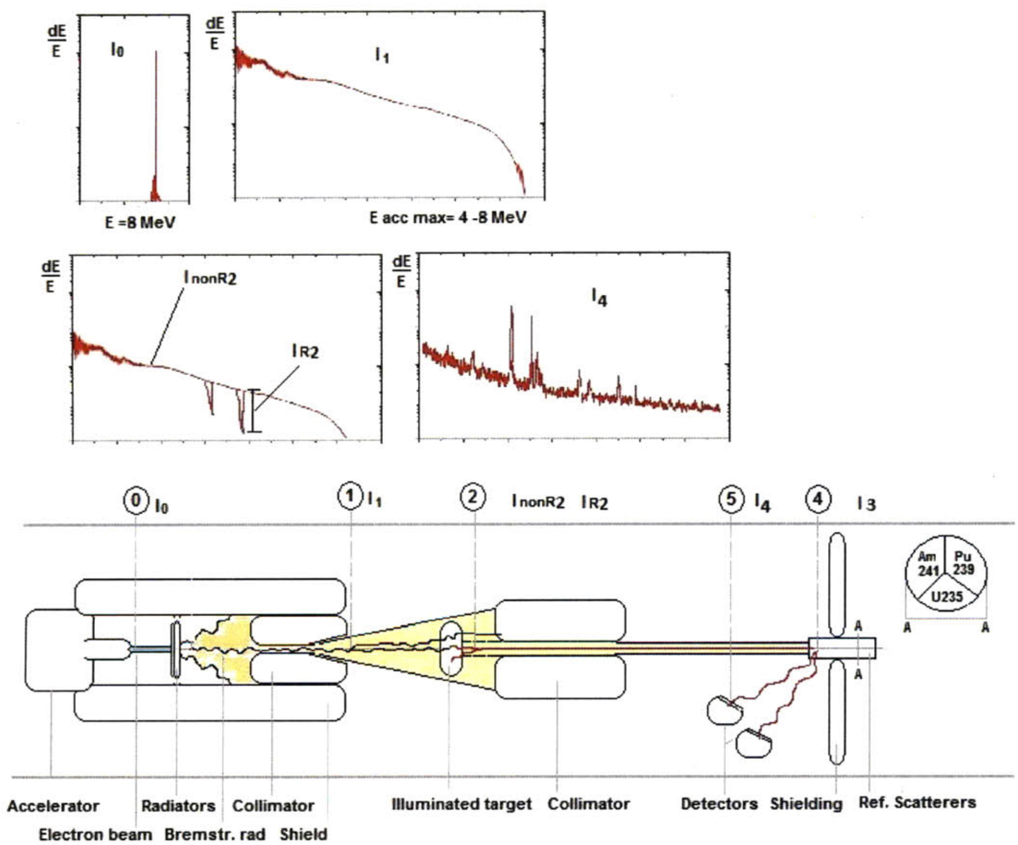

Figure 1. Nuclear Resonance Fluorescence experiment with transmission.

There are five areas in which the photons are tracked. The first two are just before and after the radiator. The third is after the photons have passed through the sample. The fourth is the emitted photons coming off the back scatterer. Finally, the fifth area is the detectors themselves that detect the back scattered photons.

The photons coming out of the accelerator is a mono-energetic beam of photons that has energy of 8MeV, where

$$I_0 = \text{const} = 10^{12}. \qquad (1)$$

The photons with intensity I_0 will hit the radiator which will emit photons with uniform energies up to 8MeV and has a "natural width" that represents how the beam spreads given a distance from the source. The natural width, θ, is used in determining which photons will interact with the reference scatterer. This number can be determined using the following formula:

$$\theta = m_e c^2 / E_\gamma \text{ (10MeV)} \qquad (2)$$

where m_e is the mass of an electron, c is the speed of light, E_γ is the energy of the incident beam. From here, it is important to only follow the photons that will interact with the reference scatterer. When the beam of photons arrives at the reference scatterer, the beam will have a specific diameter, D_{beam}. This can be found using the following formula:

$$D_{beam} = d * \theta \qquad (3)$$

The area of the back sample to be measured and the area of the beam provide a percentage, K, of the beam that will actually hit the back sample that can then be measured by the gamma detectors:

$$K = A_{ref\ scat} / \pi * D_{beam}^2 \qquad (4)$$

where $A_{ref\ scat}$ is the surface area of the reference scatterer. While all of the photons that interact with the reference scatterer need to be tracked, the photons that fall in the resonance range are going to interact in a different way than the photons not in the resonance range. These resonance photons will interact with the sample through resonance capture in addition to normal interaction processes. The percentage of the total photons that are resonance photons, N, can be found using the following formula:

$$N = R_{range}/E \qquad (5)$$

where R_{range} is the range of energies that fall within resonance (10eV) and E is the total range of energies for the photons (8MeV). Using equations 1 and 4, the intensity, I_1, of the photons just before the fuel sample can be found:

$$I_1 = \varepsilon * K * I_0 \qquad (6)$$

where ε is the efficiency of the radiator, assumed to be 100%. I_1 represents the intensity of the photons that would interact with the reference scatterer if there was no sample to be measured. The sample will reduce the intensity of the photon beam based on absorption rates. There are two cross sections that play a role in the change between the numbers of photons before the sample and after the sample. The first is the overall Gamma absorption rate of the sample. The second represents the extra absorption provided in the resonance range of the isotope being measured. The overall absorption is calculated while the additional cross section in the resonance range (10eV) is assumed to be 10 barns. The Cross section of each isotope is calculated using numbers from the NBSIR database[7]. The absorption cross sections are averaged over the energy range that goes from 1 to 8 MeV. The absorption for each isotope, μ_i, was found using the following formula:

$$\mu_i = \sigma_i * \rho_i \qquad (7)$$

where σ_i is the cross section of the isotope in cm^2/g and ρ_i is the density of the isotope, i. "Percentage absorptions," $\%\mu_i$, was found to see the effect of each isotope on the total absorption of the sample:

$$\%\mu_i = \mu_i * i\% \quad (8)$$

where i% is the percentage by mole of each isotope. The total absorption, μ, was found by adding together all of the percentage absorptions:

$$\mu = \sum \%\mu_i \qquad (9)$$

Similar to the method used to find the total absorption, the total density, ρ, of the sample was found using each isotopes "percentage density":

$$\rho = \sum \%\rho_i \qquad (10)$$

where $\%\rho_i$ is the percentage of the total density that each isotope contributes. The resonance absorption for the isotope being measured was found for the resonance range:

$$\mu_R = \frac{\sigma_R * N_a * 10^{-24}}{M_i * \rho_i} \qquad (11)$$

where σ_R is the absorption cross section in the resonance range (10 barns), N_a is Avogadro's number, M_i is the molar mass of the isotope, and ρ_i is the density of the isotope being measured. This formula is includes a conversion from barns/atom to cm^2/g. Using the regular cross section and the resonance cross section, the intensity of the photons after the fuel can be determined. I_{2nonR} is the intensity of the photon beam after the sample, not including the resonance photons:

$$I_{2nonR} = I_1 \frac{(E_\gamma - R_{range})}{E_\gamma} e^{-\mu t} \qquad (12)$$

where t is the total thickness of the fuel sample. In making this calculation, the resonance photon range used was 10eV. This intensity does not take into account any additional increases in radiation due to scattering within the sample or background radiation because the majority of it will not be in an angle that will allow it to hit the reference fluorescer. As previously stated, there will be additional absorption for those photons within the resonance range. The intensity of these photons, I_{2R}, after passing through the fuel sample is:

$$I_{2R} = I_1 N e^{(-\mu t - \mu_R t_i)} \quad (13)$$

where t is the total thickness of the sample and t_i represents the relative thickness of the particular isotope being measured. The first section of the exponent represents the absorption of these photons in the entire sample through regular absorption processes. The second section addresses the additional absorption in the resonance range for one particular isotope. Again in this beam it is assumed that there are no additions to the beam coming from other scattering effects. This is not entirely true as there could be some small angle scattering that allows photons within the band to stay on course to hit the reference fluorescer.

These new intensities, give an idea of the intensity of the beam as it goes into the reference fluorescer. The intensity of I_{2R} allows us to have an idea of how many resonance gammas are given off by the back sample. The reference scatterer is chosen to measure the amount of a specific isotope that is in the sample. The reference scatterer consists of a number of materials that are of interest (ex. Pu-239, U-235) that are in wedges of a total cylindrical piece. The scatterer can then be rotated to measure each isotope individually. Because this process should take less than a minute, the problem of only measuring one isotope at a time is mitigated. The reference scatterer's thickness is designed to ensure that only .01% of the resonance photons go through the sample. The interactions that occur will result in resonance gammas being given off in all directions. Therefore, the intensity, I_3 of the beam leaving the resonance scatterer that consists of the resonance gammas is:

$$I_3 = .9999 I_{2R} \quad (14)$$

This total intensity assumes that no resonance gammas are absorbed by the reference scatterer. The total intensity of the resonance photons is much higher than the intensity that the detectors experience. The detectors are arranged in front of the reference scatterer to reduce the number of photons they detect from the back scattering produced by the interactions between the non-resonance photons and the reference scatterer. The final step for the detection process is the actual detection of the resonance gammas that are given off by the reference scatterer in response to the absorption of the resonance photons.

The number of gammas that the detectors count is based on the geometry of the detection system. In this system there are a number of detectors that each detect gammas and aggregate them for a total count. These detectors cannot be overwhelmed by radiation otherwise their counts will be meaningless. The final intensity, I_4, represents the intensity of the resonance photons that each detector detects. The spectrum that results consists primarily of a peak of gammas in the resonance range which tells the quantity of the isotope, but also some background radiation. Without the reference scatterer, the peak visible in the resonance range would be drowned out by background radiation. The signal to noise would be too low to be of any value. The intensity can be found using the formula:

$$L_4 = L * I_3 \quad (15)$$

where L is geometric constant created through a similar method to the aforementioned geometric constant K. This assumes that the resonance gammas are emitted with an isotropic distribution. Accountancy is possible by knowing what the measurement should be based on burn-up codes. If there is variation between the measurement and the expected value, it is a sign that a diversion attempt was made. The efficiency of the detector will play a key role. What variation between the expected value and the measured value warrants a deeper search?

Success tree Method

The method used in this study to quantify the proliferation resistance (PR) of a nuclear facility is probabilistic risk assessment (PRA). PRA was first used in assessing the safety risk of reactors. Success tree logic was used to identify key features of the reactor safety systems. From there basic events were evaluated for their frequency. Through the success tree and an event tree, the probability and outcomes of each initiating event, the event that begins the series of events, could be evaluated. The PRA method used in this study follows closely the method used in Ham[1].

This model demonstrates a competition between the proliferator and the safeguarder. A proliferation attempt occurs when an agent attempt to obtain nuclear material. This occurs in one of two ways: a diversion attempt or an abrogation attempt. Additionally, a proliferator may attempt to misuse a facility in a way that makes diversion or abrogation more attractive. The proliferator must directly compete with the safeguarder, the organization(s) that seeks to keep nuclear material from being proliferated. The safeguarder employs specific systems that the proliferator must circumvent to successfully divert material without being detected. He does this by first picking a location in which to attempt diversion. This decision for location is dependent on three factors: material attractiveness, facility attractiveness, and material handling/transportation difficulty measure[1].

Material attractiveness is recognizes the quality of the material that makes it attractive to steal. This is the contents of key isotopes. If the material is pure Pu, it would be far more attractive than spent fuel containing many fission products and minor actinides. Facility attractiveness is the ease of access for the material. Obtaining material in the core would be very difficult, particularly if the reactor is under operation. Diverting material while it is in the reprocessing facility may be easier because of the different facility characteristics. Finally, material handling and transportation difficulty measures the difficulty of accessing and moving the material to be diverted. Components to think about are radiation levels, decay heat and size of material. Diverting a full fuel assembly immediately after it has been removed from the core would be very difficult because of the size of the assembly, the radiation level, and the decay heat. Obtaining pure Pu would require less shielding and based on the form of Pu, may be available in small quantities, making it simple to transfer.

After a scenario has been decided upon (for example: one or two individuals attempt to divert five to ten grams of plutonium from the waste stream in an aqueous reprocessing facility), the security systems, or safeguards, of that facility must be assessed. Additionally, external security systems that will improve security in that location must be determined. This process includes identifying the security systems as well as identifying each systems weaknesses and possible methods for circumventing. In most facilities, common security systems include security cameras, motion sensors, locked portals, etc. Additionally there are external forms of security that protect that location and prevent a successful diversion. These include long term accountancy measures done by sampling materials and comparing the samples to simulations. Satellite images provide information about transportation of large quantities of materials. IAEA inspections provide eyes in the plant that can detect misuse or theft. These forms of security occur less regularly than the immediate feedback provided by security cameras and the like. NRF is a new form of security that provides near-immediate feedback on the composition of the materials, therefore decreasing the chance that a proliferator can successfully divert materials. Compared to the sampling and comparing form of security which can take weeks, NRF can provide feedback within minutes. Identifying the security features of a location is important because it identifies the systems that the proliferator must fool, disable, or circumvent.

Once these features have been established, methods for defeating the safeguards must also be established; these are called basic events. For each safeguard, these actions can vary widely. For example, defeating security cameras could be accomplished by disabling them by cutting power to the plant, starting a fire that causing smoke that blocks the security camera's line of sight, bribing security personnel to overlook a diversion attempt. This process can be difficult because it requires the researcher to look at the diversion attempt from the proliferator's point of view. Creativity and ingenuity play a large role. In addition to determining the ways that a proliferator could defeat the safeguards, each safeguard must be analyzed for ways that it could fail stochastically. The safeguard could be installed incorrectly, software errors could render the safeguard ineffective, or the amount of material being diverted may fall within an amount that is undetectable by the safeguard. These situations, in addition to others, are ways that the safeguards could fail without the proliferator attempting to defeat the safeguards.

At this point in the process, the information is known to create a success tree. The success tree identifies the location where the diversion will occur and includes the initiating event which defines the details of the diversion attempt, the safeguards the proliferator must defeat, and the actions that the proliferator could make to defeat each safeguard. Not every strategy is necessarily leads to successfully defeating a safeguard. In some cases a single action, bribing security personnel, may render a safeguard defeated. Other strategies could involve modifying the detection system, followed by disrupting the signal. The initiating event identifies what strategies the proliferator will use in the diversion attempt. Based on these actions, success tree logic using "And" and "Or" gates, identify how single actions can lead to an overall success for the proliferator. Or gates, represented by a ■, are used to describe an event which could be brought around by any one of the sub-events. And gates, represented by a ■, designate a higher event that only occurs when *all* sub-events occur. Finally, the top event probability (a successful diversion) can be determined from the probability of success for each basic event based on success tree logic. This procedure makes up the probabilistic risk assessment. Figure 2 shows the overall structure of the success tree.

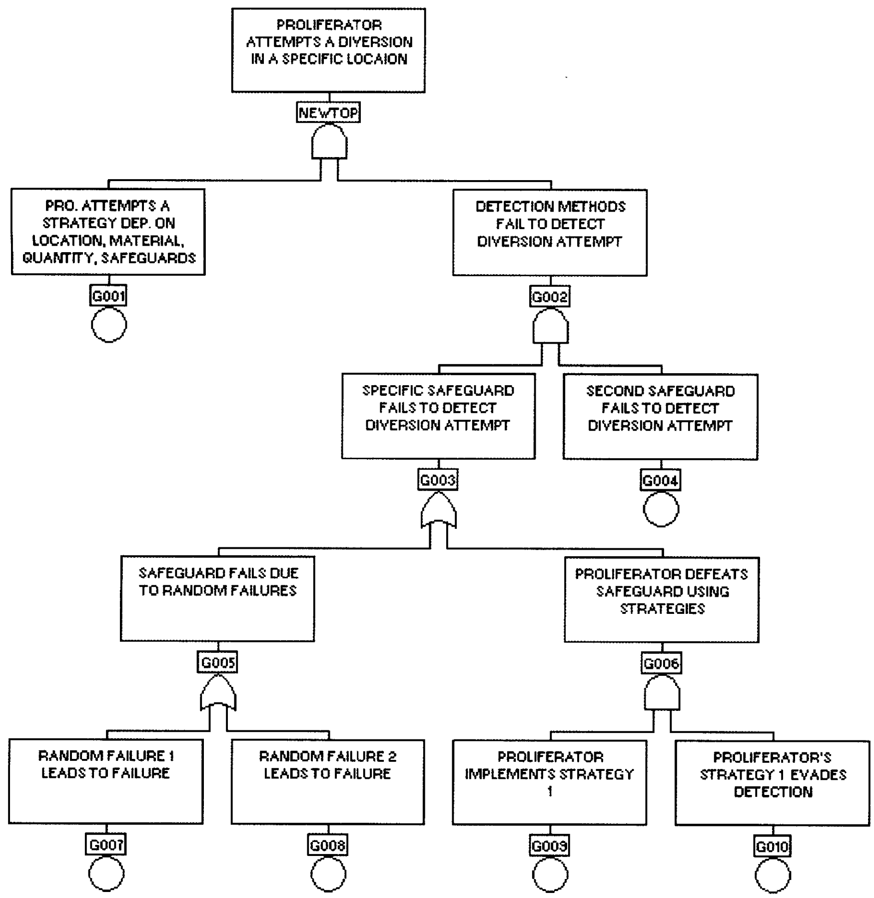

Figure 2. Overall proliferation success tree structure. This tree is designed to describe the basic structure of alternative paths to proliferation success. There is an overall top event of success, which is brought on by an initiating event. The proliferator must then elude a number of safeguard systems using a variety of strategies.

Application NRF to Success tree

The scenario identified for the application of the NRF to the success tree is a scenario in which one or two individuals attempt to divert material from the waste stream in an aqueous reprocessing facility. The amount of material that is being diverted is above the detection threshold of the NRF detector. In this strategy the proliferator(s) will face the safeguards within the reprocessing facility (including the NRF detection system), and the external safeguards that provide security to all nuclear locations. The location of the proliferation attempt is in the reprocessing facility. In this location there are four safeguards that the proliferator must defeat.

The first, and most immediate, form of safeguards is the containment and surveillance (C/S) group of safeguards[1]. This consists of portals, physical barriers, security cameras, and the like. A proliferator could defeat the C/S system through a variety of strategies. A proliferator could use fake images to fool personnel watching the security feed. Likewise, for portals and barriers, fake signals could be utilized to hide evidence of tampering or allow the proliferator to move through a portal. A proliferator may cause a fire to render the cameras incapable of detection and utilize this "accident" to allow for a hasty attempt. Finally, the C/S system could experience a stochastic failure in which the safeguards are not functioning at the time for a variety of issues including poor installation or malfunction.

The NRF detection system would provide a level of security with feedback coming not immediately, but within a matter of minutes. Because of the novel nature of the NRF, there are not well established methods for disrupting or defeating the safeguards. One possible tactic that could be employed by the proliferator to disrupt the safeguard is by staging an accident that in some way disrupts the detection capability. This would either bring the detector offline which would force operators to either continue without the NRF or halt all processes, or the accident could create a window of opportunity where the detector would be unable to detect fluctuations in the material composition. A proliferator may be able to alter the NRF software or the signal coming from the NRF in a way that masks a diversion attempt. The proliferator could also bribe personnel at the facility to overlook a diversion. These four strategies could all be done without modifying the actual detector in any way. If the proliferator attempted to disable the detector by modifying the actual detection system, shielding could be added or taken away in a way that masked a change in material, or excess material could be added. Potentially a piece of Pu could be added into the beam that would then allow the proliferator to steal all the Pu from the stream without raising any alarm.

This list of possible strategies has led to a reformulation of the detection device. One major concern was that the detection system itself could be modified or disrupted. For this reason, the detection system will be housed in a "black box." Two holes will allow the waste stream to pass in and out of the box, but all of the detection system will be within the box, preventing a proliferator from disrupting it. In addition to keeping the detection system, the box will also contain backup records of all of the measurements that have been taken. While this doesn't reduce the proliferation chance in the short term, regular inspections that have access to the files will be able to catch smaller thefts, and prevent plant operators from diverting or allowing the diversion of materials. Adding stronger, safer signals and encrypting the data would make it much more difficult for a proliferator to disrupt the NRF outside of the box. By making these changes, the only option left to the proliferator is to divert an amount of material that falls within the threshold of normal operations.

Another safeguard system that the proliferator must circumvent is that of long period material accountancy. This system achieves accountancy through outside agencies in the form of records and sampling and comparing. Periodically, records and samples are sent to the IAEA for inspection. The records are compared to what is expected and the samples are analyzed and compared to expected values based on burn-up code simulations. This form of accountancy can take much longer than the previous two methods. The time to sample and compare can range from three weeks to a few months. While this treatment could detect proliferation, it would not be fast enough to detect it before many diversion attempts could be made. A proliferator could elude this safeguard by such means as bribing officials, or falsifying records.

Finally, the IAEA sends an inspection team to each facility with a frequency of approximately twice per year. These inspectors have the ability to examine the facility and ensure that physically nothing is out of place. They would ensure the security of the NRF detector, and would also check any samples of waste materials that were on site. Measurements of radiation levels, heat signatures, and other indicators may also lead to inspectors discovering that a proliferation attempt was made. A proliferator may be able to defeat this safeguard by successfully tampering with any seals placed on areas or objects that were off limits to plant operators. There may also be a way to fool any sort of sampling and detection methods that the inspectors employ. Additionally, modified records could pass closer inspection, therefore hiding the proliferation attempt.

While there are other detection systems apart from these four, like satellite measurements to detect increased radiation levels, these four systems comprise the safeguards that a proliferator would need to defeat in order to successfully proliferate without raising alarms. Figures 3, 4, and 5 in the Appendix combine to make a full representation of the diversion scenarios in the success tree. Table 1 in the Appendix lists the components of the tree and their probabilities if they are basic events.

As previously stated, it would be very difficult for a proliferator to circumvent the NRF detection system after it is modified to act as a black box. The point of the NRF is to detect any variation in signal. If there is variation between the expected value and the signal that is measured, an alarm is raised. Any modifications to the detector itself or the signal coming from the detector is likely to result in a different signal. While it may be possible to reduce the current going to the accelerator and therefore change the shape of the signal in a way that maintains the same peak height, the overall intensity would be different, or the spectra may be skewed in a way that alerts personnel. Similarly, modifying the signal after it leaves the box would also be difficult to do in a way that doesn't raise any alarm. The primary concern is that a proliferator would be able to divert a very small amount of material without setting off the NRF. As a SQ is 8 kg, diverting 10g a day of Pu would take over two years to obtain a SQ. During this time other forms of accountancy (inspections, sampling and comparing) would have ample opportunity to detect the repeated diversion attempts.

With the tree constructed the total system's proliferation resistance level is evaluated using proliferator success probabilities for each strategy. These basic event probabilities are determined through expert opinion and are primarily based on the amount of resources that the safeguarder devotes to the safeguards. Experts who are knowledgeable in the field are able to provide accurate values for the success rates of proliferators. Multiple opinions are averaged to find an overall value for each basic event. From there, success tree logic is used to ensure the effectiveness of the NRF detection system. The total probability of success of the proliferation attempt where the proliferator attempts to divert five grams of plutonium from the waste stream is found to be $8.73*10^{-5}$. This probability includes the effects of proliferation resistance added by the NRF detector. Without the detector, the probability of success is found to be $3.39*10^{-4}$. The NRF detector adds approximately an additional order of magnitude of security.

A sensitivity analysis was carried out to see the effect that changes in the success probabilities would have on the overall probabilities for proliferator success. Because the basic event probabilities are based on expert opinion there can be variation in the value that is used to determine the top probability. Additionally, the probabilities can never be completely known, there will always be some error. The basic event probabilities in the NRF portion of the tree were inspected to find areas where a change could have a large effect on the top event probability. One basic event that stands out is the likelihood that the tampering of seals would not be detected. Tampering with seals is very difficult to hide, but even if the probability of successfully evading detection were changed from .0001 to .1 the top event probability increases to $9.20*10^{-5}$. This increase is very small, only $4.72*10^{-6}$. This event does not have a substantial effect upon the top event probability. The basic event, "Modifications to the software are not detected" has a value of .25 for its probability. If this value is increased to .75, the top event probability increases to $2.55*10^{-4}$ this is an increase by more than an order of magnitude. If this value is decreased to .1 however, the top event probability decreases to $3.70*10^{-5}$ which is only a slight increase in proliferation resistance. While there is error in the basic event probabilities for the NRF portion of the tree, the detection system still increases overall proliferation resistance, even if the probabilities are close to 1.

Conclusion

With nuclear power playing an increasing role in the energy industry, new accountancy methods must be established to provide effective proliferation resistance. NRF is capable of adding a level of accountancy that increases the proliferation resistance of a reprocessing facility. With its unique design and overall efficiency, no strategies exist that can defeat the safeguard entirely while not being detected by other safeguards. The PRA confirms that NRF adds a greater level of security to the plant.

Appendix

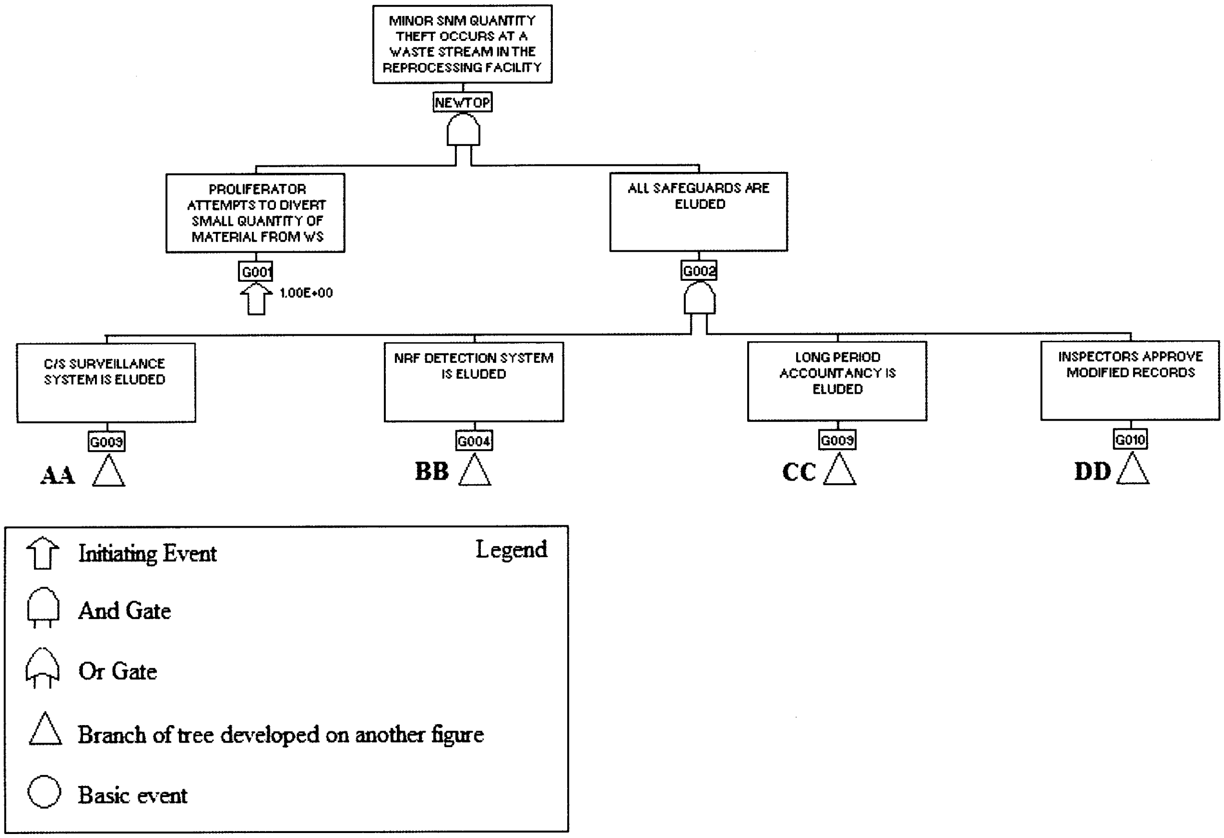

Figure 3. Full Representation of Success Tree. This figure represents the full tree with the four main sub-branches hidden for the due to size. Each of the four safeguards, C/S Surveillance System, NRF Detection System, Long Period Accountancy, and Inspections have been developed in Figures 4 thru 7.

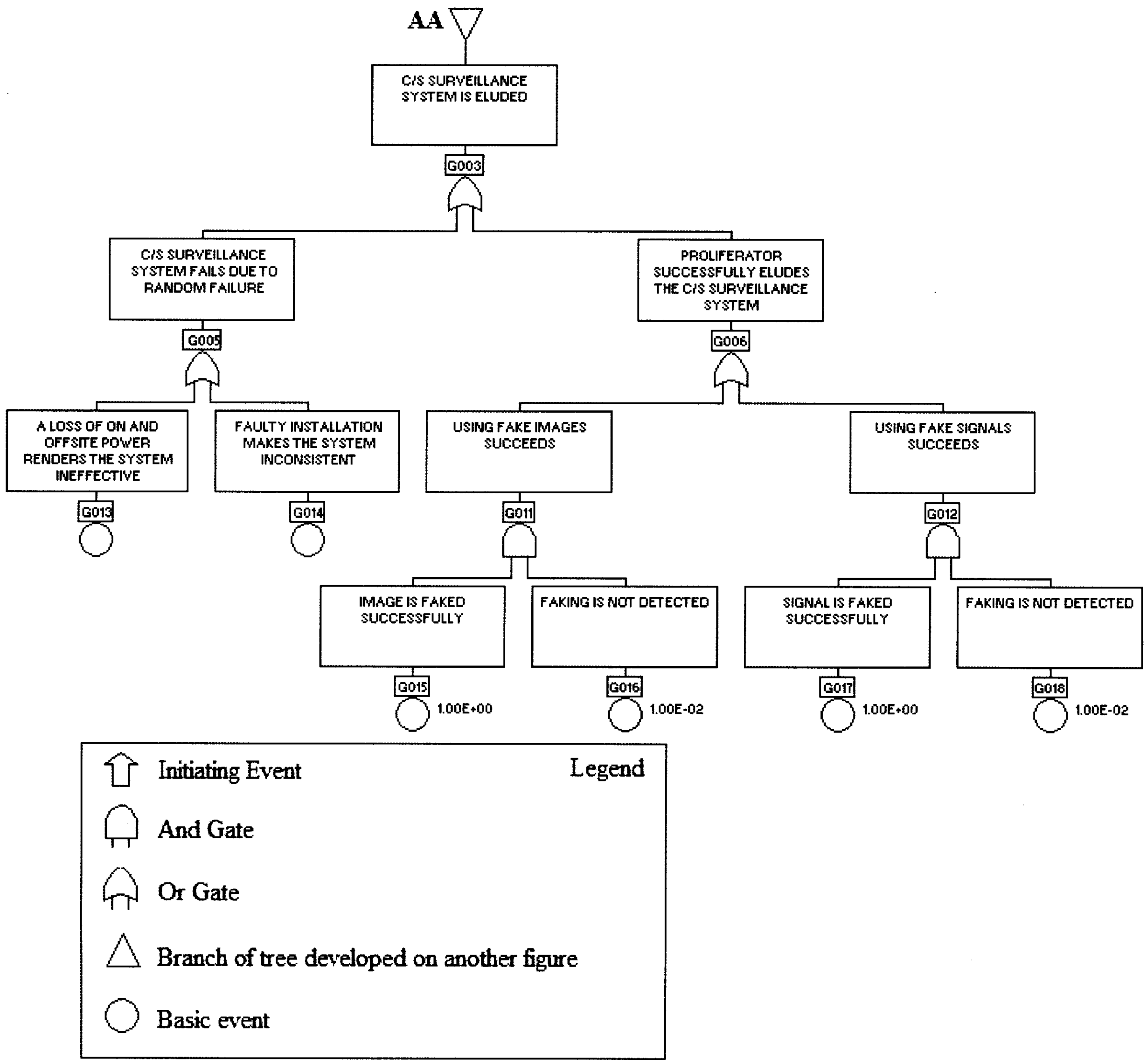

Figure 4. C/S Surveillance System Component. This figure represents the full developments of the C/S System. Each of the basic events has its probability listed below the event. If there is no probability listed, the probability is assumed to be zero.

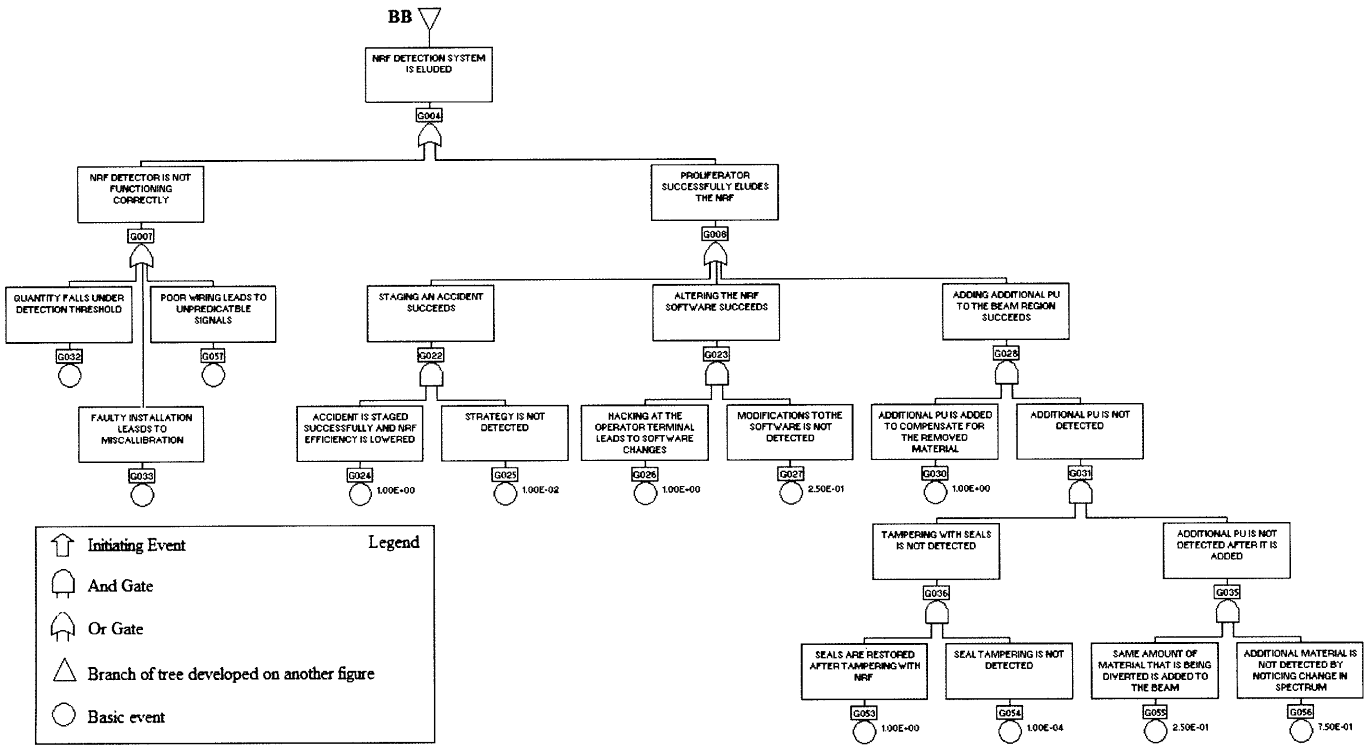

Figure 5. NRF Detection System Component. This figure represents the full developments of the NRF Detection System. Each of the basic events has its probability listed below the event. If there is no probability listed, the probability is assumed to be zero.

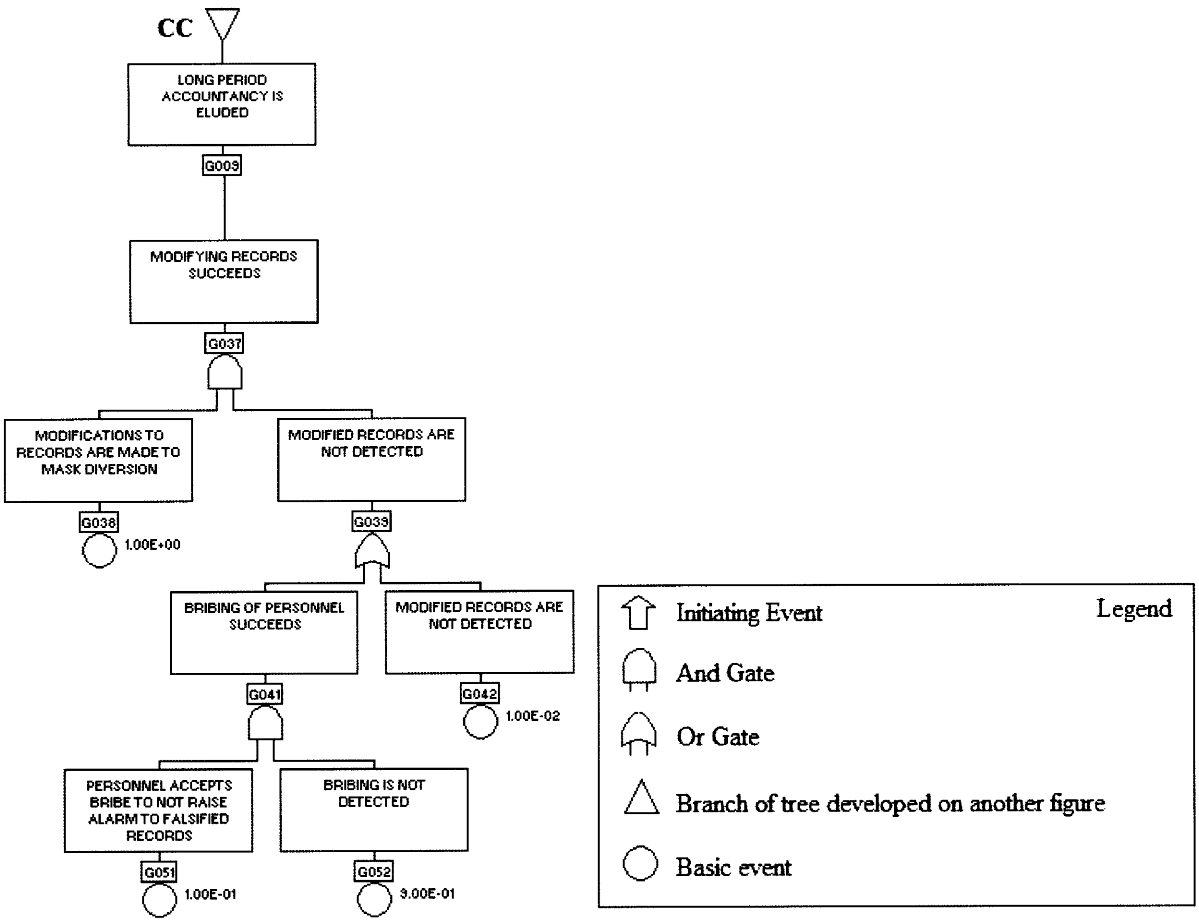

Figure 6. Long Period Accountancy Component. This figure represents the full developments of the Long Period Accountancy System. Each of the basic events has its probability listed below the event. If there is no probability listed, the probability is assumed to be zero.

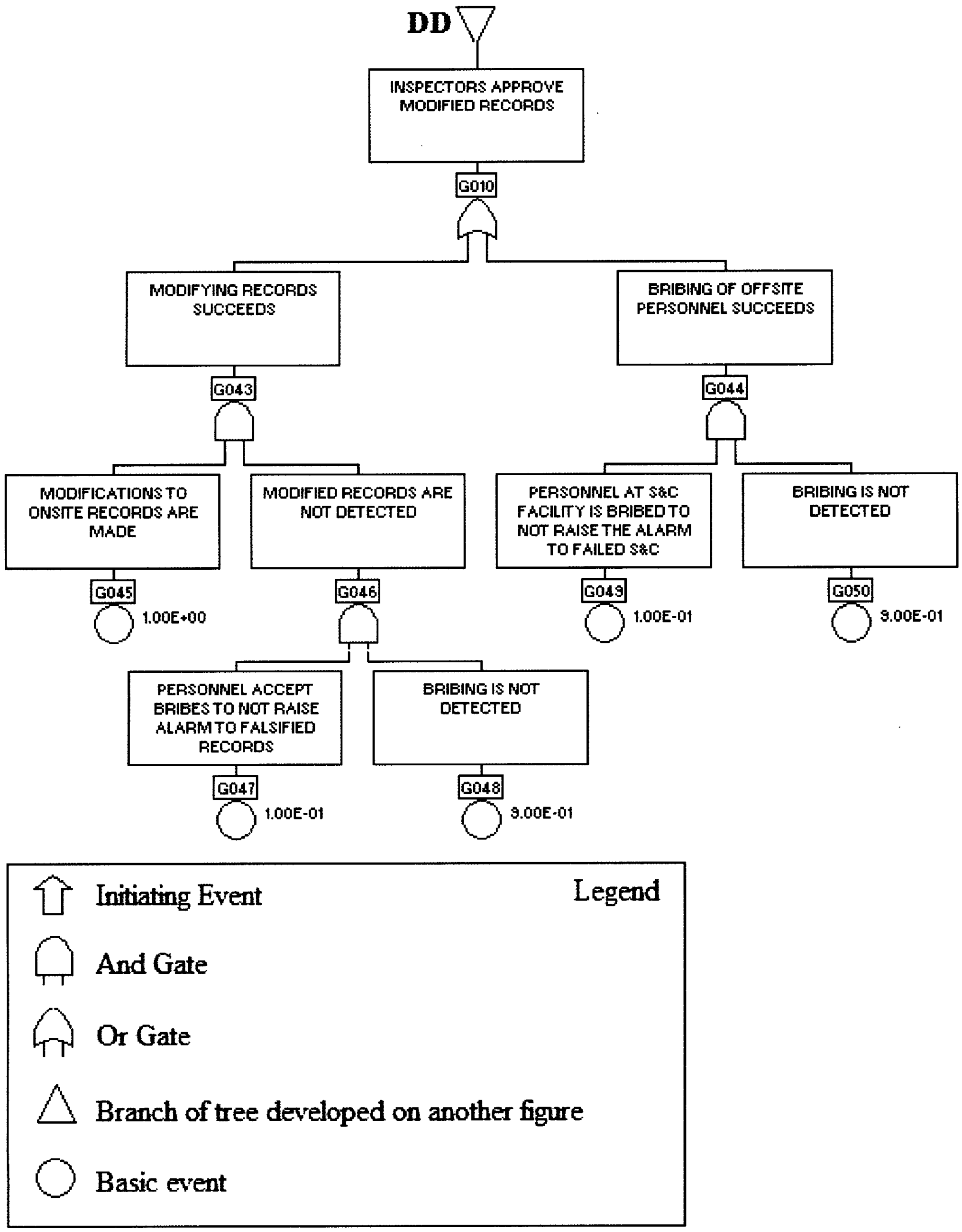

Figure 7. Inspection Component. This figure represents the full developments of the strategies required to defeat the inspectors that do bi-annual inspections of the facility. Each of the basic events has its probability listed below the event. If there is no probability listed, the probability is assumed to be zero.

Table 1. List of Components of Success Tree. This is a full list of the gates and basic events that make up the success tree. If the event is an initiating event or a basic event, its probability is given. The four highlighted components make up the four main safeguard systems.

Title of Tree Component	Gate	Probability
Minor SNM quantity theft occurs at a waste stream in the reprocessing facility	AND	8.73E-05
Proliferator attempts to divert small quantity of material from waste stream	Init	1
All safeguards are eluded	AND	8.73E-05
C/S surveillance system is eluded	OR	1.99E-02
C/S surveillance system fails due to random failure	OR	0
A loss of on and offsite power renders the system ineffective	BE	0
Faulty installation makes the system inconsistent	BE	0
Proliferator successfully eludes the C/S surveillance system	OR	1.99E-02
Using Fake images succeeds	AND	0.01
Image is faked successfully	BE	1
Faking is not detected	BE	0.01
Using fake signals succeeds	AND	0.01
Signal is faked successfully	BE	1
faking is not detected	BE	0.01
NRF detection system is eluded	OR	2.58E-01
NRF detector is not functioning correctly	OR	0
Quantity falls under detection threshold	BE	0
faulty installation leads to miscallibration	BE	0
poor wiring leads to unpredictable signals	BE	0
Proliferator successfully eludes the NRF	OR	2.58E-01
Staging an accident succeeds	AND	0.01
Accident is staged successfully and NRF efficiency is lowered	BE	1
Strategy is not detected	BE	0.01
Altering the nrf software succeeds	AND	0.01
Hacking at the operator terminal leads to software changes	BE	1
modifications to the software is not detected	BE	0.25
Adding additional Pu to the beam region succeeds	AND	1.88E-05
Additional Pu is added to compensate for the removed material	BE	1
Additional Pu is not detected	AND	1.88E-05
Tampering with seals is not detected	AND	1.00E-04
Seals are restored after tampering with NRF	BE	1
Seal tampering is not detected	BE	1.00E-04
Additional Pu is not detected after it is added	AND	1.88E-01
Same amount of material that is being diverted is added to the beam	BE	0.25
Additional material is not detected by noticing a change in the spectrum	BE	0.75
Long period accountancy is eluded	direct	9.91E-02
modifying records succeeds	AND	9.91E-02
modifications to records are made to mask diversion	BE	1
Modified records are not detected	OR	9.91E-02
Bribing of personnel succeeds	AND	0.09
Personnel accepts bribe not to raise alarm to falsified records	BE	0.1
Bribing is not detected	BE	0.9
Modified records are not detected	BE	0.01
Inspectors approve modified records	OR	1.72E-01
Modifying records succeeds	AND	0.09
Modifications to onsite records are made	BE	1
Modified records are not detected	AND	0.09
Personnel accept bribes to not raise alarm to falsified records	BE	0.1
Bribing is not detected	BE	0.9
Bribing of offsite personnel succeeds	AND	0.09
Personnel at S&C facility is bribed to not raise the alarm to failed S&C	BE	0.1
Bribing is not detected	BE	0.9

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