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A Statistical Model for Generating a Population of Unclassified Objects and Radiation Signatures Spanning Nuclear Threats

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Executive Summary

This report describes an approach for generating a simulated population of plausible nuclear threat radiation signatures spanning a range of variability that could be encountered by radiation detection systems. In this approach, we develop a statistical model for generating random instances of smuggled nuclear material. The model is based on physics principles and bounding cases rather than on intelligence information or actual threat device designs. For this initial stage of work, we focus on random models using fissile material and do not address scenarios using non-fissile materials.

The model has several uses. It may be used as a component in a radiation detection system performance simulation to generate threat samples for injection studies. It may also be used to generate a threat population to be used for training classification algorithms. In addition, we intend to use this model to generate an unclassified "benchmark" threat population that can be openly shared with other organizations, including vendors, for use in radiation detection systems performance studies and algorithm development and evaluation activities.

We assume that a quantity of fissile material is being smuggled into the country for final assembly and that shielding may have been placed around the fissile material. In terms of radiation signature, a nuclear weapon is basically a quantity of fissile material surrounded by various layers of shielding. Thus, our model of smuggled material is expected to span the space of potential nuclear weapon signatures as well.

For computational efficiency, we use a generic 1-dimensional spherical model consisting of a fissile material core surrounded by various layers of shielding. The shielding layers and their configuration are defined such that the model can represent the potential range of attenuation and scattering that might occur. The materials in each layer and the associated parameters are selected from probability distributions that span the range of possibilities. Once an object is generated, its radiation signature is calculated using a 1-dimensional deterministic transport code. Objects that do not make sense based on physics principles or other constraints are rejected. Thus, the model can be used to generate a population of spectral signatures that spans a large space, including smuggled nuclear material and nuclear weapons.

Acknowledgements

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1.0 Introduction

Performance of a radiation detection system depends upon a number of components, including the threat source to be detected, radiation flux incident on the detector from benign sources, the radiation detectors and alarm algorithms that are used, and the operational scenario. **Figure 1-1** illustrates the relationship among these components. Proper characterization and modeling of each of these components is needed to assess the performance of radiation detection systems. This report focuses on characterizing signatures[1] (both gamma and neutron) for a range of possible threat sources. Nuisance source populations and ambient background are typically modeled using empirical data and measurements from actual detector deployments. However, similar data for modeling potential threat sources are not available. In addition to being needed for evaluation of detection systems, spectra that are representative of the potential threat source population are also needed for training certain types of detection algorithms.

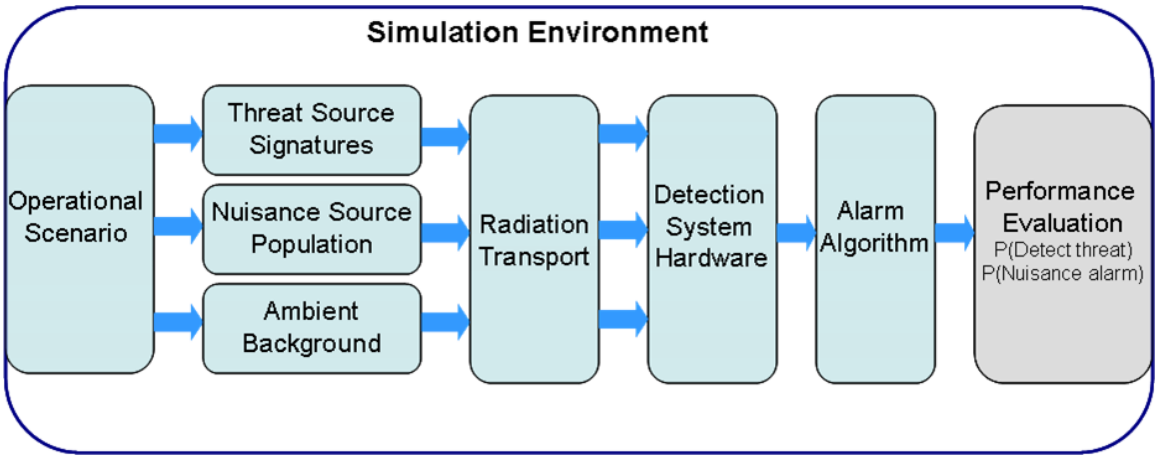

Figure 1-1. Components affecting the radiation detection system performance.

For both evaluation of detection systems and training of detection algorithms, a variety of spectral signatures that could be produced by potential threat sources is needed. However, without the aid of specific intelligence information, we do not have an a priori definition of threat objects or the shielding that may be used. If the variability of the threat space is large and the number of representative spectra used to train the system is small the system is likely to over train on those items, resulting in unsatisfactory performance when a wider range of threats is considered. Similarly, if the number of threat spectra used to evaluate system performance is small, the result is likely to be overly optimistic performance estimates.

[1] Although both gamma and neutron signatures are generated with our one-dimensional model, the neutrons are modeled primarily to account for neutron-induced gammas that contribute to the overall gamma spectrum. Our goal in this initial work is to demonstrate proof of concept for gamma signatures. Hence we do not account for variations in neutron production due to asymmetric sources.

In order to provide the capability for generating a simulated population of threat spectra that spans the potential range of variability, we have created a statistical model for generating random instances of smuggled nuclear material. This model is based on physics principles and bounding cases rather than on intelligence information or actual threat device designs. For this initial stage of work, we focus on random models using fissile material and do not address potential threats using non-fissile materials. Section 2 of this report provides a general description of the model. Section 3 provides the details of the statistical model and Section 4 gives a brief description of the procedure for generating random instances of threat spectra. Finally, Section 5 describes areas for future work.

The model presented here has several uses. It may be used as a component in a radiation detection system performance simulation to generate threat samples for injection studies. It may also be used to generate a threat population to be used for training classification algorithms. In addition, we intend to use this model to generate an unclassified "benchmark" threat population that can be openly shared with other organizations, including vendors, for use in their radiation detection systems performance studies and algorithm development and evaluation activities.

2.0 Model Description

In constructing our model, we wish to be as broad as possible within practical bounds. Our knowledge of the configuration an adversary may choose is assumed to be limited only by common sense and physical limitations. We assume that a quantity of fissile material is being smuggled into the country for final assembly and that shielding may have been placed around the fissile material for any of three reasons: 1) to enable handling of the material, 2) to hide the material from sight (concealed within cargo), or 3) to prevent detection of the gamma and/or neutron signature (engineered shielding). Because we do not assume which of these motives is driving the adversary, our model is designed to represent all three. In terms of radiation signature, a nuclear weapon is basically a quantity of fissile material surrounded by various layers of shielding. Thus, our model is expected to span the space of potential nuclear weapon signatures as well.

Our basic model is shown in **Figure 2-1**. The fissile material will be in the center of the object. We do not make any assumptions about the particular shape of this object. Thus it could be a rod, cylinder, sphere, or other shape. The fissile material may be inside of some mechanical support, such as a steel container, or surrounded by a shipping material, such as foam or wood. These near-field materials may have some influence on the spectral signature of the object if they happen to moderate or absorb neutrons and convert them to gamma rays. Around this shipping material, successive layers of shielding may be present. In our model, we arrange them from the highest Z material to the lowest Z material, but allow for the possibility of lower Z material inside higher Z layers.

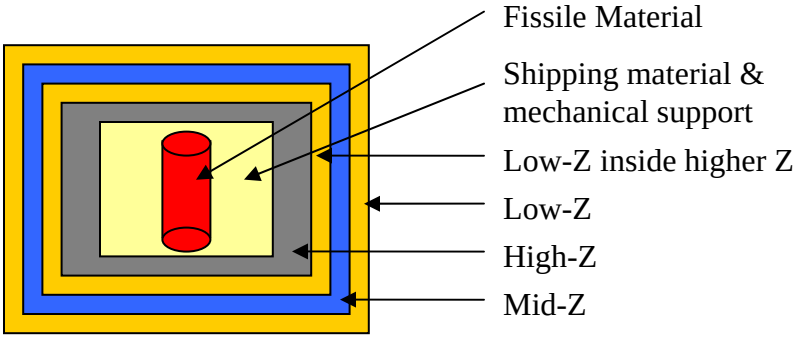

Figure 2-1. Prototype smuggled SNM model.

For computational efficiency, our simulation model uses a 1-dimensional radiation transport code. Thus, we use the generic 1-dimensional spherical model shown in **Figure 2-2** to represent all possible threat configurations. In converting to a 1-dimensional model, we have added a void in the center of the fissile material. This is needed because all of the transuranic elements that comprise fissile material are quite dense and thus have significant self-shielding. By placing a void in the center of a sphere, we can adjust the ratio of cross-section surface area to total mass to be representative of everything from a solid sphere to a cylinder and even a thin foil. The interior shipping material, even though it may be lower Z than surrounding material, could have a significant effect on the overall signature because it is so close to the nuclear material. Thus, this layer of near-field material is explicitly represented. Subsequent layers are arranged from highest Z to

lowest Z. Low-Z material produces Compton scattering in addition to attenuating gamma ray lines. However, when a low-Z material is inside of a high-Z material, the Compton scatter will be captured in the outer layer. Thus a low-Z layer followed by a higher Z layer has the same effect as a thicker layer of the higher Z material. Low-Z material between the high-Z and mid-Z layers is represented in our model by increasing the thickness of the mid-Z material to account for the areal density of the lower Z material and inserting a void between the high-Z and mid-Z layers to preserve the total thickness of the layers. For asymmetric three-dimensional objects, the 1-dimensional model is representative of a particular line-of-sight.

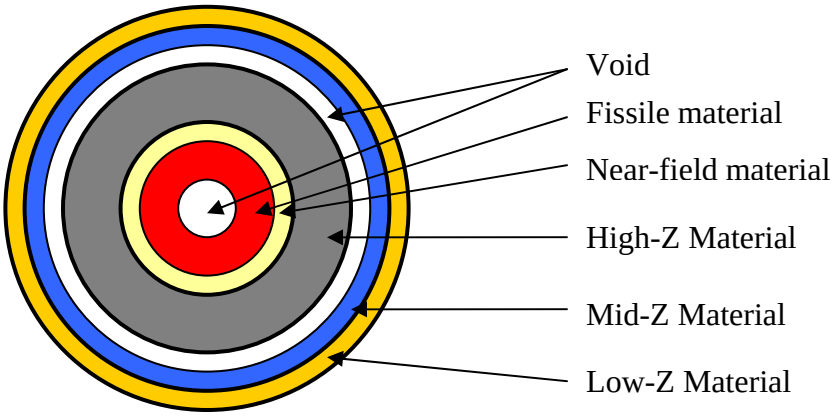

Figure 2-2. Modified 1-dimensional smuggled SNM model.

There are up to four shells surrounding the central core of fissile material. The innermost shell will be either a void, or a combination of materials with neutron absorption or reflection properties that may change the spectral shape when placed in the near-field. The next shell will be a layer of high-Z material with a random thickness. The material used for the high-Z layer will be randomly drawn from a set of high-Z materials, such as lead, tungsten and depleted uranium, that are commonly used to shield radioactive sources. The third shell will have a void of random thickness, followed by a layer of mid-Z material with a random thickness. The mid-Z material will be randomly selected from a set of materials that vary from aluminum on the low end to tin on the high end. The final shell is a layer of low-Z material with a random thickness. Any one of these shells may be absent (assigned a thickness of zero) with a specified probability in order to cover the full space of possibilities.

The spherical model described above can represent a wide range of configurations. We illustrate this using the Croft SAFKEG – HS (**Figure 2-3**). For simplicity, the air gaps (< 3 mm) between the layers have been omitted and the thicknesses of the various materials are approximate. Consider the example of an adversary attempting to smuggle 11 kg of uranium (approximately a 69 mm x 156 mm cylinder) inside this container. This could be represented by our model as a sphere of uranium with a central void surrounded by a small void, followed by a high-Z layer of depleted uranium (DU), followed by a mid-Z layer of steel with an inner void as shown in **Figure 2-4**. The sphere of uranium with

central void is sized such that the surface area of the cross-section is equal to the surface area of the cross-section of the cylindrical material. The radius of the central void is sized to preserve the total mass of uranium. Because the near-field material in the container is steel, which does not impact the spectral shape when surrounded by a high-Z material, we represent it as a void. The thickness of the DU is increased by 0.8 mm to account for the areal density of the steel and the void is sized to maintain the overall thickness of the two layers. The thickness of the outer steel layer is set to reflect the subsequent three layers of steel as well as the areal density of the two cork layers. The void is sized to preserve the total thickness of the steel and cork layers. It is not our intent to use our model to represent specific objects. However, this example illustrates the capability of the generic spherical model to represent a wide-range of realistic threat objects.

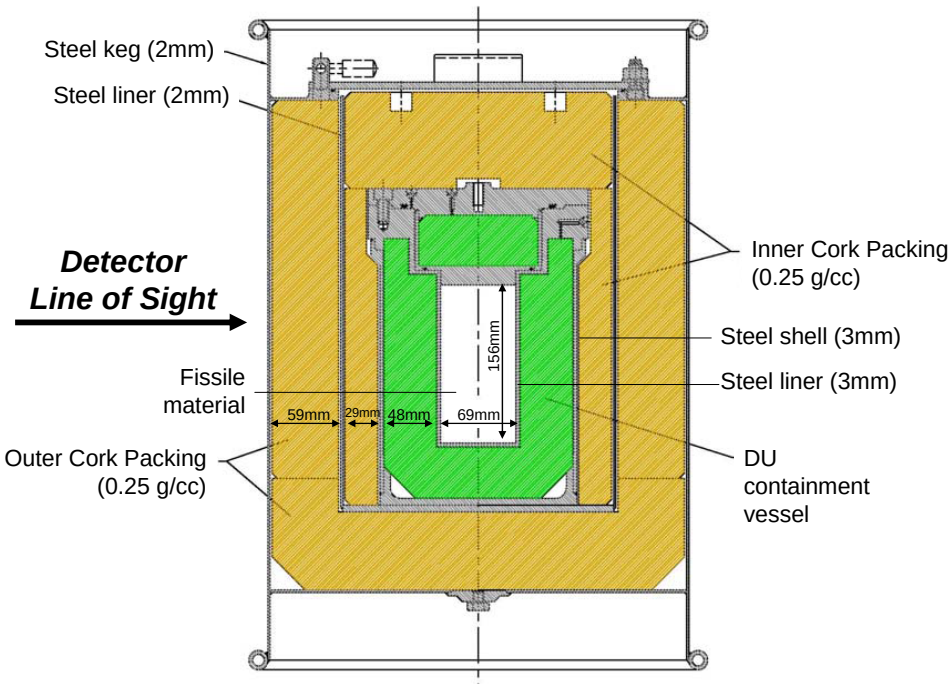

Figure 2-3. Schematic of Croft SAFKEG – HS.

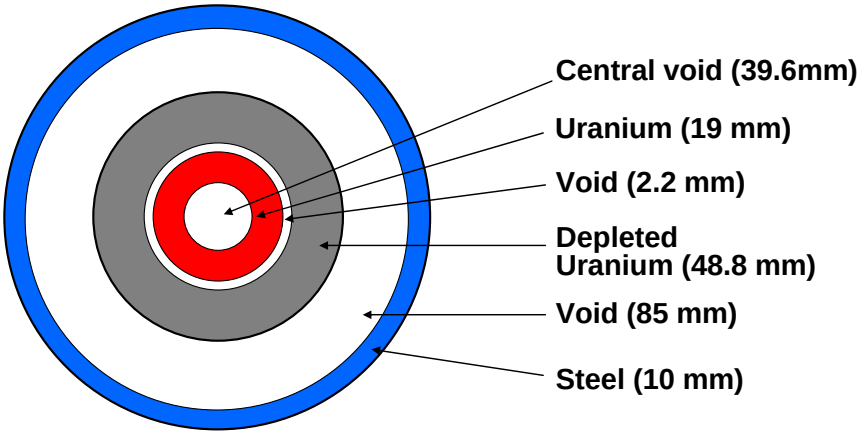

Figure 2-4. Spherical model of Croft SAFKEG – HS.

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3.0 Model Details

In the previous sections we provided a general description of our model. In this section, we define the parameter ranges and distributions that are used for generating random objects. It is important to note that the specific probability values and distributions used in our model are largely arbitrary and are not critical to generating a spanning population. We suggest reasonable values that will ensure representation of a wide range of threat object configurations. However, other values could be substituted while still achieving the intended purpose. Unless otherwise noted, we assume the natural isotopic abundance for each element. These values are given in **Appendix A.**

3.1 Fissile material core

The fissile material core is a key component of our threat model. To span the potential threat population, we must consider a spanning set of fissile materials with varying age, composition, and mass. In addition, we must choose a reasonable range for the central void, which is used to vary the surface area for any particular mass of fissile material.

The first step in generating a random threat object is to select the fissile material. There are a number of different possible materials ranging from simple enriched uranium to exotic transuranic elements such as neptunium. We do not assume the intended purpose of an adversary. For example, their intent may simply be to create a criticality or “fizzle” event, resulting in widespread contamination. Given the severe consequences from alpha damage caused by inhaling or ingesting any of the transuranic elements, we do not limit ourselves to materials that can be used to construct a fission device. However, representing too many materials can reduce a detection system’s sensitivity to any particular material. In addition, a threat object may include multiple fissile materials. In our model we allow an object to contain up to two different materials. For each possible fissile material composition, we assign a probability. The probabilities that we assign to the different material options are somewhat arbitrary. The most widely available materials are the various enrichments of uranium (HEU), weapons-grade plutonium and reactor-grade plutonium (special nuclear materials or SNM). We assign other exotic transuranic elements a low probability of occurrence.

The statistical model used to randomly select the fissile material can be represented by a tree diagram as shown in **Figure 3-1**. First we determine whether one or two materials are present using the probabilities 0.9 and 0.1, respectively. For each material, we then determine whether the material is SNM or exotic. We continue to follow the branches of the tree until a specific material type is selected. The probabilities in the tree are largely arbitrary with the intent of covering all possibilities while emphasizing the materials which seem most plausible. In the case where there are two fissile materials, the second material is assumed to be a shell around the first material.

For each material, we have specified a range of masses. We know that the maximum quantity of material that can be transported is simply the published critical mass for an unreflected sphere of the material **[1][2][3]**. For the minimum quantity, we selected the lower limit from the IAEA Category II quantities of nuclear material defined for purposes

of physical protection if such quantity was defined **[4].** This quantity is lower than the IAEA significant quantities and thus a more conservative choice. For materials that do not have a Category II definition, we use the quantity of the material that is most similar in terms of unreflected critical mass.

For some of the materials, there are numerous initial isotopic compositions. Where possible, we use ranges of compositions so that system performance will not be tuned to any unique mixture.

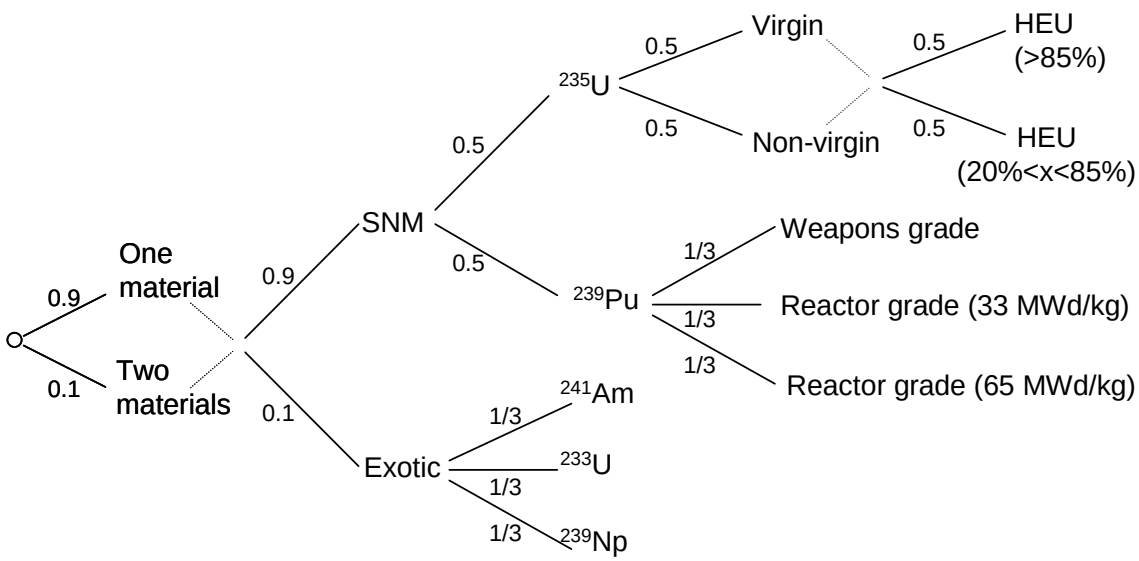

Figure 3-1. Tree diagram and probabilities for selecting fissile material.

To set the diameter range for the central void, we consider the effect of the geometry of the fissile material on its radiation signature. In terms of spectral shape, the outputs that can be produced by a given mass of a particular material depend on the surface area or thickness of the material. Minimum surface area occurs when there is no central void. Maximum surface area occurs when the material is in an elongated shape, such as a long, thin cylinder, or in the form of a hollow shell. In order to avoid producing arbitrarily thin shells of material surrounding a central void, we set the maximum radius of the void such that the thickness of the fissile material is comparable to the radius of a fuel rod (0.5 cm), which is the most extreme geometry one would expect to encounter. The maximum radius, r (cm), is calculated as the solution to the equation $\frac{4}{3}\pi\rho\left((r+0.5\,\text{cm})^3 - r^3\right) = M$ where ρ is the density of the fissile material and M is the mass of the fissile material.

The ranges for the various associated parameters that we use for each fissile material type are given in **Table 3-1.** The isotopic compositions listed for HEU are for the virgin (no ^{232}U) material. The composition of the non-virgin material is the same except for the addition of 3x10^{-8} % ^{232}U.

Table 3-1. Fissile materials and their associated parameters.

Material	Very Highly Enriched Uranium	Highly Enriched Uranium (20-85%)	Weapons Grade Pu	Reactor Grade Pu 33 MWd/kg	Reactor Grade Pu 65 MWd/kg	^{233}U	Am	Np
Composition (weight %)	^{234}U, 0.70 ^{235}U, 85-92 ^{236}U, 0.3 ^{238}U, rest	^{234}U, 0.70 ^{235}U, 20-85 ^{236}U, 0.3 ^{238}U, rest	^{236}Pu, 5e-9 ^{238}Pu, 0.015 ^{239}Pu, 93.63 ^{240}Pu, 6.0 ^{241}Pu, 0.355	^{236}Pu, 3e-8 ^{238}Pu, 1.2 ^{239}Pu, 59.0 ^{240}Pu, 24.0 ^{241}Pu, 11.8 ^{242}Pu, 4.0	^{236}Pu, 4e-8 ^{238}Pu, 4.6 ^{239}Pu, 49.36 ^{240}Pu, 23.92 ^{241}Pu, 12.49 ^{242}Pu, 9.63	^{232}U, 3e-4 ^{233}U, rest	Am	Np
Age (y)	0-65	0-65	0-20	0-20	0-20	0-5	0-20	0-20
Mass (kg)	1 – *	1 – *	0.5 – 10	1 – 13	1 – 13	1-16	1 – 60	1 – 60
Density (g/cc)	18.95	18.95	15.75	15.75	15.75	18.95	12.0	20.45

* critical mass = $644f^2 - 1185f + 607$ where f is the fraction ^{235}U.

3.2 Shielding shells

Our model allows for up to four different shielding shells, the near-field material and high-Z, mid-Z, and low-Z shielding shells. **Table 3-2** gives the probabilities with which the high-Z and mid-Z shells are present. The probabilities with which the near-field and low-Z shells are present depend on whether the fissile material core produces significant neutron radiation and are discussed in the appropriate sections below.

Table 3-2. Probability shell is present.

Shell	Probability of Presence
Near-field	See Section 3.2.1
High-Z	0.90
Mid- Z	0.50
Low-Z	See Section 3.2 4

3.2.1 Near-field shell

This shell represents any low-Z materials immediately surrounding the fissile material core that may significantly change the spectral signature of the source. Materials of interest for the near-field shell are those that may change the overall spectral shape by capturing or moderating neutrons or by direct interaction with alpha particles emitted form the source. Because they are very near the fissile material their effect is greater than if they were outside the other shielding layers and thus we model them explicitly. We will generally not be worried about gamma absorption in this layer as the higher Z layers, if present, should absorb most scatter produced in the near-field.

There are two categories of materials that will likely distort the spectral shape when placed in the near-field. The first is low-Z materials that have a large cross section for alpha-n conversions (alpha radiation converted into neutrons and gamma rays) when placed in the near-field. These materials may be present intentionally or may occur

incidentally as contaminants in packing material. For example, using Teflon as a packing material results in a large amount of fluorine, which has a large alpha-n cross section, in the near-field. We have selected some materials that contain the lowest Z elements. The actual composition of the material is unlikely to have a strong influence on its effect, thus the list is not intended to be exhaustive.

The second category is neutron absorbing materials. These materials would be selected based on their high neutron cross section and would be added to control neutron flux from the fissile material. The obvious materials for blocking neutrons are those used for control rods in nuclear reactors. These materials include silver, indium, cadmium, boron, cobalt, hafnium, dysprosium, gadolinium, samarium, erbium, and europium. Of these elements, we limit our model to the ones with the highest neutron cross sections - gadolinium, samarium, cadmium, dysprosium and boron.

In assigning probabilities to the neutron absorbing materials, we use cost as an indirect measure of availability and assign probabilities that are roughly inversely proportional to the cost. Boron is available in a number of forms, the most common of which is boric oxide (B_2O_3). Boric oxide is available for as little as $2 per kilogram. Cadmium is available as a metal and can be purchased for around $9 per kilogram. Gadolinium has the highest neutron cross section of any available material, but this huge cross section is only for thermalized neutrons. Gadolinium metal is available at $130 per kilogram and borated aluminum at approximate $200 per kilogram. Dysprosium metal is more expensive at $300 per kilogram. Samarium costs over $1300 per kilogram. The most likely materials based on cost are boron and cadmium metal. Dysprosium and samarium are not included in our model as they seem unlikely based on cost. The assignment of probabilities based on cost is arbitrary.

The statistical model used for selecting the near-field material depends on whether the fissile material core is a neutron emitter. In the case where it is a significant neutron source, we select the material by following the tree diagram depicted in **Figure 3-2**. If the fissile material core is not a neutron emitter, we eliminate the “Neutron absorbing” branch of the tree and begin with the branch determining whether the near-field layer is absent or present. Because we don’t expect packing materials with large alpha-n cross sections to be present very often, with 0.5 probability the composition of packing material is modeled as a void, meaning that it affects the overall size of the object, but does not affect its spectral signature. While they reflect some logic, as described above, the actual probabilities assigned to the branches of the tree are largely arbitrary. Parameters for the thickness, density, and compositions for the materials in this shell are given in **Table 3-3**.

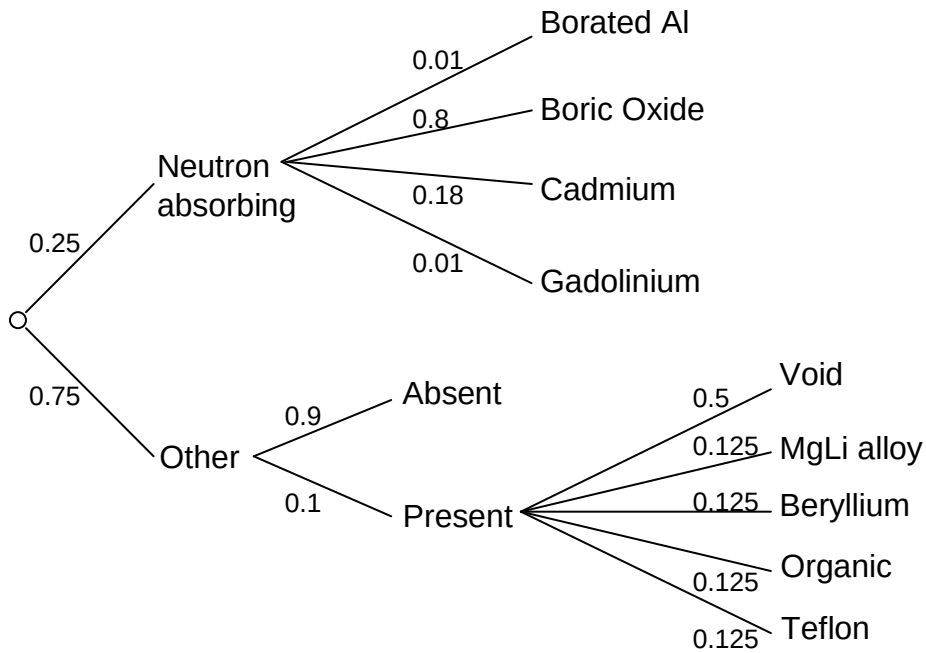

Figure 3-2. Tree diagram and probabilities for selecting near-field material.

Table 3-3. Near-field material parameters.

Material	Thickness (cm)	Density (g/cc)	Composition
Void	0 – 5	0	
Magnesium Lithium Alloys	0 – 5	1.4	Li, 9% Al, 3% Zn, 3% Mg, rest
Beryllium	0 – 5	1.82	Be, 100%
Organic (Carbon, Oxygen)	0 – 10	0.2 – 1.0	H, 3-10% C, rest N, 5% O, 25-40%
Teflon (fluorine)	0 – 5	2.2	$(C_2F_2)_n$
Borated Aluminum **[5]**	0 – 5	2.7	^{e}B, 0.5-4.5% Aluminum Alloy, rest
Boric Oxide (boron)	0 – 5	1.44	B_2O_3
Cadmium	0 – 2	8.65	Cd, 100%
Gadolinium	0 – 2	7.9	Gd, 100%

3.2.2 High-Z shell

The high-Z shell represents shielding placed near the source with the primary intent of reducing gamma rays. The key physical properties for this shielding layer are a high density and high atomic number to produce a large photoelectric effect for gamma rays. Obvious choices include depleted uranium, lead, and tungsten. Depleted uranium is commonly found in pigs used to transport radioactive material. Sale of depleted uranium is regulated in the United States, but the material is available from many sources worldwide. Lead is cheap and available at $2.60 per kilogram. Tungsten is available as scrap or pure metal with prices ranging from $35 to $170 per kilogram. Of the set, tungsten also has the highest thermal neutron cross section. Bismuth is also a possibility as it has a high atomic number. Bismuth is currently replacing lead for many applications. As a result of demand, the price of bismuth has risen to $30 per kilogram. The probabilities assigned to these materials are arbitrary, but are roughly inversely proportional to their cost. The materials considered for this layer, their probabilities, and associated parameters are given in **Table 3-4**.

Table 3-4. Probabilities and parameters for high-Z shielding layer.

Probability	Material	Density (g/cc)	Age (yrs)	Composition	Thickness (cm)
0.47	Depleted Uranium	18.95	0-65	^{235}U, 0.2-0.4% ^{234}U, 0.0015% ^{238}U, rest	1.0 – 7.5
0.47	Lead	11.34	NA	Pb, 100%	1.0 – 7.5
0.04	Bismuth	9.78	NA	Bi, 100%	1.0 – 7.5
0.02	Tungsten	19.8	NA	W, 100%	1.0 – 7.5

3.2.3 Mid-Z shell

This shell represents mid-Z shielding from aluminum at the low end to tin at the high end. Though lower in density than the high-Z shell, these materials can also stop gamma rays effectively. Some metals such as nickel and copper also have a moderate ability to capture thermal neutrons. The materials considered for this layer, their probabilities, and associated parameters are given in **Table 3-5**. Metal compositions are based on the London Metal Exchange where available **[6]**.

Table 3-5. Probabilities and parameters for mid-Z shielding layer.

Probability	Material	Density (g/cc) [7]	Composition	Thickness (cm)
0.27	Aluminum Alloy	2.7	Si, 7.5-12% Cu, 1.5-4% Zn, 1.0-2.9% Fe, 1% Mn, 0.1-0.5% Ni, 0.3-0.5% Sn, 0.1-0.35% Mg, 0.1-0.5% Al, rest	0.5 – 15.0
0.04	Tin Billet	7.3	Impurity, 0.15% Sn, 99.85%	0.5 – 7.5
0.55	Carbon Steel (Iron)	7.9	C, 1% Cu, 0.6% Mn, 1.65% P, 0.4% Si, 0.6% S, 0.05% Fe, rest	0.5 – 7.5
0.10	Copper	8.9	Cu, 100%	0.5 – 7.5
0.04	Nickel	8.9	Ni, 100%	0.5 – 7.5

As discussed in Section 2.0, the mid-Z shell may include an inner void. Our model assigns a probability of 0.25 to the presence of this void and a thickness ranging from 1.25 – 4.0 cm.

3.2.4 Low-Z shell

This shell represents low-Z materials in the outermost layer. There are two possible reasons that a low-Z layer might be present. The first is packaging such as foam, plastic or wood. To avoid being specific to any particular material, we use a generalized composition. For example, polyurethane foam is a common packing material that has two variable organic groups. Thus the actual elemental composition of polyurethane can vary widely depending on composition of those groups. We represent this variability by specifying a range of oxygen, hydrogen and nitrogen content.

The second reason for a low-Z layer is a deliberate attempt to reduce the neutron signature. Atomic nuclei interact with neutrons slowing them down. This process thermalizes neutrons making them easier to capture. The end result is a reduction in the neutron flux at the exterior of the object, making the neutron signature less visible. The largest number of atomic nuclei per mass occurs in hydrogen. Thus materials such as hydrocarbons are good candidates for neutron shielding. Hydrocarbons, however, have very poor neutron cross sections, thus commercial neutron shields mix these with other elements such as boron to capture the neutrons. Some neutron shielding materials also

include lead or other high-Z materials to absorb gamma rays produced by neutron capture. Examples of commercial neutron shielding materials include Premadex (organo-lithium salt), borated polyethylene, enriched borated aluminum, and paraffin with boric acid and lead shot. The probabilities assigned to these materials are roughly inversely proportional to their costs.

The statistical model used for selecting the material for the low-Z layer depends on whether the fissile material core is a neutron emitter. In the case where it is a significant neutron source, we select the material by following the tree depicted in **Figure 3-3**. If the fissile material core is not a neutron emitter, we eliminate the "Neutron shielding" branch of the tree and begin by determining whether packaging is absent or present. Parameters for the thickness, density, and compositions for the materials in this shell are given in **Table 3-6**.

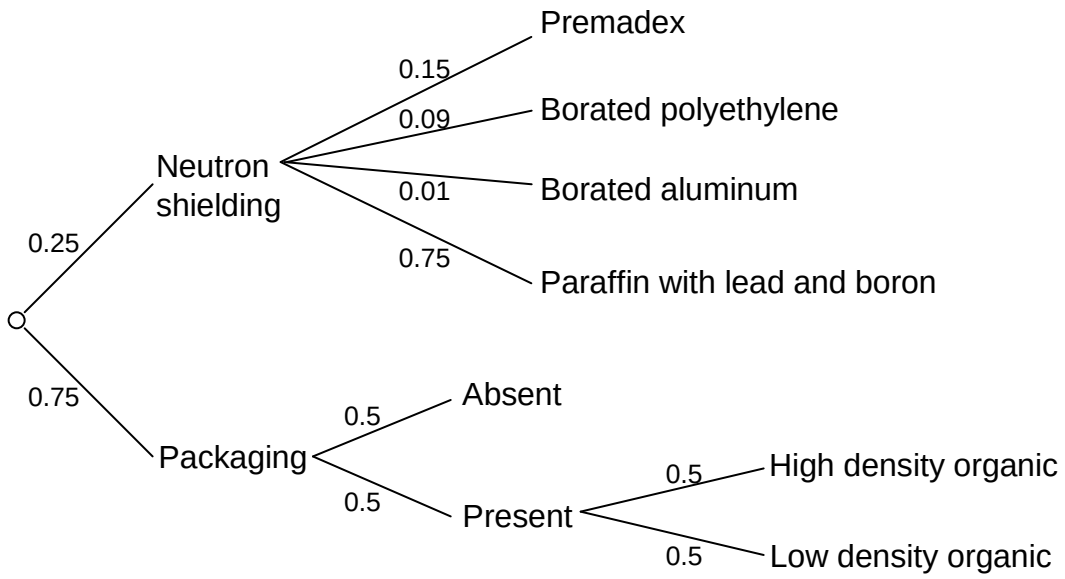

Figure 3-3. Tree diagram and probabilities for selecting low-Z material.

Table 3-6. Low-Z shielding materials and their associated parameters.

Material	Density (g/cc)	Composition	Thickness (cm)
High density organic	0.5-1.5	H, 3-10% C, rest N, 5-30% O, 25-40%	2.5 – 12.5
Low density organic (i.e., Polyurethane)	0.02-0.2	H, 3-10% C, rest N, 5-25% O, 25-40%	7.5 – 25
Premadex **[8]**	1.0	H, 11.4% ^{6}Li, 0.095% ^{7}Li, 1.205% O, 39.9% C, 47.4%	5.0 - 25.0
Borated Polyethylene	0.941	B, 1-5% $(C_2H_4)_n$, rest	5.0 - 25.0
Borated Aluminum	2.7	^{e}B, 0.5-4.5% Aluminum Alloy, rest	2.5 – 12.5
Paraffin with lead and boron	Depends on Pb concentration	B_2O_3, 0-30% Pb, 0-10% $C_{25}H_{52}$, rest	5.0 - 25.0

3.3 Restrictions on models

Our basic model has many random parameters for which reasonable ranges have been established. However, when parameter values are independently selected, although each of the individual values may make sense, in combination they may not. For example, a threat object that produces no spectral signature would not be useful to include in a training set. Models that are of too great intensity or near criticality do not make sense, and for some applications, size and mass may also be a limiting factor. Thus, after generating a set of random threat objects, we reject those that fall outside the range of interest.

3.3.1 Rejection based on intensity

Our statistical model is designed to produce a range of radiation signatures. If it produces a threat object that has no radiation output, then it is not useful for algorithm training. Thus, if the threat population is being generated as a training set for detection algorithms, a lower bound on intensity may be defined in terms of counts per time interval in the detector of interest at a specified distance. Objects with signatures below this threshold would be rejected. If our purpose is to develop a threat population for performance studies, we do not reject objects on the basis of low intensity. If a source is extremely bright, a reasonable adversary is likely to assume that it would be detected and add

additional shielding material. Thus, in all cases, we reject objects that have a dose rate greater than 100 microrem per hour at one meter. This level is ten times the common carrier transportation limit.

3.3.2 Rejection based on mass or physical size

For some applications, we may be interested only in threat objects that can be transported by a particular means, e.g., man-portable, or a particular vehicular class. In this case, threat objects are rejected if they have a total mass or a physical volume that exceeds the limits for the particular application. Our use of spherical objects with central voids to represent non-spherical geometries can result in excessive mass or volume when compared to non-spherical models with similar spectral signatures. Thus, for the purposes of computing an object's physical dimensions and mass, we convert the spherical model to the most compact physical representation that has an equivalent radiation signature. This will be an equivalent cylindrical model if the cylindrical model is more compact then the spherical model. The fissile material core in the equivalent cylindrical model has a radius equal to the thickness (or radius in the case where there is no central void) of the fissile material in the spherical model. The height of the cylindrical core is adjusted to obtain the same total mass of fissile material. The cylindrical core is then surrounded with shielding layers of the same composition and thickness as in the spherical model.

3.3.3 Rejection based on criticality

Our threat model emphasizes smuggled fissile material with engineered shielding. We assume the material has not been assembled into any particular configuration where criticality is likely to be achieved. This is a logical assumption in that an adversary that has shielded an item to a point near criticality will have made the smuggled material more visible (due to multiplication) than it would be otherwise. Thus, we reject any configuration which is a near-critical assembly. We take a conservative approach and reject configurations with a multiplication factor greater than 0.9. The multiplication factor is estimated by the radiation transport code.

4.0 Procedure for Generating Samples

To produce a random population of threat objects, we use an automated approach to create random instances from the statistical model described in the previous sections. A simple computer code using Perl is used to sample from the appropriate distributions for each parameter and produce the corresponding 1-dimensional geometry description file. Discrete parameters, such as material type, are sampled using the given probabilities. Ranges are provided for numerical parameters, such as mass, thickness or composition, and the values are assumed to be uniformly distributed within these ranges. At this point, an initial screening for objects that are too heavy or too large (as discussed in Section 3.3.2) is performed in cases where a limit has been specified. We then apply the Los Alamos National Laboratory deterministic transport code DANTSYS **[9]** through an interface in the Sandia National Laboratories code GADRAS **[10]**. Objects that are determined by the transport code to be near-critical or super-critical or to have too high an intensity are rejected. The outputs (spectral signatures) for all remaining objects are saved. Depending on the application, objects may also be rejected on the basis of low intensity. **Figure 4-1** provides an overview of the procedure.

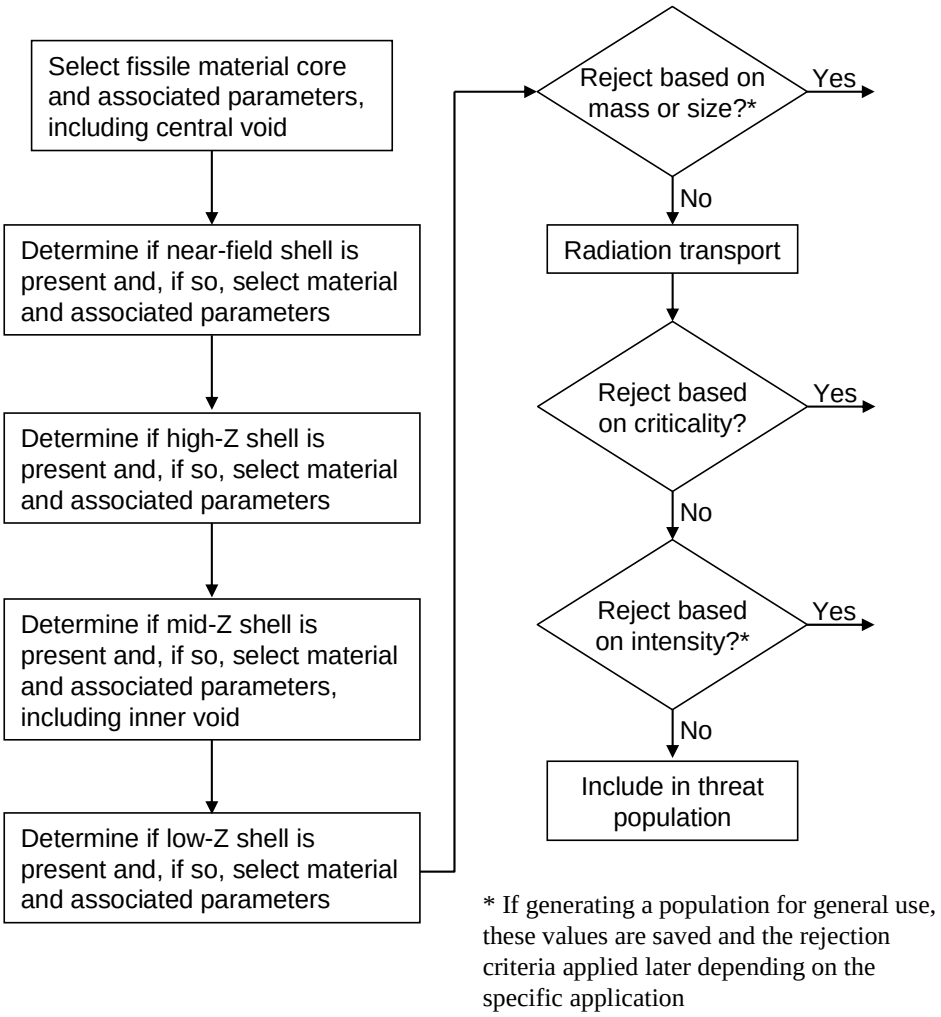

Figure 4-1. Overview of procedure for generating random instances of threat spectra.

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5.0 Future Work

The statistical model described here is expected to undergo improvement and modification over time. The ranges used for the various parameters in the model represent bounding cases for the most part, and assuming a uniform distribution over each range is somewhat naïve. Similarly, the probabilities assigned to different material types and to whether the various layers are present are largely arbitrary. The ability to refine these parameters is limited by the desire to keep the model unclassified and available for open distribution, but improvements should be made where possible.

Currently, the spectra generated by the model are intended to span the range of potential threat objects containing fissile material. We plan to extend the model to include potential threats using non-fissile radioactive materials such as ^{137}Cs and ^{60}Co. We also plan to perform analysis comparing populations of spectra generated by this model with a range of classified and unclassified sources to assure that the populations do indeed cover the potential threat space.

Another limitation of the current model is that asymmetric objects are assumed to be seen by the detector from only one orientation. The capability of a detection system that sees objects from multiple angles to detect and identify asymmetric objects would not be accurately captured using the population generated by this model. Representing multiple views of an asymmetric threat object is a level of complexity that is beyond the scope of this simple 1-dimensional model.

We expect this model, or at least a population of spectra generated by the model, to be used by a broader community involved in radiation detection algorithm development and performance studies. Undoubtedly, suggestions for modification and improvements will be forthcoming. We will do our best to be responsive to this feedback in future work.

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Appendix A Isotopic Abundance

Throughout this document, unless otherwise specified, we have assumed that all elements are found in their natural abundance. As different isotopes of the same element can have a different neutron cross section, this abundance may influence the outcome of simulations. For elements with multiple common isotopes, we show the isotopic compositions by molarity in **Table A-1**.

Table A-1. Table of isotopic abundances for neutron cross section purposes

Element	Symbol	Composition
Hydrogen	H	^{1}H, 99.985%; ^{2}H, 0.015%
Lithium	Li	^{6}Li, 7.5%; ^{7}Li, 92.5%
Beryllium	Be	^{9}Be, 100%
Natural Boron	B	^{10}B, 18.8%; ^{11}B, 81.2%
Enriched Boron	^{e}B	^{10}B, 95%; ^{11}B, 5%
Carbon	C	^{12}C, 98.9%; ^{13}C, 1.1%
Nitrogen	N	^{14}N, 99.634%; ^{15}N, 0.336%
Oxygen	O	^{16}O, 99.76%; ^{17}O, 0.038%; ^{18}O, 0.21%
Magnesium	Mg	^{24}Mg, 78.99%; ^{25}Mg 10%; ^{26}Mg, 11.01%
Aluminum	Al	^{27}Al, 100%
Silicon	Si	^{28}Si, 92.23%; ^{29}Si, 4.67% ; ^{30}Si, 3.1%
Phosphorus	P	^{31}P 100%
Sulfur	S	^{32}S 95.02%; ^{33}S, 0.75%; ^{34}S, 4.21% S; ^{36}S, 0.02%
Vanadium	V	^{50}V, 0.25%; ^{51}V, 99.75%
Manganese	Mn	^{55}Mn 100%
Iron	Fe	^{54}Fe, 5.8%; ^{56}Fe, 91.72%; ^{57}Fe, 2.2%; ^{58}Fe, 0.28%
Nickel	Ni	^{58}Ni, 68.077%; ^{60}Ni, 26.233% ; ^{61}Ni, 1.14% ; ^{62}Ni, 3.634%; ^{64}Ni, 0.926%
Copper	Cu	^{63}Cu, 69.15%; ^{65}Cu, 30.85%
Zinc	Zn	^{64}Zn, 48.6%; ^{66}Zn, 27.9%; ^{67}Zn, 4.1%; ^{68}Zn, 18.8%; ^{70}Zn, 0.6%
Galium	Ga	^{69}Ga, 60.11%, ^{71}Ga, 39.89%
Cadmium	Cd	^{106}Cd, 1.25%; ^{108}Cd, 0.89%; ^{110}Cd, 12.49%; ^{111}Cd, 12.8%; ^{112}Cd, 24.13%; ^{113}Cd, 12.22%; ^{114}Cd, 28.73%; ^{116}Cd, 7.49%
Gadolinium	Gd	^{152}Gd, 0.20%; ^{154}Gd, 2.18%; ^{155}Gd, 14.80%; ^{156}Gd 20.47%; ^{157}Gd, 15.65%; ^{158}Gd, 24.84%; ^{160}Gd, 21.86%
Lead	Pb	^{204}Pb, 1.4%; ^{206}Pb, 24.1%; ^{207}Pb, 22.1%; ^{208}Pb, 52.4%
Bismith	Bi	^{209}Bi, 100%