Purdue University Nuclear Engineering Qualifying Exam Journal Article Review

Conventional and Non-Conventional Nuclear Material Signatures

Summary, Review, and Analysis of Five Special Nuclear Material Detection Techniques

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Based on the paper:

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Abstract

Tsahi Gozani presents a discussion of accelerator applications in the field of special nuclear material detection. The paper is motivated by the current need for a fail-safe and hard-to-defeat detection methods for national security. Gozani discusses the detection of nuclear material by the presence of fissionable material or by other methods. A companion paper presents those methods using fission of these materials to identify them[5]. In this paper, Gozani uses other qualities to detect nuclear material presence, and presents four methods (and one method of combining existing methods). The four methods are split into two groups: detection of nuclear material by their nuclear levels and shells, and detection of nuclear materials by their high Z number. Pulsed Fast Neutron Analysis (PFNA) and Nuclear Resonance Fluorescence (NRF), the two methods utilizing their shell structure, take advantage of inelastic scattering and fluorescence when excited by a γ. They differ in that PFNA is able to provide spatial resolution without an array of detectors. The methods of detecting the high Z number of the nuclear materials are Dual X-Ray Radiography and High Energy Bremsstrahlung Backscattering. These use the attenuation and backscattering of γs in high Z materials as a method for detection.

Gozani's summary of these methods is cursory and hardly comprehensive. Despite providing only this cursory description, one does not get a good perspective on the possible applications of any of these techniques. Gozani would have been better served providing more details that could help a technical reader, or to provide economical or implementation details to help a non-technical reader that may have to choose between technologies. In general, though Gozani's motivation for this paper is noble, his discussion of these methods provides little use to the reader.

To extend the paper, a better comparison of the methods was attempted. This comparison was done by utilizing four factors: the complexity of the design, the efficiency of detection vs. number of particles accelerated, the spatial resolution of the technique, and added value of the techniques. To determine the efficiencies of these methods is beyond the scope of this paper, but for those that have efficiencies stated in the literature, the overall factor was calculated. The overall performance factor for PFNA, NRF, Dual X-Ray Radiography, and High Energy Bremsstrahlung Backscattering are $1.834 + \lambda_{eff,PFNA}$, 0.406, $0.622 + 2 \cdot \lambda_{eff,DXR}$, and $0.406 + 2 \cdot \lambda_{eff,HEBB}$, respectively. It can be seen that with realistic values for the efficiency, it is likely that PFNA is the most advantageous method presented.

Overall, Gozani provides a succinct view of the current state of interrogation techniques. His paper has not largely contributed to the literature on any of these methods, and would need a novel expansion to create a paper with any real impact.

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Nomenclature

BOM - Bill of Materials

IAEA - International Atomic Energy Agency

PFNA - Pulsed Fast Neutron Analysis

PNNL - Pacific Northwest National Laboratory

TMFD - Tensioned Metastable Fluids Detection

TRL - Technology Readiness Level

Part I

Summary of the Article

This summary is based on work by Tsahi Gozani [6].

I|A Introduction

I|A.1 Motivation

Terrorist activity has made the detection and tracking of nuclear material a matter of world security. Current techniques have been employed in many of the world's busiest ports. These techniques are passive and leverage the spectra of γ rays emitted from SNMs. Several direct neutron detection methods have been employed, using ^3He tubes, but have been limited because of the increasing cost of the raw materials involved. The current passive techniques are easily saturated (for example with medical waste) and do not provide "unequivocal and hard-to-defeat detection" [6, p. 599].

Methods that leverage the fission spectrum, nuclear structure, and the high Z number of SNMs have been created. These methods are active and depend on the activation of the atoms in question. Gozani has defined the methods using the fission spectrum as conventional, and other methods as non-conventional. Gozani's paper [6] and it's companion [5] serve to describe and summarize the possibilities for interdiction of special nuclear material.

Gozani's companion paper, "Fission Signatures for Nuclear Material Detection" [5] describes the techniques for determining the presence of fission. These techniques are centered around four specific signatures, namely:

- Prompt Fission Release
  - Neutrons
  - Gamma Rays
- Delayed Fission Release
  - Neutrons
  - Gamma Rays

The difficulty in these techniques come in the detection of these signatures despite varying factors. These signatures must be detected while saturated in source ns or γs, and for delayed signatures, the intensity of response is very small. The difficulty in ameliorating these disadvantages has prompted the inspection into other techniques, name those deemed by Gozani as non-conventional [5, 6].

I|B Methods

I|B.1 Nuclear Levels as Signatures

The nuclear structure of SNMs is a vital and important characteristic for detection of these materials. These materials all exhibit a large (n, γ) cross section, where upon incident neutrons, the nucleus will be excited and emit a γ. These γs can be detected, and as γ detection and spectrometry is a well developed field, analysis can be done on these signatures. This is amplified in fissile materials in two ways, as the fission process multiplies source neutrons and emits γs. The following techniques leverage the nuclear levels and (n, γ) cross section of SNMs to detect their presence.

I|B.1.1 Inelastic Scattering and Fast Fission Neutron Induced Reactions

Pulsed Fast Neutron Analysis (PFNA) was conceived by Gozani, Sawa, and Ryge in 1987 and has since been employed in many different capacities. The technique consists of a several step process. An incident beam of accelerated neutrons is collimated at the material in question. As an intermediate step, this beam of neutrons is chopped and bunch. Thus, a pulse beam of neutrons hits the material in a specific location. Upon interaction with the material, inelastic scattering causes a γ release from the material. This γ release is then detected by arrays of detectors (generally NaI). By analysis of the γ energy and temporal profile, a spatial and temporal map of the materials in question can be deconstructed from this process. A diagram of this process is shown in Figure 1 [6, 17].

There are physical limitations to the PFNA process. In general, the process is limited in that it

- May only detect materials with large (n, γ) cross section.
- May be corrupted by scattering of n in materials - causing increase of voxel size.
- May be eliminated by full attenuation of n beam in materials.
- Is adversely effected by finite time of flight of γ which causes disturbance of voxels.

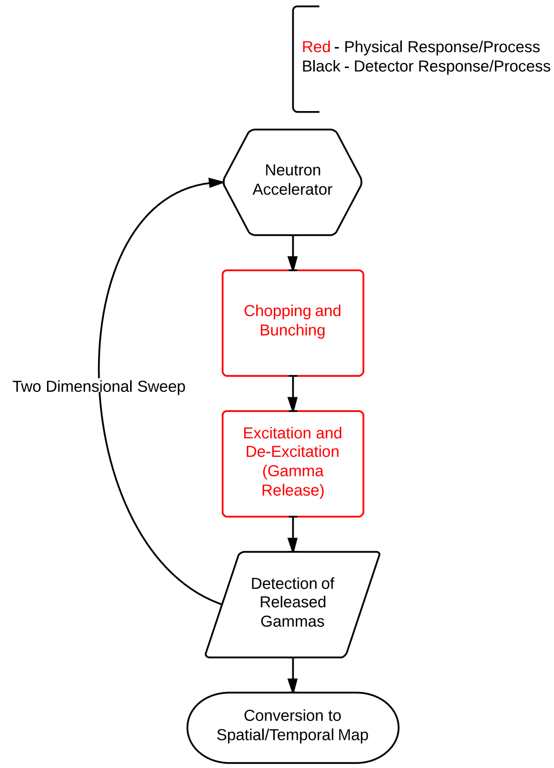

Figure 1: PFNA Process Diagram [4, 6, 17]

Although these limitations are present, they have not deteriorated the impact of PFNA: it is still applicable and practical for many material sensing applications [4].

The practicality of PFNA comes from the coincidence of distinctive signatures with material that is dangerous to work with. Generally, each material will emit either quantized peaks of γs or a continuous spectra of γ energies. The original use for PFNA was for the detection of explosives. This application benefited from the distinctive lines in the spectra of γ release from nitrogen (which is present in large quantities in all conventional explosives). Happily, though, there is an even more distinctive spectra available from SNM. Because of neutron multiplication within the material, an increased (n, γ) cross section, and the emission of fission γ, an amplified and distinctive fission spectrum is detection when PFNA is used on SNM. In this way, PFNA easily transitions from use in detecting conventional explosives to SNM and is a viable technique for this application [15, 6].

I|B.1.2 X-ray Based Gamma Nuclear Resonance Fluorescence (NRF)

Besides having available (n, γ) cross sections, many SNMs and materials of interest also have a large NRF cross section. NRF is the process of nuclear excitation by incident γs, and emission of γs by decay [1]. This process will show very high amplitude peaks for SNM materials because the cross sections of these materials are in the several hundreds of barns. This process is described in Figure 2.

The NRF technique has several large drawbacks. The process is a very high-Q system (the $FWHM$ of each peak is much smaller than the amplitude). Thus, an extremely high resolution detector is needed so as not to miss each characteristic peak. Usually Ge detectors are used. The process also has no inherent spatial resolution, so in order to create voxels, many tiled detectors must be used. Finally, the only practice source of γs for this process is a very conversion efficiency Bremsstrahlung source, which must be driven at very high power [6].

I|B.2 High Z Detection

The Z number of a material has a direct correlation to the attenuation coefficient of the material. The attenuation coefficient logarithmically affects

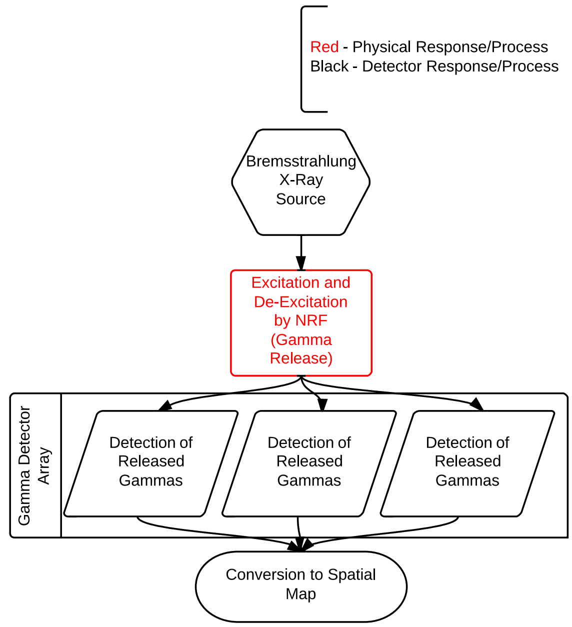

Figure 2: NRF Process Diagram [1, 6]

the reduction in intensity of a γ or n beam through the material, as given by the following correlation:

$$I = I_0 \exp\left(-(\frac{\mu}{\rho}\rho x)\right) \tag{1}$$

where I_0 is the incident intensity of the beam, $\frac{\mu}{\rho}$ is the mass attenuation coefficient of the material, ρ is the density of the material, and x is the distance of beam travel through the material. The concept of high Z detection has been used for many years, in X-Ray interrogation, to investigate luggage and cargo. Several new techniques using this principle could extend it's usefulness to SNMs.

I|B.2.1 Dual Energy X-Ray

The simplicity of the Dual Energy X-Ray technique is its main attractor. In this technique, two separate beams of X-Rays are focused on the material, one with higher energy than the other (generally used beams are $6\,MV$ and $9\,MV$). Because of the higher attenuation coefficient at higher energies in high Z materials, the intensity ratio of these beams can tell some information about the makeup of the material. This creates a mathematical relationship of the material and can be used to interrogate any material with significant differences in Z number of materials. This process is depicted in Figure 3 [6].

The Dual Energy X-Ray technique has many of the same physical limitations as the NRF technique. The sensitivity of the detector (this time resolution in intensity space, not in energy space) is required to be high. Also, the detector provides only one beam and thus a one dimensional map of the material. A sophisticated mobile system, or an array of systems must be used to create voxels for this process. This limitation has been somewhat ameliorated by the creation of digital fluorescent screens (as is used in medical X-Ray diagnosis) {cite!}. Finally, the integral equation created by the ratio of beam intensities through unknown material may only be solved by assuming binary systems (only high Z or only low Z) as well as other geometric assumptions. This technique is only applicable in specific instances [3].

I|B.2.2 High Energy Bremsstrahlung Backscattering

Electrons lose energy in material through the Bremsstrahlung emission, especially in the backscatter regions. This effect is more common and prominent with high energy x-rays in high Z materials. By passing electron beams through material and

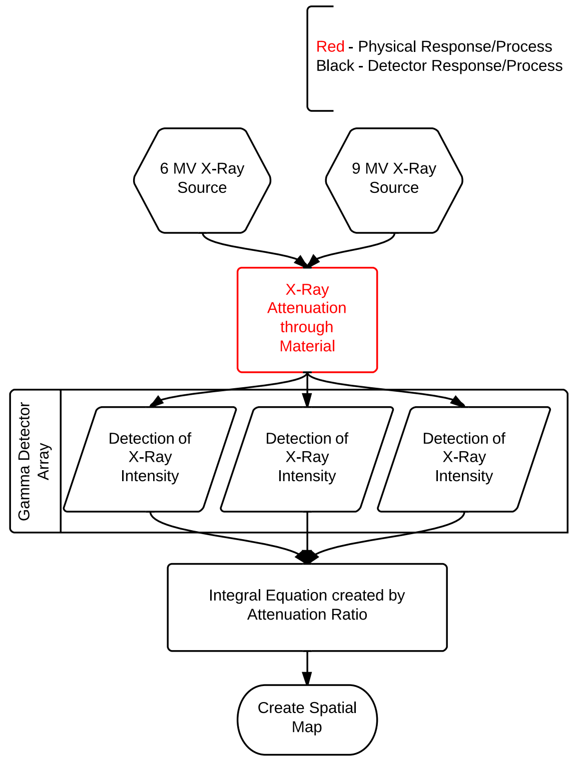

Figure 3: Dual Energy X-Ray Process Diagram [6, 3]

comparing the Bremsstrahlung spectra detected, distinguishing characteristics can be determined for certain high Z materials, most notably tungsten. The physical setup of this process is very similar to Dual Energy X-Ray Process and thus a new diagram has not been created. The simple difference is that there are detectors placed in backscatter regions that compare the Bremsstrahlung spectrum.

Limitations of this system are very similar to Dual Energy X-Ray interrogation. In this case, the collimation of the beam has a direct influence on the voxel size, but also has an indirect influence on the number of X-Ray detectors needed. This causes an optimization problem for the amount of collimation. The intensity resolution requirement is very large, as the estimated amount of Bremsstrahlung is $10^{-12} \frac{\gamma}{cm^2 \cdot e^-}$. This process does show distinguishing characteristics, but has few practical uses at it's current level of technological sophistication [6].

I|B.2.3 Dual Species Radiography

Supplementation of any X-Ray interrogation technique with a fast neutron analysis technique generates exponentially more information. This is because of the fundamental interactions between neutrons and X-Rays in high Z materials. The discrimination of high Z material becomes much higher resolution, and certain materials that would shield will not effect the others, creating a much more robust detection technique. This has been shown as a successful and promising technique since 1999 [14, 6].

I|C Summary

Gozani's paper lays out the motivation for SNM detection techniques, and discusses the history of techniques. He makes a defining split between conventional methods and non-conventional methods, and then describes the methods he considers non-conventional. His paper discusses two separate types of non-conventional methods, by detecting the nuclear levels of SNMs, and by detecting the high Z of SNMs. The methods that detect the nuclear levels are that of PFNA and NRF, of which he describes PFNA in most detail (as he is one of the founders of this technique). Finally, he discusses the high Z techniques, which all leverage the attenuation of γs inside of SNM. He lays out a table describing the properties of each technique in a table.

Part II

Critique of the Article

II|A Motivation

Motivation for work on SNM detection is well placed and exceedingly important. The prevention of nuclear terror has been listed as one of the 14 grand challenges for engineers in the next century [13]. The prevention of nuclear terror has several different fronts: to intercept weapons already constructed, to disable groups capable of creating weapons, and to safeguard materials needed to create these weapons. The detection of SNMs is paramount in both the first and third of those. By detecting SNMs, it will be possible to quarantine any suspicious packages that may be nuclear terror weapons incoming in the nations ports, and also to block shipment of any material possible to be enriched to SNM as it leaves the country. The motivation Gozani uses to write this paper is noble and has significant support behind it as the country and world moves forward.

With this motivation in mind, Gozani had a choice on the direction the paper should move from there. The paper could be written to a very technical audience, such as other Ph.D. level scientists in his field (as would likely be present at the Application of Accelerators in Research and Industry International Conference, where this paper was presented). This type of paper, which will be referred to as a high level technical paper in this critique, would include theory behind each of the detection methods, the experimental setups used to determine the efficiency and results presented, and future work that may be done. A high level technical paper should provide enough information for a well equipped laboratory to replicate the findings. Another type of paper, a low level industrial paper, would be focused towards an audience of venture capitalists and portal administrators. This type of paper would provide viability information and implementation schemes to describe how the detection techniques might be practically employed.

Gozani's paper did not meet the requirements of either of the two types of papers described. While he discusses lightly the theory behind the techniques, he generally does not provide any experimental information, and in some cases no results. It would be impossible to replicate his findings from only this paper. On many of these techniques, Gozani does not even describe the type of detector employed. Gozani obviously chose not to write a high level technical paper, which is prudent, as each of the different techniques has several papers written describing the high level theory and experimental setups used for discovery and optimization of that technique.

Gozani, though, does not provide a pragmatic paper, either. The final summary of Gozani's paper is a table describing the differences between detection technique. This table lists the basis, source, technique, reaction type, specificity, and sensitivity of each technique. This provide enough information for a college student doing a project on the state of the art of SNM detection, but does not provide enough information for industry professionals to make decisions on implementation of these methods, or for research scientists to begin optimizing or utilizing any method.

Presenting to a group of professionals and researchers in applications of accelerators, Gozani chose not to write an overtly technical paper. He kept his paper to a brief overview of various techniques, and succinctly compared these techniques. While well placed in his motivation, and prudent not to be overly technical in his description, Gozani lacks any important information that a research professional or portal administrator might need to implement the techniques described. He describes the techniques very well, but the effort is wasted as solely a summary paper with no added value to it.

II|B Methods

There are five different detection methods that Gozani discusses. Each of these methods have their distinct advantages and disadvantages, as spelled out by Gozani in the paper. The critique of this paper should not focus on any of the techniques, as the point of the paper is to summarize and not to present new techniques. Gozani himself does most of this critiquing, and specific information about the applicability and merits of each technique are detailed in Part I and in references [1, 3, 6, 9, 14, 15, 17].

II|C Impact

II|C.1 Citations and Referencing

As should be expected from a paper commissioned by an industrial corporation (in this case, Rapiscan Laboratories, Inc.), Gozani's paper is heavily biased towards the techniques developed by his company and their collaborators. Each citation is from an author that has been published on a paper with Gozani in the past. This shows that there is not much diversification or reproduction of Gozani's work, and he has had to rely only on his laboratory group to provide results. This lack of diversification should raise a red flag to reviewers: those that do not have external verification may be lacking major components needed for reproduction, or have chosen a technique so specific that other users would not benefit from using the technique. While it is understandable that Gozani writes a paper on only his discoveries (as that is what he has set out to do), he should diversify the citations about each of the different techniques to provide a broader perspective about the techniques. The paper is a summary on the state of non-conventional SNM detection, not on the work being done at Rapiscan Laboratories.

Gozani also leaves out several important players currently in the SNM detection field. Generally, in SNM detection, new technology is developed in two fields. One is the mathematical and algorithmic optimization of current methods of SNM detection, which is partially spelled out in the companion paper [5]. The second is the development of new non-conventional techniques. One such technique is Tensioned Metastable Fluids Detection (TMFD), which leverages the (n, n) reaction and it's recoils to provide directional information on neutron sources in a passive manner. This technique is unique suited for accelerator applications, as it can be phase locked against the incident accelerator source, and detect only the fission neutrons. TMFD is similar other non-conventional techniques in that it works on detecting as directly as possible the neutrons emitted from SNMs. Gozani focuses on techniques that are well removed from the direct emission of the neutrons in SNMs, and thus his summary paper about active interrogation is instead outdated and incomplete in its summarization.

II|C.2 Portal Monitoring and Transportation Safety Impact

This paper in general has had very little impact on portal monitoring and transportation safety. In general, portals currently use ^3He tube technology and spectrum analysis algorithms to determine the presence of SNM in containers passing through their boundaries. This is a conventional technique that is spelled out in the companion paper by Gozani [5]. The non-conventional techniques spelled out in Gozani's paper are currently under development and not prepared for field use. Of the techniques described, PFNA has the highest Technology Readiness Level (TRL) and will likely be implemented in the field first. This is because of it's use of less expensive γ detectors (NaI vs. Ge detectors) and the inherent information about two dimensional geometry in a single system. While all of these techniques require a prohibitive amount of electronics back end and high cost components, the components used in PFNA are the most easily accessible.

The impact of these techniques on portal monitoring is small not only because of their low TRLs, but because of the complexity of each of the systems. Presented at an accelerator applications, it is only sensible that these techniques are active techniques. They require the targeting and excitation of the material to be detected, which requires that all material passing through the portal be targeted and interrogated. This is temporally prohibitive in the time sensitive world of shipping, as well as power and resources consumptive. The price and complexity of each system is also prohibitive. At minimum, each system requires one γ detector tube, an amplifier, a high voltage supply, a preamplifier, a signal discriminator, and a multichannel analyzer. Many require computing resources to deconstruct the spectra, and many require multiple units of above described systems to provide any resolution. Finally, and most importantly, each of these techniques detects at the least a secondary event. Many of these detect a tertiary event of fission or nucleus excitation. The detections caused will have false positives from other materials with similar spectra or Z numbers, and thus the techniques become exceedingly time prohibitive because of the amount of cargo that will need to be rechecked.

Part III

Extension of the Article

III|A Introduction

There are several aspects of this article that should be extended upon. As a summary of non-conventional techniques for SNM detection, the article includes neither sufficient theory nor application details. In this way, it may be useful to expand the article in one of these directions. For the extension given below, application details and possible details for implementation will be given. This extension will serve to replace the Gozani's summaries for each technique. As a final deliverable, a more comprehensive and usable table comparing the methods will be developed.

III|B Methods

In order to provide a full implementation description of each technique, the equipment used, efficiency for detection, spatial resolution achieved, and any added-value benefits of each technique should be listed. The techniques analyzed will be only those discussed by Gozani in his article, although there are many others that could be investigated. In general, literature review and a working knowledge of experimental setups were used to compile the information required.

III|B.1 Equipment Involved (Bill of Materials)

The equipment involved can be gleaned from Gozani's description of each technique. These techniques use a combination of different types of γ detectors, and neutron, e^-, or γ accelerators. Thus, a working knowledge of these detectors and the drive-train electronics must be employed to provide an accurate Bill of Materials (BOM). The complexity of these systems makes the bill of materials prohibitively long, so only major components will be used[10].

III|B.2 Efficiency of SNM Detection

In order to analyze the efficiency of SNM detection, several factors must be taken into account. A metric which could be used to vet these is the standard of detection of an 8 kg sphere of Plutonium set by the International Atomic Energy Agency (IAEA)[7]. This type of analysis is beyond the scope of this review and has not been carried out. A separate metric on which to analyze these techniques is to compare to current standards. Pacific Northwest National Laboratory (PNNL) has generated a standard for non-proliferation. This standard depends on the ability to detect SNMs as they are transported. This standard describes a detection criteria to which the techniques listed by Gozani can be held. The standard requires that absolute detection efficiency should be above 2.5 $\frac{cps}{ng}$ of ^{252}Cf at a standoff of $2\,m$ from the geometric center of the system[11]. In the cases that the literature states a count rate and a source strength, an efficiency will be defined as $\eta_{eff} \equiv \frac{\#\, detections}{\#\, source\, particles}$. This will be an exact efficiency of the application of the accelerator. In cases that the literature does not state these results, MCNP modeling could be done to determine this. Input decks for geometry and cell definitions have been created and could be used to create these simulations. The plane source, materials, and importance weighting in each case should be determined by the experimenter. This is beyond the scope of the experiment, as the literature does not provide accelerator nor detector information for many of the cases present.

III|B.3 Spatial Resolution

Gozani does a sufficient job of describing the spatial resolution of each of these techniques. For some of the techniques, the voxel size is dependent on the number of detectors used, and thus will be analyzed only for the BOM given. This should be considered in the final overall rating, as these types of systems could be optimized for cost vs. resolution.

III|B.4 Added Value

The added value of certain systems will be discussed on a case by case basis, from the advantages given by Gozani.

III|B.5 Overall Rating

The creation of an overall rating is not as straightforward as the compilation of the above material. The design process for a rating system is as follows:

- ➢ Determine quantitative value for each of the above sections
  - ≻ Bill of Materials - the complexity, cost, and common modes of failure will increase with each part in the BOM. Thus, the BOM factor will be determined solely off of the number of total parts in the BOM, $\lambda_{BOM,i} = 1 - \frac{n_i}{n_{max}}$, where n_i is the number of parts in the current technique, and n_{max} is the maximum parts of any technique analyzed. More advanced weighting schemes could be developed, for instance the parts could be weighted on their cost, power consumption, probability of failure, or difficulty to use.
  - ≻ Efficiency - an increase in the efficiency of the detector is desired, and this quantity is already normalized. Thus the value used to determine the efficiency factor is $\lambda_{eff,i} \equiv \eta_{eff,i}$ where $\eta_{eff,i}$ is the efficiency of the technique as calculated above.
  - ≻ Spatial Resolution - the increase of the spatial resolution is desired, thus a normalized quantity directly proportional to the resolution should be used. This value will be defined as $\lambda_{res,i} \equiv \frac{res_i}{res_{max}}$ where res_{max} is the maximum resolution of any technique given, and res_i is the resolution of the current technique. The resolution of the current technique (res_i) will be given by the number of voxels per square inch.
  - ≻ Added value - this will not be involved

in the overall rating, as it will be implemented as a supplement for each system. As such, the added value section will not include any essential features.

➢ Determine weighting scheme for each of the above sections - The weighting of these schemes is the most difficult and convoluted process. For different applications of these detectors, different weighting schemes would be important. For the application of a portal monitor, an adaptive weighting scheme will be used. The adaptive scheme is verbally defined as this: For techniques in which the $\lambda_{BOM} < 0.50$, the efficiency and spatial resolution will be weighted as twice their nominal values. For techniques in which the $\lambda_{BOM} \geq 0.50$, the expression $\lambda \equiv \lambda_{BOM}^2 + \lambda_{eff} + \lambda_{res}$ will be the overall factor. To explain this verbal definition, performance will excuse the increased cost and complexity, whereas for an elegant design, this is it's main selling point (although this effect should be mitigated by the performance). This is, admittedly, quite an arbitrary scheme. It would be possible to either interview portal monitor administrators, or to develop a neural network to weight the methods correctly.

➢ Determine additive or product scheme - The scheme must be additive, as the normalization of the above factors have determined the range to be $\lambda \exists [0, 1]$. If the scheme were product, certain overall factors would be trivial.

➢ Calculate Overall Performance Factors.

III|C Results

The following pages serve as white sheets for the four techniques Gozani provides. The BOMs have been developed straight out of Gozani's descriptions [6], and any missing components testifies to Gozani's lack of detail. The calculations provided have been done as transparently as possible and show the performance factor developed for each component.

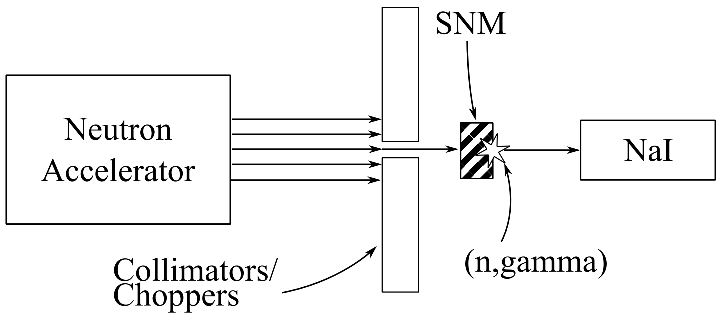

Figure 4: PFNA Detector Schematic

Table 1: PFNA Bill of Materials

	Part	#	**Assembly**
1	Neutron Accelerator ($8.5\,MeV$)	1	Activation
2	Collimator	1	Activation
3	Neutron Chopper	1	Activation
4	Gantry	1	Activation/ Detection
5	γ Detector (NaI)	1	Detection
6	Amplifier	1	Detection
7	Multi Channel Analyzer	1	Detection
8	Data Acquisition	1	Detection/ Analysis
9	Data Processor	1	Analysis

$$\lambda_{BOM,PFNA} = 1 - \frac{n_{PFNA}}{n_{max}} = 1 - \frac{9}{104} = 0.913$$

$$\lambda_{eff,PFNA} \equiv \eta_{eff,PFNA}$$

$$\lambda_{res,i} \equiv \frac{res_i}{res_{max}} = \frac{3.22\,voxel/in^2}{3.22\,voxel/in^2} = 1 \quad [12, \text{p. } 1]$$

$$\lambda_{PFNA} = w_{BOM,PFNA}(\lambda_{BOM,PFNA}) + w_{eff,PFNA}(\lambda_{eff,PFNA}) + w_{res,PFNA}(\lambda_{res,PFNA})$$

$$\lambda_{PFNA} = (0.913)^2 + \lambda_{eff,PFNA} + 1 = 1.834 + \lambda_{eff,PFNA}$$

Added Value: Temporal Resolution

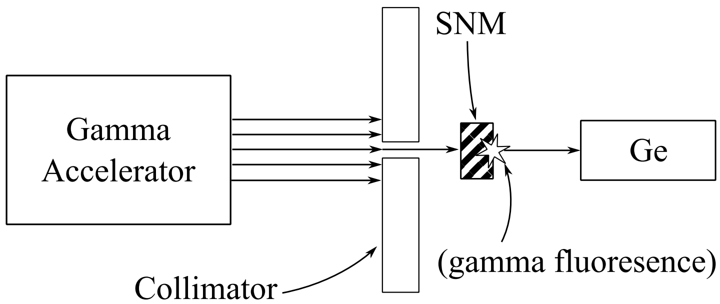

Figure 5: Nuclear Resonance Fluorescence Schematic

Table 2: NRF Bill of Materials

	Part	#	**Assembly**
1	Bremsstrahlung CW Electron Based X-Ray Source Accelerator	1	Activation
2	Collimator	1	Activation
3	Neutron Chopper	1	Activation
4	γ Detector (Ge)	25	Detection
5	Amplifier	25	Detection
6	Multi Channel Analyzer	25	Detection
7	Data Acquisition	25	Detection/ Analysis
8	Data Processor (Compare Bremsstrahlung Peaks)	1	Analysis

$$\lambda_{BOM,NRF} = 1 - \frac{n_{NRF}}{n_{max}} = 1 - \frac{104}{104} = 0$$

$$\lambda_{eff,NRF} \equiv \eta_{eff,NRF} = \frac{28\,counts}{1 \times 10^5\,\frac{\gamma}{s} \cdot 3600\,s} = 7.78 \times 10^{-8} \quad [16, \text{p. } 015103\text{-}3]$$

$$\lambda_{res,NRF} \equiv \frac{res_{NRF}}{res_{max}} = \frac{0.654\,voxel/in^2}{3.22\,voxel/in^2} = 0.203 \quad [2, \text{p. } 2]$$

$$\lambda_{NRF} = w_{BOM,NRF}(\lambda_{BOM,NRF}) + w_{eff,NRF}(\lambda_{eff,NRF}) + w_{res,NRF}(\lambda_{res,NRF})$$

$$\lambda_{NRF} = 0 + 2 \cdot (7.78 \times 10^{-8}) + 2 \cdot (0.203) = 0.406$$

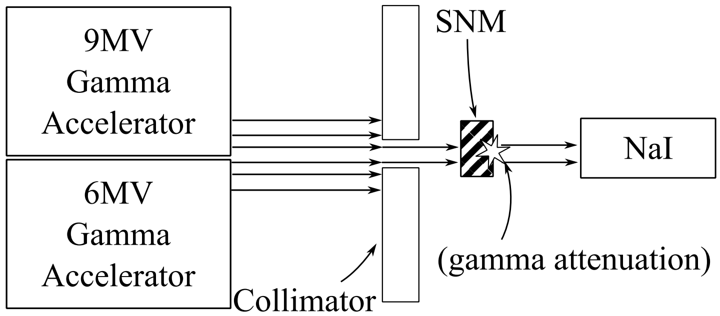

Figure 6: Dual X-Ray Radiography Schematic

Table 3: Dual X-Ray Radiography Bill of Materials

	Part	#	Assembly
1	Electron Accelerator (6 MV or 4.5 MV)	1	Activation
2	Second Electron Accelerator (9 MV or 6 MV)	1	Activation
3	Attenuators	1	Attenuators
4	γ Detectors (NaI)	25	Detection
5	Amplifier	25	Detection
6	Multi Channel Analyzer	25	Detection
7	Data Acquisition	25	Detection/ Analysis
8	Data Processor (Compare Bremsstrahlung Peaks)	1	Analysis

$$\lambda_{BOM,DXR} = 1 - \frac{n_{DXR}}{n_{max}} = 1 - \frac{104}{104} = 0$$

$$\lambda_{eff,DXR} \equiv \eta_{eff,DXR}$$

$$\lambda_{res,DXR} \equiv \frac{res_{DXR}}{res_{max}} = \frac{1\,voxel/in^2}{3.22\,voxel/in^2} = 0.311 \quad [8,\text{ p. } 98]$$

$$\lambda_{DXR} = w_{BOM,DXR}(\lambda_{BOM,DXR}) + w_{eff,DXR}(\lambda_{eff,DXR}) + w_{res,DXR}(\lambda_{res,DXR})$$

$$\lambda_{DXR} = 0 + 2 \cdot (\lambda_{eff,DXR}) + 2 \cdot (0.311) = 0.622 + 2 \cdot \lambda_{eff,DXR}$$

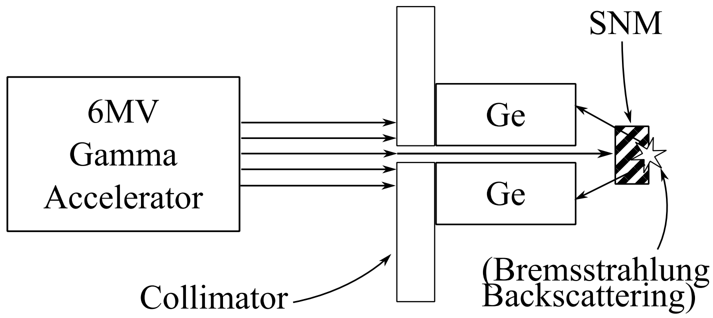

Figure 7: High Energy Bremsstrahlung Backscattering Schematic

Table 4: High Energy Bremsstrahlung Backscattering

	Part	#	**Assembly**
1	Neutron Accelerator	1	Activation
2	Collimator	1	Activation
3	Neutron Chopper	1	Activation
4	γ Detector (Ge)	25	Detection
5	Amplifier	25	Detection
6	Multi Channel Analyzer	25	Detection
7	Data Acquisition	25	Detection/ Analysis
8	Data Processor (Compare Bremsstrahlung Peaks)	1	Analysis

$$\lambda_{BOM,HEBB} = 1 - \frac{n_{HEBB}}{n_{max}} = 1 - \frac{104}{104} = 0$$

$$\lambda_{eff,HEBB} \equiv \eta_{eff,HEBB}$$

$$\lambda_{res,HEBB} \equiv \frac{res_{HEBB}}{res_{max}} = \frac{0.645\, voxel/in^2}{3.22\, voxel/in^2} = 0.203 \quad [2, \text{p. } 2]$$

$$\lambda_{HEBB} = w_{BOM,HEBB}(\lambda_{BOM,HEBB}) + w_{eff,HEBB}(\lambda_{eff,HEBB}) + w_{res,HEBB}(\lambda_{res,HEBB})$$

$$\lambda_{HEBB} = 0 + 2 \cdot (\lambda_{eff,HEBB}) + 2 \cdot (0.203) = 0.406 + 2 \cdot \lambda_{eff,HEBB}$$

III|C.5 Overall

The overall factors are given below in one table.

Table 5: Overall Factor Scores of Techniques

Technique	Overall Performance Factor
PFNA	$1.834 + \lambda_{eff,PFNA}$
NRF	0.0412
DXR	$0.0967 + \lambda^2_{eff,DXR}$
HEBB	$0.0412 + \lambda^2_{eff,HEBB}$

III|D Conclusion

White pages for each different technique have been created, with an overall factor scheme created to compare the techniques against each other. It is quite difficult to create this scheme. As an academic exercise, a scheme was created. In practice, a scheme using MCNP to model the efficiency of each detector, and interviews or a neural network to determine the importance of each identified factor to the portal monitoring industry.

Part IV

Conclusion

Gozani outlines only several methods: those that he and his colleagues have been involved with. These methods are Pulsed Fast Neutron Analysis, Nuclear Resonance Fluorescence, Dual X-Ray Radiography, and High Energy Bremsstrahlung Backscattering. The PFNA is an active interrogation technique which utilizes the inelastic neutron scattering cross section of SNM. The advantages of this technique are that it achieves spatial resonance without using multiple detectors. NRF takes advantage of a fluorescent reaction in SNM during γ irradiation, and an array of detectors provides spatial resolution. The disadvantage of NRF is that it requires very high resolution detectors such as Germanium. Dual X-Ray Radiography compares the difference of attenuation between two different X-Ray sources and is able to back out high resolution images from this process. The difficulty in this process is the deconvolution of the spatial distribution of attenuators. Large assumptions of the geometry and composition must be made. Finally, High Energy Bremsstrahlung Backscattering takes advantage of a peak of Bremsstrahlung in the backward directions in SNM. Again, this requires a high resolution detector such as Germanium, and also has extremely low efficiency because of the requirement of backscattering for detection.

Overall, Gozani does not diversify the techniques reviewed well. Many of the materials he offers are those of his and his colleagues research. While this is expected for papers published about certain technical areas, Gozani bills his paper as a summary of techniques. Finally, the end result of a comparison table Gozani promised is provided, but only provides succinct descriptions of each factor. If one were to use this table as a tool to compare these techniques, very little information would be able to be determined.

To extend this article, a process was created by which the techniques could be compared on a portal administrator sophistication level. This process culminates in a overall performance factor, given by the expression

$$\lambda_i = w_{BOM,i}(\lambda_{BOM,i}) + w_{eff,i}(\lambda_{eff,i}) + w_{res,i}(\lambda_{res,i})$$

where

$$w(\lambda) = \begin{cases} \lambda_{BOM}, 2 \cdot \lambda_{eff}, 2 \cdot \lambda_{res} & \lambda_{BOM} < 0.50 \\ \lambda_{BOM}^2, \lambda_{eff}, \lambda_{res} & \lambda_{BOM} \geq 0.50 \end{cases}$$

Without efficiency values for each technique, the comparison of the techniques is impossible. MCNP modeling could be used to determine efficiencies for the techniques in which the efficiency was not found. Currently, the results of this weighting are found in Table 5. They show that PFNA, Gozani's own work, is likely so advantaged by it's simple BOM, that for reasonable efficiencies of other detector, it would be the preferable detector.

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