FAST ENRICHMENT SCREENING FOR 'GO/NO GO' CLASSIFICATION OF LARGE CONTAINERS

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ABSTRACT

Methods for rapid non-destructive uranium enrichment classification of large containers are of importance to waste consignors, safeguards and counter-terrorism agencies. There is often a need to quickly categorize and segregate suspect containers as 'depleted' or 'enriched' on a 'Go/No Go' basis.

Recent improvements in gamma spectroscopy technologies have provided the capability to perform rapid field analysis using portable and hand-held devices such as battery-operated medium and high resolution detectors (including lanthanum halide and high purity germanium). Furthermore a new generation of portal monitors are currently under development with advanced spectroscopic capabilities. Instruments and technologies that were previously the domain of complex lab systems are now widely available as touch-screen "off-the-shelf" units. Despite such advances, the task of enrichment analysis remains a complex exercise. This is particularly so when surveying large items such as historic waste drums and crates containing debris of unknown density and composition contaminated with uranium.

The challenge is equally applicable to safeguards inspectors evaluating large items and for interdiction of illicit special nuclear materials in mass transport e.g. shipping containers at ports and borders. The variable shielding, container size, lack of matrix knowledge, wall thickness and self-shielding compound this problem. Performing an accurate assessment within the short count time window demanded of the field operative, leads to the need for a reliable method that can adapt to such conditions and is robust to a wide dynamic range of counting statistics.

Several methods are evaluated with reference to the performance metrics defined in applicable standards (such as ANSI N42.43-2006). The primary issue is to minimize the bias that can result from attenuation effects, particularly as the gamma emissions from U235 are low energy and therefore highly susceptible to absorption in large containers with metal scrap. Use of other radiometric signatures such as bremsstrahlung radiation and neutron emissions are considered in addition to photopeak ratio analysis. Benchmark comparisons are performed against well-established enrichment analysis methods such as PC-FRAM, MGAU, and the Enrichment Meter. The suitability/limitations of the more traditional methods is discussed.

INTRODUCTION

A need exists for non-destructive assay equipment and techniques that can perform rapid uranium enrichment classification. In particular the ability to perform real-time 'Go/No Go' segregation of large objects and containers as 'depleted' or 'enriched' provides a major transformational impact for waste consignors, safeguards inspectors and counter-terrorism agencies. Materials being released from nuclear facilities must be categorized for appropriate waste sentencing as well as domestic and international materials control and accountability. At ports and borders, the same technology can be used to screen large containers suspected to contain illicit shipments of enriched uranium with a sufficiently high throughput and accuracy to minimize impact to the flow of commerce.

REQUIREMENTS

The specific requirements include:

1. Capability to perform non-destructive/non-intrusive scanning of a whole container at a time. Container sizes will vary from small suitcase size packages through to full size intermodal shipping containers.

2. One of the greatest technical challenges involves compensating for the presence of matrix materials inside the container including mixtures of organics and metals with varying density.
3. Survey times must be configurable to the specific application. For example in a high throughput customs/border application the survey must complete in less than five minutes. In the safeguards arena more time is available but generally in order to be effective operationally, the survey must be completed in one hour or less for the entire container in order to achieve a reasonable throughput. The performance goal is very much driven by the need to minimize false alarms (i.e. mis-categorization).
4. Reliability and ruggedness of the equipment must also be taken into account when designing a system for the end user. Hard working long life components should be sought. Electronics should feature minimal gain drift or automatically compensate for this. Tough field conditions must also be taken into account, operating in four seasons in extreme real world environments from the desert to the arctic.
5. Ease of operation and maintenance is another factor. Self- or auto-calibration should be included in the design and where possible off-the shelf components used for detectors and electronics. Ready access for spare parts and servicing is critical for the long term viability of such a system. The system software and user interface must be designed for rapid operation in the field.

TRADITIONAL METHODS FOR ENRICHMENT MEASUREMENT

The analysis of uranium centers on accurate enrichment measurements. Most software will quantify using one isotope (U235 or U238) and then apply the enrichment factor for determining the other uranium isotopic content. The U234 component is determined mainly by assigned alpha ratios for a cascade even though in some instances it may be directly measured. There are three methods for determining enrichment (see Table 1).

Infinite Thickness Method

The Infinite Thickness Method (or Enrichment Meter Technique) uses either two or three region-of-interests to measure the 185.7 keV peak and its associated background area. This method is applied only for uranium enrichment measurements and it is based on a calibration using reference samples. The most prominent gamma transition of 185.7 keV from the decay of U235 is measured under a well-defined geometry (i.e., solid angle of the sensitive detector volume relative to the gamma source). The measured counting rate of the 185.7 keV photons is proportional to the U235 abundance. The method is best suited for bulk samples (e.g., uranium oxides and fluorides in storage containers), which easily meet the infinite thickness requirement. Enrichment measurements based on the infinite thickness method require physical standards containing a sufficiently large amount of uranium reference material for calibration. The enrichment of a uranium bearing item is the fraction of U235 to the total uranium present in the item. The infinite thickness method is applicable to items containing depleted uranium (< 0.72% U235 fraction) up to highly enriched uranium (HEU) with greater than 90% U235 enrichment. In general, three sample conditions must be met for the enrichment meter principle to be applicable:

- First the sample must have a uniform distribution of material that is isotopically uniform and a uniform matrix distribution. The waste cannot be mixed uranium but must be a pure uranium compound (UF6, UO2, etc.).
- Second, the daughter activities must be in secular equilibrium with the parent uranium activities.
- Finally, the material must be infinitely thick with respect to the 185.7 keV gamma peak throughout the entire field of view of the detector as defined by the sample attenuation, collimator, and detector.

This measurement technique is calibrated using two or more reference samples of know enrichment. Using references that are representative of unknowns with respect to container thickness, material type and enrichment, it is possible to make measurements with relatively good accuracy. The method

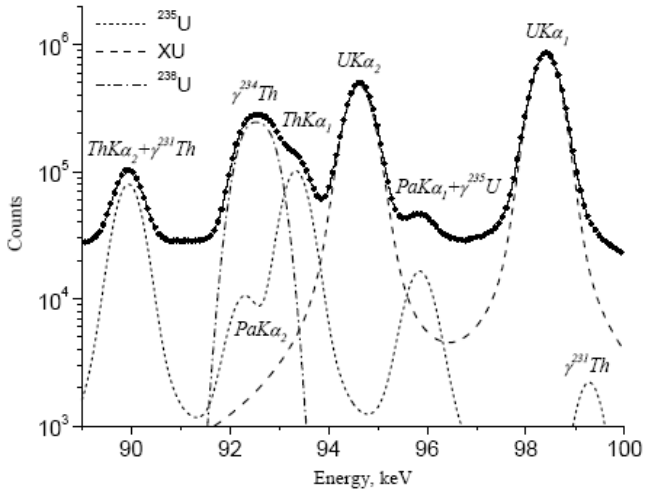
becomes less accurate when non-representative references are available or the material type, packaging and gamma ray background is varying from sample to sample. Also, a large gamma ray background can reduce the accuracy of the results.

In particular, the enrichment meter relies upon the sample container wall being well known. A simple correction can be made where the reference standard's container wall differs from the measured sample. If there is variability in the thickness of the container wall among samples, then a dynamic correction factor is required (usually this requires an ultrasonic measurement of the container wall).

Peak Ratio or Intrinsic Calibration

Measurements based on the intrinsic calibration method avoid the need for calibration with physical standards. Here, the isotopic ratios are determined from the measured gamma spectrum using corresponding gamma and x-rays from the decay of all isotopes, taking into account physical phenomena such as the energy dependence of detector efficiency, self-absorption in the sample and attenuation in the container and filters. For uranium spectra, the x-ray analysis method [1] uses analysis of the XKα region (89-99 keV) where fairly abundant but strongly overlapping gamma and x-ray signatures from the U235 and U238 daughter nuclides Th231 and Th234 occur. This approach requires secular equilibrium between U238 and its daughter nuclides, which is reached about 80 days after chemical separation: the method is, therefore, not suited to freshly separated uranium materials.

The x-ray region is highly susceptible to interference from other x-rays that may be present in the sample (such as elevated Th, Np237, and Ac227). For this reason, the intrinsic calibration method has also been further developed to include a full-spectrum analysis mode that analyzes peaks across the full energy of the spectrum [2].



U238	Uranium
92.38 keV	98.43 keV (UKα1)
92.80 keV Th234	94.65 keV (UKα2)
U235	
93.35 keV (ThKα1)	99.28 keV (Th231)
89.96 keV (ThKα2)	95.86 keV (PaKα1)
96.09 keV (U235)	92.28 keV (PaKα2)

Figure 1. Uranium spectrum in the 89- to 100- keV region.

The peak ratio methods analyze the 89-100 keV and 121-1001 keV energy regions and require no calibration (outside the detector parameters). This technique is used only with high-resolution (HPGe) systems. For wall thicknesses of greater than 10 mm of steel, the low energy (89-100 keV) region is heavily attenuated, so the higher energy region is favored. With this method it should be noted that it is not necessary to gauge or know the cylinder wall thickness as the response function algorithm corrects for the automatically.

Whereas MGAU exclusively uses the low energy region, PC-FRAM is supplied with several 'parameter files' that allow an intelligent user to select an appropriate analysis route. Furthermore, non-equilibrium conditions between U238 and Pa234m can be corrected for with PC-FRAM. However, in all situations, the user must pay careful attention to the possibility of interfering lines and non-physical response functions that can result from energy calibration drift, poor counting statistics

or other sources of bias. In particular the presence of elevated levels of thorium can cause problems for the PC-FRAM analysis in the 121 – 1001 keV region.

Other commercial software packages such as ISOTOPIC [3] software follow similar principles to the PC-FRAM method using peaks across the full energy region of the spectrum.

In general, four sample conditions must be met for the peak ratio principle to be applicable:

- First the sample must be in secular equilibrium (PC-FRAM is the only code that can correct for this provided that separation time is known).
- Second, the presence of other x-rays can give the incorrect answer if the analysis is performed in only the x-ray region.
- Third, the user must we aware of interference that can occur in the higher energy regions, for example from the presence of high levels of thorium.
- Finally, when using the low energy region (the only available region in MGAU), the wall thickness of the item must be thin (< 10 mm). This can be overcome with use of the high energy region available in PC-FRAM.

HEU is challenging unless there are enough counting statistics for measuring the U238 in full-spectrum analysis mode.

Table 1. Software for Enrichment Measurements

Method	Detector Resolution			Software	Availability	Max Wall Thickness (Steel)
	Low	Med	High			
Enrichment Meter	X	X	X	WinU235	GBS	15 mm
	X	X	X	WinUF6	GBS	
			X	MGA ++	Ortec	
			X	MGAU	Various	
Peak Ratio			X	U235HI	LLNL	5-15 mm
			X	UEnrich	Portsmouth	
		X		CZTU	Ortec	
		X	X	MGAU	Various	
		X	X	MGA ++	Ortec	
			X	ISOTOPIC	Ortec	
		X	X	PC FRAM	Various	
Peak Fit	X			NaIGEM	R. Gunnick	15 mm

Peak Fitting Method

An improvement to the traditional enrichment-meter method of determining U enrichments applicable to material containing reactor returns, is made by fitting computed response profiles to the observed data of NaI spectra in the 130 to 290 keV region. This new method has been incorporated into a computer analysis code called NaIGEM [4] (NaI Gamma Enrichment Measurements). Analysis improvements include automatic correction for changes in gain and detector resolution between and during data acquisition. Additionally, the calibration of the system requires only a single reference sample spectrum. The calibration can be permanent and be applied to any detector collimator assembly of identical design. Since peak fitting is applied to the spectrum, large Compton continuum and interference peaks can be accounted for.

Designed specifically for the IAEA verification of UF_6 cylinders, a fully integrated electrically cooled portable HPGe system is available from AMETEK Ortec known as the Portable UF_6 Cylinder Verification System [5]. This package includes a tungsten collimator and the system is operated on

the device using a touch screen LCD display with on board software that is an adapted version of the IAEA NaIGEM enrichment meter. The 50mm diameter x 30 mm depth HPGe detector is cooled with a Stirling Cooler that can operate on battery or AC power.

RECENT ADVANCES IN SPECTROSCOPY

The past decade has seen numerous improvements in commercially available gamma spectroscopy technologies. Driven by the need for improved field analysis capabilities for security and safeguards, many software packages have been developed for rapid analysis and identification of nuclides. Portable and hand-held battery operated devices have entered the market with on board spectral de-convolution and automated nuclide identification. Lanthanum halide based scintillators now offer improved resolution and larger volume detectors over traditional medium resolution detectors such as cadmium zinc telluride.

When evaluating the practical implications in deployment of advance spectroscopic methods it is useful to consider the recent developments in radiation portal monitors (RPMs). These devices are widely used in the United States and now scan the majority of freight moving through the US ports of entry. Most of these RPMs use PVT plastic scintillation detectors and neutron detectors and thus have a limited ability to discriminate nuclides. This capability is augmented by hand-held radioisotope identification devices (RIIDs) which are also in use at ports. Standard procedures at ports usually involve a container driven through the 'primary screening' RPM. When an alarm is raised (gamma or neutron count rate above a pre-defined threshold) the container will be diverted to an area (usually a lane) dedicated to secondary screening.

Detectable amounts of radioactive material are present in a significant fraction of ordinary cargo. High levels of naturally occurring radioactive material (NORM) can commonly cause false alarms. During secondary screening, the suspect container may be examined with a spectroscopic RIID, which is capable of identifying illicit radioactive materials.

A new generation of Advanced Spectroscopic Portal monitors (ASPs) have been developed to address the nuclide identification need in primary screening. However, the current performance levels of these detectors (usually based on low resolution gamma spectroscopy) have led to re-evaluation of the logistical benefits of this technology compared to traditional primary/secondary screening process. Consider the scenario of a container that triggers a primary alarm in a PVT based RPM. It may take 15 minutes or more to resolve this alarm, depending on the port of entry configuration and the relative ease of identifying the source of radiation. ASPs do not reduce this delay for containers that trigger a primary alarm. The result of deploying ASPs that meet the required nuclide discrimination criteria (with a lower false alarm rate) would only be a slight reduction in the time spent in screening overall.

Screening cargo with a handheld RIID may take several minutes or more, depending on how rapidly the alarm can be resolved. However, the time required to carry out screening is only one factor in the overall impact on operations at ports. As a result, the system of radiation screening, using non-spectroscopic RPMs and secondary screening with RIIDs, does not significantly impede the flow of commerce.

The conclusion drawn here is that when developing new spectroscopic evaluation technologies it is essential that equal weight must be given to both technical performance and the impact upon logistical processes used in screening.

PERFORMANCE SPECIFICATION

In order to define specific performance requirements for rapid enrichment screening, it is useful to examine relevant existing standards in homeland security, safeguards and waste disposal.

The US Department of Homeland Security Domestic Nuclear Detection Office (DNDO) has adopted the ANSI/IEEE American Standards Committee on Radiation Instrumentation N42 standards against

which to test and evaluate radiation detection instruments. The two most relevant standards relating to technical performance criteria are: ANSI N42.34-2006 and ANSI N42.43-2006.

American National Standard Performance Criteria for Mobile and Transportable Radiation Monitors Used for Homeland Security (ANSI N42.43-2006) specifies the operational and performance requirements for transportable and/or mobile radiation monitors used in homeland security. Performance requirements and tests are given in relation to radionuclide identification. The standard broadly covers devices that do not have permanent mounting platforms including those mounted to vehicles, trailers, watercraft and cranes and those used while being carried by a person such as a backpack.

American National Standard Performance Criteria for Hand-Held Instruments for the Detection and Identification of Radionuclides (ANSI N42.34-2006) defines U235 and U238 as nuclides of interest but does not call out the need for the instrument to be able to determine enrichment of any uranium identified.

ISO 22188:2004 specifies methods and means of monitoring for inadvertent movement and illicit trafficking of radioactive material. It provides guidelines on the use of both stationary and portable (e.g. hand-held) instruments to monitor for radiation signatures from radioactive material. Emphasis is placed on the operational aspects, i.e. requirements derived for monitoring of traffic and commodities mainly at border-crossing facilities including maritime ports, airports, and similar locations where goods or individuals are being checked. This standard does not address the issue of detection of radioactive materials at recycling facilities, although it is recognized that trans-boundary movement of metals for recycling occurs, and that monitoring of scrap metals may be done at the borders of a state.

The IAEA has developed a series of guidelines and prescriptive specifications relating to performance of instrumentation used for detecting radioactive materials crossing international borders [6] and an extensive study has been performed on existing equipment and techniques [7]. These IAEA standards are broadly in line with the ANSI N42 requirements.

Another relevant international project is the Illicit Trafficking Radiation Assessment Program (ITRAP). This falls under the organization of the European Union in collaboration of the IAEA, World Customs Organization (WCO), INTERPOL and the US DNDO. ITRAP provides funding and laboratories for collaborative studies and testing of equipment for border monitoring. The aim of ITRAP is to develop consensus standards, establishing technical requirements and address practical issues that relate to border radiation detection equipment [8].

Waste disposal standards/acceptance criteria may also be considered. The Waste Acceptance Criteria at US DOE's Low Level Waste Repository at the Nevada Test Site [9], states that "*waste containing uranium with an enrichment of less than 0.90 percent U235 by weight…does not provide a fissile material concern*". NTS requires that consignors report the enrichment of uranium in excess of this threshold and apply specific fissile material limitations to each package. The Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant [10], requires that radioassay on contact handled waste is performed and should, at a minimum, be capable of identifying, measuring (or reporting the absence of) U235 in order to calculate the fissile gram equivalent (FGE) content of each waste consignment. For remote handled waste, WIPP has limitations on the enrichment of soil/sludges at less than 0.96% U235 enrichment.

Drawing on the above standards and requirements we can define broad specifications for rapid enrichment screening with mobile and portable devices as follows:

- The device shall have capability to detect a verifiable signal from U235 and/or U238.
- It shall be capable of classifying the detected uranium as one of the following:
    - DU- Depleted Uranium (i.e. %U235 less than 0.72%)
    - Nat U – Natural Uranium (i.e. %U235 of 0.72%)

  - LEU- Low Enriched Uranium (i.e. %U235 in the range 0.72% to 20%)
  - HEU – High Enriched Uranium (i.e. %U235 greater than 20%)
- The lower limits of detection shall be:
  - 4.5 kg for DU (nominally 0.2% U235),
  - 2.0 kg for Nat U (nominally 0.72% U235),
  - 1.0 kg for LEU (nominally 3% U235)
  - 0.2 kg for HEU (nominally 93.5% U235),
- The maximum count time for primary evaluation shall be 1 - 3 minutes maximum, depending on object size.
- The maximum count time for secondary evaluation shall be 10 - 30 minutes, depending on object size. Secondary evaluation defined as a more detailed survey of objects that produce ambiguous results from a primary scan.
- Source sample thickness of 10 mm (for self-shielding purposes).
- Source is either unshielded or shielded by 3 - 5 mm of steel.
- Source nominally at 50 cm from detector (ranging from contact up to 400 cm).
- Capability to detect and classify in the presence of masking radiation e.g. 0.5 μGy/h dose from Cs137, Co57 or Eu152.
- Capability to detect and classify in a background dose rate up to 0.25 μGy/h. The background can be considered to be a continuum over the range 60 keV to 1500 keV.

FAST SCREENING TECHNIQUES

The quickest and simplest means of discriminating HEU from DU is comparison of the strongest photopeaks i.e. 185.7 keV for U235 and the 1001 keV Pa234m daughter of U238 (assuming the U238 is in secular equilibrium with its daughters). This comparison can be a useful indicator: a strong 185.7 keV line without 1001 keV line present will be a good indication that the material is highly enriched. Conversely with depleted uranium it is very likely that only the Pa234m daughter peaks will be visible with the U235 low energy peaks dropping below the Compton continuum as combined result of their weak emission on strong absorption in surrounding shielding materials.

However, caution should be applied when attempting to get a meaningful measure of enrichment by a ratio of the two lines. The significant difference in attenuation can lead to large errors in enrichment unless the shielding, matrix and source materials are well characterized. Therefore a more suitable photopeak for enrichment determination is the 258 keV (Pa234m) peak. This peak is emitted at one tenth of the production rate of the profligate 1001 keV line so this requires a more substantial quantity of uranium in order to be detected under the reference scenarios. Under the reference performance evaluation conditions defined above, this line is detectable for 200g HEU in 600 seconds. For a 60 second count, 750g HEU is required. With depleted, natural, and low enriched (5-10%) uranium, this peak is detectable with their respective reference quantities of uranium in 60 seconds.

For the 258 keV peak, the weak branching ratio is not the only issue. This low energy line will not penetrate more than 3 cm of steel. However, it should be noted that for a large ISO shipping container (heterogeneously filled with a distributed steel matrix), the “visible” outer 3 cm would represent around 3,000 - 4,000 kg of steel. In other words, this is the portion of the box from which the emitted 258 keV photons are detected. Assuming such a container has a net weight in the range 10,000 – 20,000 kg, a gamma based enrichment survey would cover 15-40% of the box contents. Furthermore if we make an argument that the source material is most likely in the form of multiple sources randomly located rather than localized in a single “worst case” point, there is only a small probability that all the uranium present would escape the surveyed region.

It is therefore possible to develop a simple threshold criterion for various survey scenarios by comparison of the 258 keV peak with U235 peaks. The strong peak at 205 keV is most suitable as it lies closest in energy. A simple peak area comparison (205/258 keV) can be developed as follows:

- Mock up the survey scenario with various enrichment sources (e.g. from DU to 10% LEU enrichment and HEU if available).
- Take measurements on these sources with an HPGe detector at various positions with a suitable collimator.
- Repeat the surveys with varying thicknesses of steel plate in front of the detector to simulate shielding (1mm, 3mm, 5mm).
- Analyze the data with a suitable enrichment analysis software e.g. PC-FRAM. Note that the uranium parameter files bundled with PC-FRAM v4.3 and later take care of most of the known issues (interference from thorium etc.) over the range 121 keV to 1001 keV.
- For a representative sample of survey scenarios at different positions and compare the ratio of net peak areas at 205 keV and 258 keV to the known enrichment and correlate to FRAM's measured enrichment.
- For the DU, Nat U, LEU and HEU boundaries:
    - Determine spectral quality indicators that allow correction for shielding and the presence of interfering photopeaks (e.g. thorium).
    - Determine the threshold peak ratios that define each boundary.

Another means of discrimination of HEU from DU is by evaluation of the bremsstrahlung radiation spectrum. The bremsstrahlung spectrum above 100 keV is produced from the high energy beta particles emitted from Pa234m decay. This produces a gamma-ray continuum with a mean energy of 400 keV [11]. This continuum lies underneath the gammas usually used for uranium identification. Such radiation is useful for identifying HEU, particularly in shielded scenarios. HEU normally has very weak photon production in the 1001 keV region, but the bremsstrahlung radiation from Pa234m decay (U238 daughter) produces a strong signal with sufficient energy to penetrate the shielding. By measuring a region of the bremsstrahlung spectrum (e.g. 400 - 600keV) and comparing to the major photopeaks at 185.7-, 258- and 1001 keV it is possible to classify the uranium enrichment and make an evaluation of the nature of the shielding involved.

Finally some consideration should be given to the sample's neutron emission. U235 does not produce spontaneous fission neutrons and U238 produces only a very weak signal from this mechanism. However neutron emission by (alpha, n) does occur in uranium compounds and is often easily detected. U234 is the dominant source of this emission and the U234 fraction follows strongly the U235 enrichment - in fact there is little variation in U234/U235 ratio for DU, NatU and LEU (see Table 2). Of course in the case of pure metal, the neutron emission is negligible regardless of enrichment, but for uranium oxide and uranium hexafluoride the neutron emissivity will be a strong indicator of enrichment. A simple measure of enrichment can therefore be provided by comparing the total neutron count rate with the 1001 keV photon. This method is potentially one of the least susceptible to bias due to attenuation effects as both the emitted fast neutrons and high energy photons can penetrate through thick layers of metal debris. Care should be taken to verify that no other source of neutron emission could be present in the sample (for example Pu240, Cf252 and Cm244).

Table 2. Isotopic composition of uranium

Uranium	U-235	U-234	U-238
Depleted	0.2	0.0012	99.7988
Natural	0.72	0.0055	99.2745
Enriched	2 – 5	0.019 – 0.048	Rest
	3.5	0.03	96.47
High enriched	> 20	> 0.019	Rest
	90	0.88	9.12

CONCLUSIONS

The measurement of uranium enrichment can be a relatively straight-forward approach as long as the measurement is made in a clean environment under well-defined conditions and parameters. Unfortunately, real-world applications do not meet these criteria. Whether measuring waste or cargo the measurement is complicated by high backgrounds, interfering signals (NORM, medical isotopes, etc), unknown shielding characteristics, and stand-off distance.

While the 1001 keV peak of U238 can be detected in most real-world applications, further information as to the enrichment of the uranium is problematic since the presence of the 185.7 keV peak of U235 is susceptible to high backgrounds, shielding, and stand-off. Other enrichment techniques using x-rays or low-energy gamma peak ratios are also hampered. For measurements of waste containers or inspections of UF_6 cylinders and facilities, the problems encountered with possible interferences is overcome with longer counting times and some knowledge as to the attenuating characteristics of the item. However, in security environments (ports of entry) the need is for quick analysis with very limited information on the item being measured.

Masking is the phenomenon that occurs when benign radioactive materials (NORM, medical isotopes) obscure the signature of a radionuclide of interest. This occurs when the benign radionuclide either overwhelms the detector with a stronger signal or creates spectral signals that compromise the algorithm's ability to analyze the spectra. Multiple radionuclide sources in the cargo, including masking materials, produce spectra that are linear sums of the spectra of individual radionuclides. The geometry of the source and masking materials can affect the spectrum, because different radioactive materials can be located in different positions relative to the detectors and any shielding materials.

Masking can be particularly problematic for determining uranium enrichment. In a shipment of kitty litter, for example, the signal is compromised by the natural presence of uranium and thorium in the litter. The masking signal may contain a larger amount of U238 skewing the results of the hidden uranium.

The current state of nuclear detection can be described as one where critical mass quantities of HEU can be shielded and freely transported to almost any destination, easily bypassing the limited radiation detection systems in place at US borders. Due to the low radioactivity of HEU which can be further attenuated by shielding (lead or concrete), a proposed network of fixed radiation detectors dispersed throughout a city or area will not suffice to detect HEU let alone provide for any reliable enrichment measurement.

Performance tests of ASPs showed that they did not meet DNDO's main performance assumption in the cost-benefit analysis of correctly identifying HEU 95 percent of the time it passes through portal monitors. The 95 percent performance assumption included ASPs' ability to both detect bare, or unmasked, HEU in a container and HEU masked in a container with a more benign radiological material. Based on NIST's assessment of the performance data, the ASP prototypes tested at NTS identified bare HEU only 70 to 88 percent of time. NIST reported that the best ASP prototype DNDO tested that won a procurement contract was able to correctly identify masked HEU and depleted uranium only 53 percent of the time. Similarly, the ASP prototypes submitted by the other two companies that won DNDO's ASP procurement were able to identify masked HEU and DU only 45 percent and 17 percent of the time [12].

The inability to detect HEU from a distance, "stand-off", reduces the barrier to HEU trade on the black market since kilogram quantities of HEU can be freely transported to almost any destination worldwide. While an unshielded source of HEU may be seen at distances usable in portal monitors, the real-world scenario where the material is shielded or masked creates difficulty in accurately determining the presence or enrichment.

The only known exception to overcoming background, shielding, and stand-off is when the uranium was produced from nuclear reactor feedstock or in facilities previously contaminated by reactor feedstock. In this case, there may be traces of U232 present that emit highly penetrating gamma rays useful for detection through the shielding. In this special case, shielded uranium can be detected from a greater distance of possibly several meters or over shorter timescales using fixed or mobile detectors. However, the detection of U232 only indicates the presence of uranium and not information on the enrichment.

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