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Abstract

Trafficking of illicit nuclear or radiological materials is a global threat, which can involve and adversely affect any country. Ultimately, it is the responsibility of each state to prevent and combat illicit nuclear trafficking by screening all cargo and travelers entering, exiting, and transiting through its borders. As a part of the national radiation detection infrastructure of the United Arab Emirates (UAE), a reachback program was established at Khalifa University (KU) to provide capabilities for adjudication of radiation alarms at Khalifa Port and other radiation portal monitor (RPM) locations. In addition to the main mission, KU Reachback aims to educate and prepare local talent to lead these vital efforts in the future. This is particularly important because the UAE, similar to other newcomers to the nuclear industry, faces human capital challenges which can be addressed using domestic or regional solutions.

I. Introduction

A. Illicit trafficking of radioactive materials

Illicit trafficking of radioactive materials includes any unauthorized transportation of radioactive materials within or across a state's boundaries. In recent years the number of reported incidents have grown, partially due to an increased use of radiation detection equipment to stop illicit trafficking and an

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increased uses of radiological materials throughout the world. Recent occurrences of radiological incidences related to the Middle East include a stolen (and later recovered) 90 kCi ^{192}Ir source in Iraq **[*1*]** and four incidents in Moldova of smugglers looking to sell radioactive materials (various isotopes of uranium and cesium) to extremists in the Middle East **[*2*]**. After the September 11th, 2001 terrorist attacks, many countries strengthened their efforts to combat illicit trafficking **[*3*][*4*]**. Recorded incidents of illicit trafficking include a variety of isotopes of varying strengths. However, incidents involving weapons grade materials, highly enriched uranium (HEU) or plutonium, are uncommon and often involve small quantities of material. **[*3*]** Although weapons grade materials pose the greatest threat, detection and interdiction of other harmful materials are also of high importance. Non-weapons material can include such items as radiological dispersal devices (RDDs), radiological exposure devices (REDs), and even unintentional transportation of "orphan sources" **[*3*]**. Orphan sources are radioactive materials, which have been lost and are now outside regulatory control.

The most comprehensive global list of reported lost, stolen, etc. radioactive materials is the International Atomic Energy Agency (IAEA) Incident and Trafficking Database **[*5*]**. However, access to this database is not publically available so other resources can be used, such as the Center for Nonproliferation Studies' Global Incidents and Trafficking Database, found at www.ntiorg/traffiing **[*6*][*7*]**. From this database it can be seen that in 2013 and 2014 there were very few incidents of SNM (10% of total incudes) and only one of these involved weapons useable material. This material consisted of less than 1 gram of HEU in an instrument, which went missing **[*7*]**.

B. Measures to prevent illicit trafficking

There are several measures, which can be taken to combat and prevent illicit trafficking of nuclear or radiological materials. These include:

- Better security and materials accountancy at nuclear facilities to prevent theft of these materials. More training and regulations can be implemented with users of nuclear or radiological materials to prevent the accidental loss of these materials.
- Once these materials have left regulatory control and are in the possession of smugglers, they can still be recovered through the use of radiation portal monitors (RPMs) at border crossing locations.
- After these materials leave their country of origin, increased international communication regarding potential trafficking events will significantly aid in the detection and recovery efforts.
- Even if these materials reach their intended target, measures can still be taken against them to reduce the consequences of their use and to apply nuclear forensics capabilities to identify those involved in the smuggling process. This deterrence will help stop would-be adversaries from attempting to smuggle the materials in the first place.

This paper is primarily focused on the detection of nuclear or radiological materials at RPM locations and other areas to combat illicit trafficking will not be examined further.

C. Radiation portal monitors

The main objective of an RPM system is to effectively detect (and, if possible, to identify) a wide variety of radiation-emitting materials. These materials can be grouped in to several broad categories:

- Naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM). These are typical commercial cargo, which contain radioactive isotopes in the ^{232}Th, ^{235}U or ^{238}U decay chains or ^{40}K (ceramic tile, fertilizer, etc.).

- Medical radioisotopes. These are radioactive isotopes used for medical diagnosis or treatment, such as ^{99}Mo/^{99m}Tc and ^{131}I.
- Industrial radioisotopes. These are radiation sources used in various industry applications and can include radioactive isotopes such as ^{60}Co, ^{192}Ir, and ^{241}Am-Be (neutron source).
- Illicit radioactive and nuclear materials. These are materials, which are outside of regulatory control including radioactively contaminated materials, orphaned sources, and radioactive sources for malicious purposes. Isotopes from these materials can range from ^{60}Co to ^{239}Pu.

While the most commonly detected radioactive materials are benign and legal radioactive shipments, there are potentially a few, which could be illicit and dangerous. The ability to discriminate which initial alarms should be investigated further is highly dependent on the detector type used for the RPM. The three main types of gamma-ray detectors used in RPMs are:

1) Polyvinyltoluene (PVT) is a type of plastic scintillator used as a gamma-ray detector. Because of its low cost, this detector material is perhaps the most common detector type in RPM application. The main disadvantage of PVT is its poor energy resolution. Because of this poor energy resolution, alarms from PVT detectors often need to be further investigated with better spectroscopic capable radioisotope identification device (RIID) **[*8*]**.
2) Sodium-Iodide (NaI) offers better energy resolution than PVT but still has some difficulties identifying isotopes with closely located gamma-ray energies, such as ^{123}I (159 keV) and ^{235}U (186 keV). Although NaI has generally better spectroscopic capabilities than PVT, its cost is estimated to be ~20 times higher than that of PVT **[*9*]**.
3) High-purity germanium (HPGe) detectors have a considerably larger initial purchase cost than any other gamma-ray detector types. Due to the good energy resolution of HPGe detectors (typically 30 times better than NaI) **[*8*]**, it is estimated that the reduction in nuisance alarms can achieve up to 1<30,000. This leads to a significant reduction in secondary inspections, which over time will financially compensate the initial investment cost in RPMs based on HPGe **[*10*]**. Previous measurements within the United Arab Emirates (UAE) using HPGe RPMs estimate that less than 0.03% of all cargo will create an alarm, which requires further investigation. An additional advantage (and disadvantage) of HPGe detectors is that they are cooled to liquid nitrogen temperatures and thus not susceptible to temperature related gain stabilization issues, unlike NaI detectors **[*8*]**.

The minimum detectable activity (MDA) and minimum identifiable activity (MIA) are defined as the minimum amount of a specific isotope which must be present in a particular measurement setup to detect the presence of the radioactive material and to identify the isotope the radiation is coming from. These values are highly dependent on many factors including detector system efficiency, energy resolution, background signature, and measurement time. When determining the MDA and MIA of a detector system, all of these factors must be considered **[*11*]**.

Other aspects, which should be considered when selecting a detector type, are the construction materials around the RPM location and the local weather conditions. Research has shown that construction materials, such as concrete, located near an RPM can have an impact on the background count rate due to the relatively high concentrations of ^{40}K, ^{232}Th, ^{235}U, ^{238}U and their radioactive daughters **[*12-14*]**. It has also been shown that the count rate in RPMs increases after rainfall due to ^{222}Rn being washed out of the sky and being concentrated on the ground **[*15*]**. Both of these potential challenges are mitigated through the use of high-energy resolution spectroscopic detectors, such as HPGe detectors.

As with gamma-ray detection, there are several different types of neutron detectors, which can be used. These different types include ^{10}B, ^{3}He, ^{6}L, etc., in various chemical compounds and detector technologies.

- Detectors, which use ^{10}B, are often found as a proportional counter with BF_3 used as the fill gas. This type of detector has two main disadvantages: BF_3 is a hazardous material and works best as a fill gas at pressures of 0.5-1.0 atm, thus requiring larger detector volumes. ^{10}B can be applied has a coating on the inside of a proportional counter using a better fill gas, however, due to the short distance which alpha particles travel, the ^{10}B coating must be thin. ^{10}B has been used with other detector technologies, such as boron-loaded scintillators; however, they are less common **[*16*]**.
- The isotope ^{3}He is often used in neutron detection due to its large neutron absorption cross-section and inert chemical properties. Because helium is a noble gas it can only be used as a proportional counter. Unlike ^{10}B, ^{3}He is not found in nature in useful quantities and instead must be extracted from the decay of ^{3}H. Because the production rate of ^{3}H (and thus ^{3}He) in recent years is small and the usage of ^{3}He for nuclear security applications has increased, the price of ^{3}He can be significant. This large cost can make ^{3}He financially not viable **[*17*]**.
- ^{6}Li is another common neutron detection material. Unlike boron or helium, lithium chemically cannot be used as a gas; however, it is well suited as a scintillator. Although the absorption cross-section of ^{6}Li is lower than ^{10}B or ^{3}He, this is made up for in the fact that the density of the ^{6}Li scintillator (~2.5 g/cm^3) is significantly higher than that of gases. The scintillator can be combined with glass to form fiber optic cables up to 2 m long, allowing for better detection geometries **[*16*]**.

Other neutron detection technologies exist, such as fission chambers and fast neutron recoil detectors, but their usage in RPMs is limited at this time.

II. Reachback

The primary purpose of a reachback program is to provide technical expert advice, analysis, and adjudication of radiation measurements and alarms when needed. It is likely that a state, which has installed RPMs at numerous locations, will not be able to staff a radiation detection expert at each location due to financial and human capital constraints. Instead, it is common to train personnel operating the radiation detectors in the basic use and analysis of the detection equipment. If a situation occurs in which an alarm and basic analysis warrant additional expert analysis, the radiation detection personnel will request “reachback” for expert assistances. Situations in which expert assistance is needed could include detection of an unusual medical or industrial radionuclide or the detection of potentially malicious material, such as HEU or plutonium.

Reachback programs exist in several states, with the most extensive in the United States (US). The US reachback model consists of several regional and national programs, including the Regional Reachback Program, the Joint Analysis Center, and Triage. These programs are staffed by non-deployable groups of scientists and engineers primarily from the US national laboratory system who provide 24-hr assistance to analyze site-specific data and confirm radioisotope identification **[*4*][*18*][*19*]**.

A. Reachback in the UAE

Similar to the US reachback model, the UAE is developing its own radiological reachback program, which provides 24/7 technical assistance and advice on radiological matters, including analysis of radiation spectral data. The UAE Reachback program is currently staffed by, and located at, Khalifa University. The University has scientists trained in nuclear science and engineering along with a variety of hand-held radiation detection equipment **[*20*]**. The hand-held detectors at Khalifa University include HPGe **[*21*]**, cadmium zinc telluride (CZT) **[*22*]**, NaI **[*23*]**, and survey meters **[*24*]**. These hand-held detectors represent different detector types, which might be used by Customs and law enforcement officers at RPM sites. Not only do these detectors allow the Reachback staff to become intricately

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familiar with their operation, but also allow for advanced testing and calibration. Through the use of radiation transport codes, MCNP6 and MCBEND **[*25*][*26*]**, these detectors' responses to illicit materials, such as SNM **[*27*][*28*]**, RDD, RED, and improvised nuclear devices (IND), can be determined. This allows for improved measurement procedures and better radiological material identification.

Currently the initial stage of reachback mechanism implementation in the UAE described above is complete. At the next stage a separate agency or multi-organizational team of experts will be assembled. Khalifa University will also continue to educate future experts in radiation detection and emergency response through its Masters of Science in Nuclear Engineering program **[*20*]**. At the current stage of development, one on-call Reachback scientist is sufficient to provide timely reachback support due to the low frequency of assistance requests. However, to provide defense in-depth, a minimum of two on-call Reachback scientists are available at all times.

B. Challenges

The UAE is a newcomer to the nuclear industry with only recently in 2008 adopting an official policy to use peaceful nuclear energy. Because of this, many of the nuclear related institutions found in countries with developed nuclear infrastructures do not exist in the UAE, or are newly formed **[*29*]**. The UAE Reachback program faces several potential challenges, the most significant being human capital. While reachback programs in other countries, such as the US, can draw upon hundreds of nuclear scientists and engineers, the resources of the UAE are more limited. However, human capital resources in the UAE can be expanded by including other radiation experts besides those at Khalifa University. These other experts can come from academia **[*30*][*31*]**, government organizations **[*32*]**, and industry **[*33*]**. This expansion would allow for large number of experts with broader background to contribute to the reachback process. It would also allow for better continuity of knowledge and training of future experts. Another advantage of incorporating organizations in different areas of the nuclear field is that organizational holidays, such as spring break, will have a reduced impact on maintaining the 24/7 Reachback program.

Other regional countries may experience even stronger human capital constraints when developing their own domestic reachback programs. A potential solution to this challenge could be to establish a regional reachback center that would pool nuclear experts together and improve the resilience and capabilities of the region.

III. Example Location: Khalifa Port

A. Introduction to Khalifa Port

Khalifa Port was launched formally on December 12, 2012, and is designed to become the primary port for all goods entering, exiting, or transiting through Abu Dhabi. The port is located 50 km North East of Abu Dhabi and 75 km South West of Dubai, which allows it to serve both cities. The port is dredged to a depth of 16 m and can currently handle a capacity of 2.5 million TEU's of container traffic and 12 million tons of general cargo annually, with this number expected to grow to 15 million and 35 million respectively by 2030. Khalifa Port is not only one of the primary ports in the UAE, but it also serves as a primary transit point that connects western countries with the local region **[*34*]**.

B. Cargo scanning systems

In 2012, AS&E and ORTEC were awarded a $24.6 million contract to install an in-depth cargo screening system at Khalifa Port **[*35*]**. This system consists of gamma ray and neutron radiation portal monitor systems **[*10*]**, x-ray backscatter systems **[*36*]**, and multi-energy transmission x-ray systems **[*37*]**. All measurement systems are integrated with a multidirectional optical camera system to automatically identify each cargo container and its declared invoice, thus reducing the human capital burden. As of 2014, these systems were installed to provide the capability for all cargo entering the UAE, and all cargo exiting the UAE transiting to the US, to be scanned for contraband, including radioactive materials. Cargo, which causes an alarm by the RPMs, is quarantined and the UAE reachback program is activated. The cargo is further examined using portable HPGe detectors to determine if a radiological exposure hazard exists **[*21*]**, the location of the radioactive material, and to obtain a spectroscopic measurement for further analysis by the UAE reachback program. This procedure is similar to that recommended by the IAEA, shown in Fig. 1 **[*3*]**.

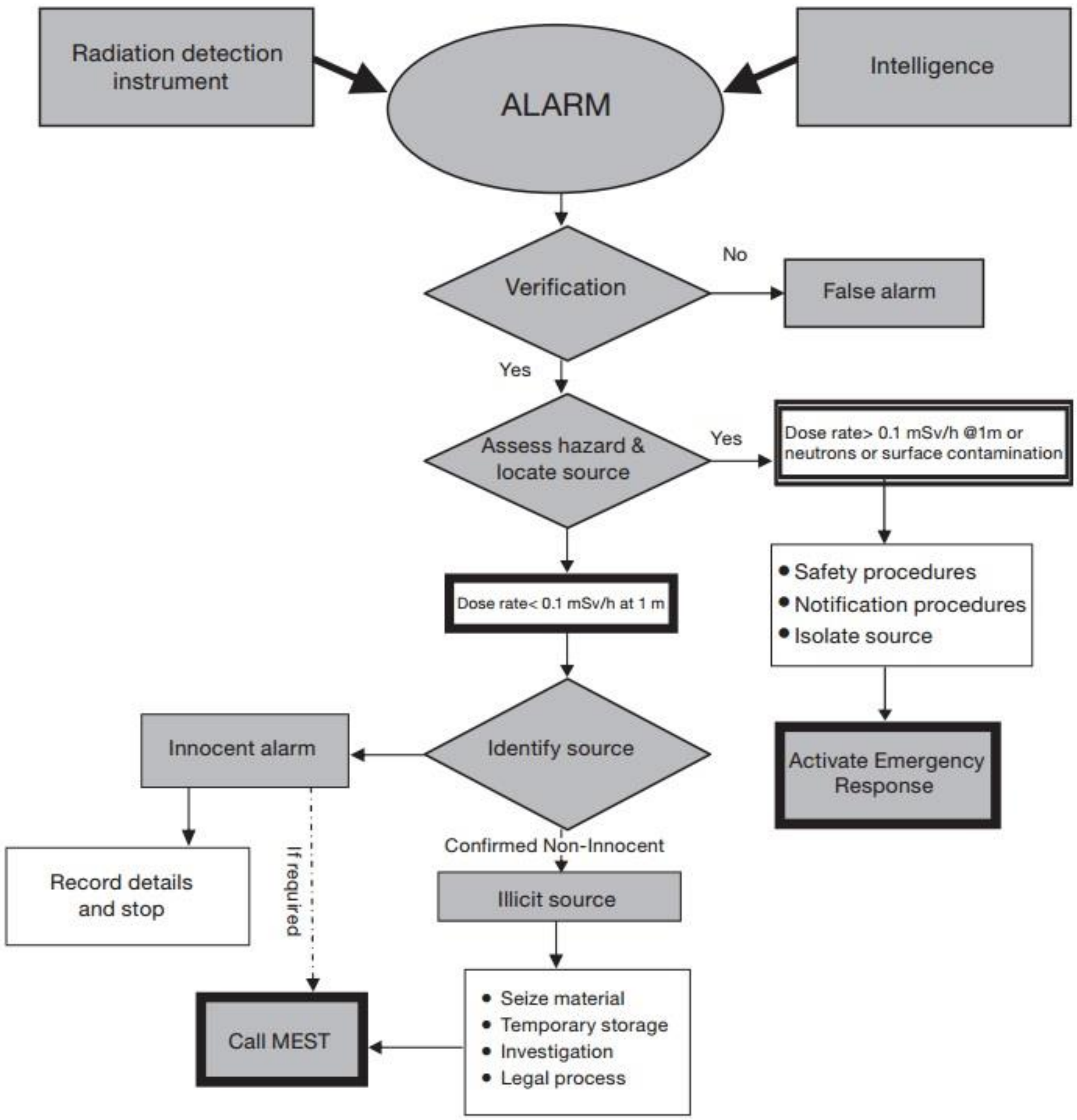

Figure 1: Alarm procedure recommended by the IAEA [*3*]. MEST stands for mobile expert support team.

The gamma and neutron radiation portal monitor systems at Khalifa Port consist of the ORTEC Detective-SPM systems. Each Detective-SPM systems consists of 16 IDM-200-P mechanically cooled HPGe detectors and 4 ^{6}Li neutron detectors. Each IDM-200-P has a crystal diameter of 85 mm and a length of 30 mm, with a relative efficiency of approximately 50% and a FWHM of 2.3 keV at 1332 keV.

The dimensions of the HPGe crystal are specifically chosen to optimize the detection of SNM, which mostly emits gamma rays below 1 MeV **[*10*][*38*]**.

X-ray backscatter images are made using the AS&E Z Portal system. This system uses three (both sides and above) 220 kV x-ray imaging systems to detect objects that are heavily shielded and traditional contraband. The radiation dose to people within the vehicle is estimated to be less than 0.05 μSv per scan **[*36*]**.

For transmission x-ray imaging the AS&E Omni view Gantry system is used. This dual energy x-ray imaging system uses 4 MeV and 6 MeV x-rays to image cargo up to an equivalent steel thickness of 400 mm at a maximum resolution of 0.8 mm. This system allows not only for the detection of contraband such as drugs, weapons and explosives, but can also identify heavily shielded radioactive sources **[*37*]**.

Reachback exercises with Khalifa Port were conducted in 2015 and 2016, with Khalifa Port being added to the list of active reachback RPMs on February 14, 2016. Historical alarm data from January 2014 to January 2016 for the RPMs showed that there were only 56 alarms which would have needed adjudication from Reachback, a large portion of which were created during system characterization and evaluation testing. In addition to these 56 alarms, there were 39,653 nuisance alarms, which the HPGe RPM system could automatically identify and adjudicate, thus significantly reducing the burden on reachback and customs while maintaining the flow of legitimate traffic through the port.

IV. Conclusions

Trafficking of Illicit nuclear or radiological materials is both a global and local threat that must be prevented. One of several ways to combat this threat is through the use of RPMs at border crossings. These RPM locations will occasionally require the advice of radiation detection experts located in the countries reachback program. The UAE has established its own Reachback program with its scientists in this first phase of development coming from the Department of Nuclear Engineering at Khalifa University. Khalifa Port is given as an example of one location, which can request assistance from Reachback. It is expected that these requests will be infrequent due to the spectroscopic capabilities of the HPGe RPM at the port. Human capital challenges exist for the Reachback program in the UAE, but potential domestic and regional solutions exist.

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