

**ACTIVE DETECTION OF SNM:
TEN YEARS OF COLLABORATIVE
ACTIVE INTERROGATION WORK BY
THE ATOMIC WEAPONS ESTABLISHMENT**

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Abstract

Between 1993 and 2018 almost 3500 incidents of radiological/nuclear material being handled outside of regulatory control occurred, some 1250 were possibly related to trafficking and malicious use with 27 incidents involving Special Nuclear Material (SNM). Finding material outside of regulatory control presents many well understood challenges, not least of which is the potential for weak radiation signatures due to the standard constraints of time, distance and shielding. At issue is the potential to fail in the detection of such material which can, at face value, only be alleviated through the disruption of commerce by slowing cargo (increasing detection time), placing detectors right up against cargo (reducing distance) or opening cargo (bypassing shielding). An alternative approach is to increase the radiation signal by inducing fissions using an external source of radiation, thus allowing the resultant fission radiation signature to be detected through any shielding present on detectors placed outside the cargo, all within a timeframe which does not unduly interfere with the stream of commerce. This technique is termed Active Detection.

Since the turn of the century, Active Detection of shielded special nuclear material (SNM) for nuclear security applications has been the focus of a great deal of work by agencies worldwide. Inducing fissions in order to assay material is not a new concept and has been used since the 1960s for nuclear materials accountancy, processing/quality control etc. Such Active Non-Destructive Assay techniques tend to look to determine material mass/isotopics in geometries that allow small standoff in well characterised environments over long periods of time, the challenge is making this technique work in a border security scenario.

The Atomic Weapons Establishment (AWE) alongside the UK Government have maintained a programme to develop Active Detection techniques and technologies since 2008 and much work has been done, both by AWE and in collaboration with international partners during this decade. Significant progress has been achieved across a range of radiation sources, radiation detectors, data acquisition systems, and data analysis tools. This body of work leads us to the conclusion that Active Detection works, that currently available technologies, when correctly configured and integrated, can successfully detect shielded SNM in a wide variety of realistic configurations. The paper describes ten years of experimental campaigns: from bench-top trials to multimillion-pound demonstrator systems, to show how the resulting data validates active interrogation as a technique and discuss the remaining challenges.

1. INTRODUCTION

Incidents of nuclear and radiological material being handled outside of regulatory control, while by no means commonplace, have been known to occur. The IAEA Incident and Trafficking Database (ITDB) lists almost 3500 such incidents between 1993 to 2018 with some 1250 possibly related to trafficking and malicious use and 27 involving Special Nuclear Material (SNM). In an ideal world there would be no need to detect the presence of nuclear and radiological material, in the real world this is a useful capability and the subject of much work.

Radiological and nuclear material can both potentially be found through the detection of the passive radiation they naturally emit. Passive radiation detection is well established and bound by the standard constraints of time, distance and shielding, each of which has consequences when applied to cargo in transit. In order to detect a given radiation signal, that signal must not be shielded to the point it cannot be seen and one must be both close enough and detect for long enough. Cargo in transit could contain shielding and it must not be slowed to an unacceptable level by having to get either close to detectors or remain in such a configuration for too long.

An alternative to passive detection is to induce a larger signal than would be naturally present in material of interest, this is generally only possible with nuclear material and is accomplished by using an external

radiation source (either neutron or photon) to induce fissions, thereby increasing the radiation output to be detected. The two main advantages of this approach are that the signal can be raised to a level where it can escape any shielding present and that the detection can be done as quickly as required.

Inducing fissions in order to assay material is not a new concept and has been used since the 1960s for nuclear materials accountancy, processing/quality control etc. Such Active Non-Destructive Assay techniques are usually applied, alongside passive gamma-based techniques, to determine detailed material mass/isotopics in geometries that allow small standoff in well characterised environments over long periods of time. Application of these techniques to the border security scenario necessitates less well characterised environments, shorter timescales and potentially longer standoff distances, the compromise being that one aims to simply detect the presence of material, as opposed to determining exact mass/isotopic information.

The Atomic Weapons Establishment (AWE), funded by the UK Government have maintained a programme to develop Active Detection techniques and technologies since 2008 and much work has been done, both by AWE and in collaboration with international partners during this decade. Significant progress has been achieved across a range of radiation sources, radiation detectors, data acquisition systems, and data analysis tools. This body of work leads us to the conclusion that Active Detection works, and that currently available technologies, when correctly configured and integrated, can successfully detect shielded SNM in a wide variety of realistic configurations. The paper describes a technical overview of the work after ten years of collaborative theoretical and experimental campaigns: from bench-top trials to multimillion-pound demonstrator systems, to show how the resulting data validates active interrogation as a technique and discuss the remaining challenges.

2. SYSTEM CONSTRAINTS

Systems applicable to this mission space are broadly bounded by maturity, cost, dose and throughput. Performance can be traded for cost/dose/throughput.

Maturity: High Technology Readiness Level (TRL) demonstrations, which have been tested and yielded good results in terms of detection performance, are from predominantly US funded companies such as Rapiscan Systems and Passport Systems Inc. Such full systems are not cheap and require manpower of approximately two to three people full time to operate. In essence such systems are only viable if they are multimodal i.e. detect more than just radiological and nuclear threats. These also represent the most expensive systems.

Cost: The upper cost envelope for systems is defined by full high TRL systems. Minimum cost systems involve adding fission detectors to existing radiography sources capable of inducing fissions ($>5.5\text{MeV}$ photon energy). The benefit of these systems is still an ongoing area of research, suffice to say the cost of relevant detectors is low and the cost of integrating these into an existing system, while higher, is arguably still orders of magnitude less than that of dedicated full systems. Networking is also required, which adds cost although no added local manpower would be assumed necessary, with data collected and transferred for analysis.

Dose: Radiation is input, there are legal limits and time constraints. Photon dose is capped at ~ 0.5 Gy and the endpoint energy is limited to 10 MeV due to food regulation constraints. Systems have given good performance within this envelope. Higher dose and higher energy improve performance and heavily shielded material has still proven reliably detectable. Improvements to the source show scope to close the gap between low and high dose performance substantially; a near ideal source would be within the above limits but give the same benefit as a standard (broadband Bremsstrahlung) source with approx. 20 times lower dose. Neutron dose is limited in a similar manner to photon but with a dose limit of ~ 0.01 Gy; good performance has been proven well below this limit, therefore it is not considered to be a concern at the present time.

Throughput: While the direct relationship between cost and cargo throughput is clear (more systems equates to higher throughput), this constraint has added levels of complexity. Systems that are capable of scanning all cargo (thousands per day) are possible but expensive as multiple $\sim \$10\text{M}$ systems would be required at each point of entry. An alternative approach is to only scan cargo which cannot be cleared reliably by extant passive systems. Systems capable of scanning tens to hundreds of cargos per day are also possible, however, the focus has been on high throughput systems with scan times of order minutes.

3. SYSTEM TECHNOLOGY

The fundamental concept of active detection is to induce a signal that is indicative of the presence of material of interest. In its current form, radiation is input as either photons or neutrons or both, and photons or neutrons or both are detected. The input can be continuous or pulsed and the detected signal can be of prompt radiation (produced during the fission event) or delayed (produced after the fission event) and detected during irradiation or in gaps between irradiations (if there are gaps). The distinction between prompt and delayed signal is further complicated by the fact that the output radiation will not be detected until it interacts with the detectors i.e. ~3 ns per metre for photons, ~50 ns per metre for faster neutrons (~2 MeV), increasing to 500 micro seconds per metre for slow (thermal) neutrons. With four potential inputs and eight potential outputs there are literally thousands of possible combinations of technology which could be designed and tested.

In Table 1 shows potential inputs while Table 2 show potentials outputs, both tables list which sections of this paper go into more detail.

TABLE 1. INPUTS

Section 4	Continuous	Pulsed
Photon	4.1	
Neutron	4.2	

TABLE 2. OUTPUTS

Section 5	Continuous	Between pulses
Prompt Photon	5.1	
Delayed Photon		
Prompt Neutron	5.2	
Delayed Neutron		

The following two assumptions are often made about system technology,

- Detect a different particle type than the one you input, so as to guarantee low background. This assumes you have sufficient penetration on both input and output (cargo dependant).
- Cargo dominates the detected signal (and/or input signal) i.e. look for neutrons in high-z cargo (which absorbs photons more effectively than neutrons) and photons in low-z cargo (which absorbs neutrons more effectively than photons).

Both assumptions are broadly incorrect, generally one input will dominate in almost all cargo (whichever type your source is better at producing) and that same particle will be a good option to detect between pulses. Fundamentally if a particle can get into the cargo then it can also leave and detection between pulses is a reasonable way of achieving low background.

4. INPUT RADIATION

Input radiation can be photon, neutron or mixed and such sources can be continuous or pulsed.

4.1. Photon input

Where photons are used as input to stimulate fissions in threat material, there has always been the assumption that they perform well in low atomic number material where they have high penetration while they perform less well in high atomic number material where they are more attenuated. This is in general true, however, cargo is constrained by limits on weight for transport containers and the containers themselves are of a standard size, thus it is possible to penetrate all shielding with an intense enough source. Excellent results have been obtained within the EU legal limits for irradiation without food licences (0.5Gy photons, 0.01Gy neutrons), well above limits for passive systems. Such intense photon sources are readily available as Commercial Off the Shelf (COTS) items making them comparatively cost effective and reliable relative to more bespoke systems; medical x-ray systems are often used. The most significant negative of using these easily available intense photon sources is that they are broadband in output x-ray energy. They emit a large number of low energy x-rays well below the photo-fission threshold ($\sim 5.5\text{MeV}$ in the materials of interest) which can neither penetrate to the threat objects nor induce fissions and are therefore wasted. These wasted photons represent both an inefficiency in source operation, as energy is used to create them, and unnecessary dose to the cargo as many are absorbed.

Continuous photon input has the potential to maximise the input dose and therefore induce the highest signal. The unintended consequence of this is a high background which is also continuous, making detection of photons difficult. If the input photons are greater in energy than around 6MeV there will also be neutrons generated in the cargo for some materials and detection of neutrons is also non-trivial in this configuration. This type of source is used by one deployed US system, Multi-Modal Automated Resolution Location & Identification of Nuclear Material (MARLIN) [1], the source is somewhat expensive though this is also being addressed.

Pulsed photon sources are cheaper than continuous (factors of a few) and allow the option to detect delayed products between pulses as well as during input pulses. Pulsed sources tend to have less potential for very high dose simply due to having lower than 100% duty cycles, however one must be careful not to assume that pulsed photon sources are low power. A number of high performing tested systems have used COTS pulsed medical x-ray sources, notably Photo-fission Based Alarm Resolution (PBAR) [2] and Differential die-away Analysis Photon-Neutron Experiment (DAPHNE) [3].

4.2. Neutron input

Where neutrons are used as input in an active system, there has always been the assumption that they perform well in high atomic number material where they have less energy loss per scattering event relative to that experienced in material of lower atomic number. This is in general true, however intense neutron sources are not as easily obtainable as intense photon sources, therefore, one must be careful when comparing neutron input to photon input, i.e. what matters is not just the relative fraction of particles that penetrate cargo but also how many particles are readily available to direct into the cargo. Another big advantage of neutron sources is that the threat materials respond uniquely to low energy neutrons where interaction cross sections are extremely high, whereas photon sources induce fissions in a wider range of materials, including natural uranium and thorium, with lower maximum interaction cross section. The increase in fission cross section for neutrons does present a challenge in optimising their use for an active detection system as one needs to penetrate through the cargo while reaching the target, ideally with minimum energy. If the neutrons are not moderated enough by the time they reach the target, then they will not have maximum fission cross section; conversely if moderated too effectively, they will never reach the target. Neutrons take time to moderate and are often moderated during detection which means source and detected populations will overlap more than is the case with photons.

Continuous neutron sources have the potential to induce high fission signals as well as generating associated high neutron backgrounds. Capture gamma lines would also be a potential issue in detected photon backgrounds as they would also be continuous in nature. The potential to activate cargo and or the system structure is also a concern for high rate neutron sources. Such sources have been successfully used in tested US systems, e.g. Nuclear car wash [4], where the main advantage over photon systems is a significantly lower broadband photon background and known neutron background (neutron background energies will be equal to, or lower than, the input neutron energies).

Pulsed neutron sources leave the potential to detect between pulses as an option for detection, although, this is partly dependant on the neutron thermalisation time. Such sources are also generally cheaper than continuous sources. Interestingly, high intensity pulsed sources could be used to irradiate large volumes (entire cargo container) in a single pulse, although such sources are unlikely to be cost effective and there are obvious safety concerns. Such sources are often DD or DT and therefore effectively isotropic, this means many of the generated neutrons will not end up interacting with the threat target and both signals as well as background may be small. As with continuous neutron sources there is the potential for capture gammas to contribute to the photon background as well as the potential to activate cargo or system structure. A pulsed neutron source has been used on one high performing tested US system DAPHNE [3]. The longer lived nature of neutron pulses, relative to photon pulses, means the optimum detection pulse structure may well be different for each.

5. DETECTED RADIATION

The phase space of fission product detection in continuous vs. pulsed environments is complex, as prompt signals are orders of magnitude larger than delayed and only visible during irradiation whilst the induced background is also orders of magnitude higher during irradiation than in gaps between pulses, i.e. there is both a higher signal and higher background for continuous systems. Detection in gaps for a pulsed system will usually be of delayed products and is, in essence, an entirely different signal to that dominating during continuous irradiation.

While it is possible to shield any signal, cargo is limited in weight and the nature of active detection means the induced signal needs to exceed that which can be shielded. It is also logical that the shielding itself would be difficult to conceal if there were enough present.

5.1. Photon Detection

Photons will generally escape from low atomic number cargo more easily than from high atomic number cargo and there has always been the assumption that photon detection would hit some form of limit against high atomic number shielding. Tested active systems have performed well even against high levels of both high and low atomic number shielding.

Prompt photons detected during interrogation (either continuous interrogation or during pulses) are difficult to detect if photons are used as input because photons above the fission threshold are also above the natural photon background. Signals during continuous input will also be continuous thus no time variation can be used and all sources produce some photon background. This signal can be used if neutrons are input and the background is well understood [4].

Prompt photons detected during gaps in input would be associated with significantly less background than during continuous input, however, this signal is almost impossible to detect as the prompt photons are produced on the fs timescale, thus they would not be present in the gaps between pulses. One could use this signal if only neutrons are input and one US system (DAPHNE [3]) gets close although this system aimed to detect prompt neutrons in gaps between pulses of a mixed photon/neutron source.

Delayed photons detected during continuous interrogation would be possible if a neutron interrogation source were used, although cargo-dependant capture gammas make this challenging.

Delayed photon detection during gaps in input is more tractable than prompt photon detection during gaps as either a photon or neutron interrogation source could be used. Optimum gaps between pulses of seconds are a potential limit on input radiation and therefore cargo throughput, however, this approach has shown some promise on at least one US system tested (DAPHNE [3]).

5.2. Neutron Detection

Neutron detection is attractive due to both the fact that the natural neutron background is low and the fact that neutrons can penetrate high atomic number material more easily than photons. It has long been recognised that significant quantities of hydrogen rich cargo would make neutron detection challenging and this has proven to be the case. As a complement to photon detection there is the potential to add significant value, however it is

difficult to optimise for simultaneous detection of both photons and neutrons as a low background source for one is usually a high background source for the other.

Prompt neutrons detected during interrogation is tractable if no neutrons, or only low energy neutrons, are input, fission neutrons have a distinctive spectrum. This type of approach does not utilise any time variation and relies on spectroscopic analysis, which is challenging. One deployed US system, MARLIN [1] makes use of this signal for photon interrogation.

Prompt neutron detection during gaps in input is also possible, assuming neutrons from fissions limits applicable gaps to micro seconds i.e. time of flight for the neutrons. This signal is detected by one US system, DAPHNE [3]. Photon interrogation could be used, however, photon pulses would have to be short compared to the time of flight of neutrons in order to not waste input radiation.

Delayed neutrons detected during continuous interrogation would be a low signal compared to the prompt neutron signal on the same timescale i.e. the prompt neutron signal would be a background in this case. This would be challenging if neutrons were used as input, unless their energy differed in energy significantly from those detected and spectroscopic neutron detectors were used. In practice this would require low energy neutron input, which is unlikely to penetrate enough cargo to justify its use; further, the detection would come predominantly from the prompt fission neutrons.

Delayed neutron detection during gaps in input is possible, however the signal is small requiring large gaps for detection. In order to not affect cargo throughput, this could be achieved by detecting for many seconds post scan (while cargo is being moved) although this would require the detectors to be moved with the cargo or the cargo to be parked by detectors. This signal has been seen on a number of tested systems (those which have neutron detectors), however it is generally not the best performing signal for system level decision making.

6. TESTED SYSTEMS

A number of full systems have been tested both by the US and UK, with the UK becoming fully involved in around 2010. Numerous laboratory sub-system tests were completed by the UK in collaboration with the US [5][6]. Ultimately the testing of high Technology Readiness Level (TRL) systems, to a large extent, defines the current state of play.

Interest in scanning for SNM at ports increased post 2001 when the US Department of Homeland Security (DHS) Domestic Nuclear Detection Office (DNDO, now Countering Weapons of Mass Destruction Office, CWMD) initiated several programmes aimed at countering this threat from enhanced Radiation Portal Monitors to Active systems.

The first Active system was the Cargo Advanced Automated Radiography System (CAARS) [7] established as an acquisition program in 2006 to develop systems that could automatically detect nuclear and radiation shielding material, with multiple vendors being awarded contracts. DNDO restructured the CAARS Program in 2008 as an Advanced Technology Demonstration (ATD) Program. The CAARS program was completed around 2011 with further ATD programmes in progress by this point.

The approach of these following programmes was to locate potential threats and then resolve these alarms with another, separate, system (the primary system would scan all cargo, the secondary system only the alarms from the first). This resolution of alarms formed a separate ATD series termed Shielded Nuclear Alarm Resolution (SNAR), started around 2008 [8]. The three headline systems of this series being Passport's Multi-Modal Automated Resolution Location & Identification of Nuclear Material (MARLIN), Rapiscan's Photo-fission Based Alarm Resolution (PBAR) and Re-locatable Shielded Nuclear Alarm Resolution (RSNAR, later Differential die-away Analysis Photon-Neutron Experiment (DAPHNE)). Development and testing of these systems lasted until around 2015 with data analysis continuing after this point.

The high TRL demonstrators use standardised objects (threat and non-threat) as well as standardised cargos covering a wide range of potential cargo weights and complexities [3]. In general, the systems tested performed well against detection performance requirements (~95%) for most cargos. In general, the systems tested also performed well against the ~5% false alarm requirements even for heavily shielded threat objects. Some systems performed well even at low doses (within the current legal limits).

Testing was generally done with repeats of a given cargo and binary statistics used; this approach allows good comparison with systems tested in a similar manner [3]. System requirements were 95% detection

performance and 5% false alarm rate. A deployed system would probably sacrifice some detection performance for reduced false alarm rates as false alarms require human intervention, which is expensive.

The community, predominantly DHS CWMD, have driven a programme forward, in its current form for almost fifteen years championing Active Detection for the border protection mission. AWE has collaborated on many aspects of this work, from bench-top trials to multimillion-pound demonstrator systems from around 2008 to the present. The result of this comprehensive high TRL testing was more than just proving that Active Detection as a technique works on heavily shielded SNM; the limits of each system were tested with threat objects in dense cargos in the most difficult locations (identified during testing). The considerable range of threats and cargos tested gives confidence that systems can indeed work as required.

7. REMAINING CHALLENGES

The key limitations on the deployment of Active Detection systems for border protection are twofold,

- Cost, unit costs of full systems are high and require manpower. This is only likely alleviated where systems are multimodal, and the cost can be partly rolled into that of another system e.g. contraband detection.
- Dose, while good performance can be obtained within legal limits, great performance would be possible if sources were available which did not waste so much input radiation e.g. monoenergetic sources.

Both challenges are the subject of ongoing effort. Integration of Active Detection sub-systems to extant border detection solutions is an exciting area of work. Radiation sources are continually improving and significant gains are possible even without the need for monoenergetic photon output [9].

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