LLNL-TR-407376

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Detecting terrorist nuclear weapons at sea: The 10th door problem

D. R. Slaughter

October 1, 2008

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Abstract

While screening commercial cargo containers for the possible presence of WMD is important and necessary smugglers have successfully exploited the many other vehicles transporting cargo into the US including medium and small vessels at sea. These vessels provide a venue that is currently not screened and widely used. Physics limits that make screening of large vessels prohibitive impractical do not prohibit effective screening of the smaller vessels. While passive radiation detection is probably ineffective at sea active interrogation may provide a successful approach. The physics limits of active interrogation of ships at sea from standoff platforms are discussed. Autonomous platforms that could carry interrogation systems at sea, both airborne and submersible, are summarized and their utilization discussed. An R&D program to investigate the limits of this approach to screening ships at sea is indicated and limitations estimated.

1. Introduction and problem statement

No security system, regardless how comprehensive, is fool proof. An appropriate approach is to create a layered structure of barriers each of which improves security incrementally. But, when the stakes are high, it is important to understand the limitations of this approach. If our home has ten doorways and all of them are unlocked and standing open then we know an uninvited intruder can enter the home with little difficulty. Some believe that closing and locking nine of the doors will reduce the probability of penetration by 90%. They are wrong! A dedicated intruder will readily discover the remaining open doorway and the overall security is not improved significantly by securing nine of the ten doors. This is sometimes referred to as the "10th Door Problem"[1]. Security is improved significantly only when all ten doors have been secured.

The 10th Door analogy is applicable to the smuggling of terrorist nuclear weapons into the US. More than 90% of all commercial imports into the US arrive by sea on container ships[2] and that traffic amounts to ~ 10 million containers per year arriving at US ports. The Domestic Nuclear Detection Organization (DNDO) within the Department of Homeland Security (DHS) has undertaken a major development program to screen maritime cargo container traffic at US ports of entry and at foreign ports of origin to assure that a terrorist nuclear weapon is not delivered within this commercial flow. This traffic is a major risk factor for US security and must be addressed as comprehensively as possible.

However, smuggling organizations have operated for decades and highly successfully to bring drugs, explosives, illegal immigrants, and weapons into the US and other countries. There are many venues available to them and many are utilized. Among the potential routes are:

By sea:

- In commercial cargo containers
- Attached to the outside hull of cargo carriers
- Bulk cargo carriers such as tankers, ore haulers, and grain ships
- Small ships such as fishing trawlers & short-run cargo carriers
- Fishing boats
- Private yachts, some fairly large
- Ferry boats
- Submarines both WWII refits and new construction for smuggling purposes

By air:

- Commercial passenger aircraft
- Commercial cargo aircraft
- Small, privately owned aircraft

On land:

- Cargo hauling trucks
- Trains
- Small trucks
- Private automobiles
- Foot traffic

There are many doorways and most have not been secured yet.

Among the above venues variable buoyancy containers are available that may be submerged in liquid cargo and then commanded to re-surface upon reaching a destination. Then the containers may be tossed over the side and sink to the harbor bottom awaiting pickup by the smugglers at a later time. Some smuggled goods may be carried without knowledge of the crew. For example some containers for smuggled goods can be attached magnetically to the external hull of a vessel and carried below the water line until the ship reaches port where the smugglers or their divers remove the container from the hull. These devices may be attached to ships or boats of any size and they carry their payload below the waterline where it is difficult to detect. Contraband cargo may also be concealed in containers unknown to the ship's crew. Generally, a nuclear weapon or its component parts is not large and readily hidden even in small boats, trucks, or aircraft. Detection of an illicit weapon or its parts is a daunting challenge in the air, at sea, or on roadways. Attenuation due to intervening materials, large standoff distances, and brief exposure times all reduce the sensitivity of screening instrumentation.

2. Context for this report

It will be shown below that simple physics limits make screening cargo in some of the above venues not technologically realizable. For most of the remainder the challenge is nearly impossible, but not worse than that. Given that the challenge of nuclear weapon smuggling is the primary security threat facing the US[a] the challenges discussed here warrant high risk research approaches even if many proposed approaches ultimately fail. It is worth our time and resource commitment to study all possible approaches to this challenge, stopping short of those that are shown to be truly "impossible".

Full size cargo vessels and those larger than a few thousand tons probably fall in the regime of the "impossible" challenge[b]. Screening from standoff distances greater than > 100 m is probably in the impossible regime as well. However, there are many vessels at sea that are small but used frequently and successfully by smugglers. These vessels have transverse and height dimensions < 10 m and may fall in the regime of accessible challenges given brighter sources and larger detector arrays. Standoff distances < 100 m are realizable and make some of the above challenges fertile areas for high-risk research programs.

No solutions are presented here. Instead, the focus is on physics limits that define the regions where technological solutions are unlikely to be successful while also indicating regimes where physics limits are not prohibitive and that warrant further study. Fortunately, the regimes where physics limits do not preclude technological solutions encompass a significant number of important challenges. It is because this problem is extraordinarily important to US national security and that a number of subsets among the threat scenarios articulated above may have unrealized technological solutions that a well-directed program of long term R&D be focused on these problems at LLNL.

3. How to screen vessels and vehicles in the field

It would be desirable to effectively utilize passive radiation sensors to detect the natural decay of SNM from large standoff distances. That would facilitate clandestine surveillance of suspect vessels or vehicles without alerting their crews and possibly precipitating counter measures. For this

---

[a] *Quoting from the President's announcement of the homeland security program: "The Department of Homeland Security would make defeating this threat a top priority of its research and development efforts. This nuclear denial program would develop and deploy new technologies and systems for safeguarding nuclear material stockpiles and for detecting the movement of those materials. In particular, it would focus on better detection of illicit nuclear material transport on the open seas, at U.S. ports of entry, and throughout the national transportation system."*

[b] *Contemporary active interrogation systems have shown the capability for effective penetration of ~2-3 m thick cargo. This accesses all of the underwater volume in a vessel whose underwater dimensions are 5X5X50 m^3 and whose displacement is ~1200 MT. Doubling the penetration depth might be tractable with substantial increases in source strength and detector array size, to facilitate screening ships of ≤ 10,000 MT. For comparison, a typical container ship carries ~30,000 MT of cargo.*

purpose it would be desirable to detect SNM at standoff ranges 10-1000 km. Unfortunately, basic limitations on source intensity and attenuation in intervening materials make this impossible as explained in a later section.

Natural radiation produced by the radioactive decay of SNM consists of α, β, and γ-radiation, as well as spontaneous fission decay that produces γ-radiation and neutrons. Only the γ-radiation and the neutrons are detectable through a few cm of intervening material. Unfortunately, the important actinides have long half-lives so that their specific activity is very small and their radiation is generally hard to detect passively even when overburden is small. Attenuation in structures, fuels, and the air reduces these signals substantially so that passive detection has very limited prospects even at minimal standoff range.

Active interrogation can produce fission that produces additional radiation from SNM and thus increase the detectable signal by decades. A directed and collimated beam of neutrons or high-energy γ-radiation can be generated by an accelerator and used to illuminate a target vessel or vehicle to produce fission in any SNM that may be present. At standoff distances of $R \leq 100$ m in air or $R \leq 5$ m in water intense beams can produce fission whose signature radiation is both unique to SNM and highly penetrating in air, water, or cargo materials. A later section will describe the physics limitations that establish effective standoff ranges that are somewhat less than ideal and the CONOPS must be modified to accommodate those limitations.

The accelerators used to produce these beams can be made compact and lightweight suitable for Unmanned Airborne Vehicles (UAV), in ships at sea, or in Autonomous Underwater Vehicles (AUV). These vehicles can approach a target vessel or vehicle from above, from the surface, or from underwater. Similar platforms can carry arrays of highly efficient detectors sensitive to the characteristic radiation produced by fission in the SNM. The detector vehicles too can operate in the air, on the surface, or underwater. These vehicles carrying the beam in one platform and detectors in another (or together in a combined platform) may then approach a suspect vehicle or vessel and briefly scan it to detect the presence of SNM while discriminating against other radiation sources that might otherwise produce false positives (false alarms). Data from the scanning operation would be transmitted to an operational control platform in a surface ship, submarine, or roadside vehicle. In the case where SNM is positively detected appropriate military vehicles may then approach the target vessel and take appropriate action.

The CONOPS for a system based on the principles described above would be something like the following:

- Identify a suspect vessel or vehicle based on actionable intelligence or predetermined screening criteria.
- Bring the appropriate UAV or AUV platform with its active interrogation system to the suspect vessel.
    - For airborne or surface scanning the UAV or surface platform must be brought within $R \leq 100$ m of the suspect vessel. The vessel may continue on its way while scanning provided its dimensions and cargo density allow low-dose scanning. For a large vessel with high density cargo the interrogation may call for higher radiation dose, in which case, the vessel must be stopped and the crew removed from the area where scanning takes place.
    - For underwater scanning the AUV must be brought below the ship's hull at a distance $R \leq 5$ m. The vessel may continue on its way during scanning.
- Carry out the scan for as long as it takes to obtain high-confidence measurement results. This could be a few minutes or it could be an hour or so in the case of a vessel that is large and carries high-density cargo.
- Digest the data obtained. Produce a high confidence decision regarding the absence of SNM on board.
    - Clear the vessel in the absence of positive indications of SNM.
    - Request military support in the case of positive SNM indication.

All modes of operation including airborne, surface interrogation, and underwater interrogation of ships at sea will play a role in a detection network. Regarding ships at sea a would-be smuggler would find considerable advantage in locating the threat target below the waterline where water provides strong attenuation limiting its exposure from the side and even from above. In addition, cargo overburden adds to the attenuation when viewed from above if the threat object is placed low in the vessel. Thus, screening ships at sea might invoke more than one scanning technology but the selection would always include the underwater capability. Airborne scans may be carried out by a slow fly-over or repeated fly-overs. Similarly, surface scans may be carried out by roadside systems or from ships at sea. Underwater scans may be carried out from an AUV that approaches a target vessel from below and scans the underwater portion of the hull from the keel to the waterline, and from aft to forward. This can be done while the target vessel is underway.

Following sections will describe available technology for producing the interrogation beam, the signature radiation to be detected, the detector array, and the unmanned vehicles that provide the platforms for these components of the overall detection system. In some cases the maximum detection ranges are short enough and required beam intensities high enough that clandestine surveillance is not possible. In those cases removing them from the area being inspected may require some form of radiation protection of the crew.

4. Radiation signatures of SNM

Special nuclear material (SNM) is most readily detected by observing radiation generated by fission. Spontaneous fission or cosmic ray induced fission generates prompt neutrons (~ 2.5 per fission) with mean energy E_n ~ 2 MeV and prompt γ-rays (~ 6-7 per fission). The subsequent fission product decays generate delayed γ-rays (~ 7 per fission and delayed neutrons (0.015 per fission). However, the spontaneous fission half lives for ^{235}U, ^{238}U, ^{240}Pu and ^{239}Pu are, respectively, 1.0x1019 y, 8.2x10^{15} y, 1.1x10^{9} y, and 8x10^{13} y. Even if significant quantities of SNM are present the decay rate is too small to produce a detectable fission signature at desirable standoff distances.

Consequently, it is generally necessary to invoke active interrogation techniques to stimulate a higher rate of fission and thus a more detectable signal. But, there are two important exceptions not to be overlooked. First, spontaneous fission neutrons are captured in a hydrogenous environment (such as water or soil) to produce distinctive capture (n,γ) γ-rays at E_γ=2.2 MeV. Almost every emitted neutron ends in this reaction. Secondly, techniques developed to detect time-correlated events due to fission chains in a multiplying sample of SNM have such a low background that even infrequent fission chains lead to SNM detection if the detection range is short.

5. Detection platform

5.1 Airborne and surface screening

It would be desirable to scan vessels at sea or on roads using an airborne platform that can surveill large areas in a short time. An unmanned aerial vehicle (UAV) would be a valuable platform for this purpose. An active interrogation system includes an accelerator, target, power supply, and controls. It is expected that commercially available components can be packaged into a system whose size is V~ 2-3 m^3 and mass is m ~ 500-800 kg. Typical interrogation systems require P~5-10 kW of electrical power. Similarly, large high-efficiency detector arrays would occupy a comparable volume V~2-3 m^3 and have a smaller mass, m~ 200-400 kg. Detector power requirements are expected to be P~ 0.5-1.0 kW. The detector arrays could be co-located with the interrogation system on a single platform, or there could be two platforms where detectors and interrogation source are separated.

5.2 Airborne platforms

There are several UAVs capable of carrying these payloads[3-8]. They can be remotely operated or can proceed autonomously using highly accurate on-board navigation systems. Descriptive summaries and extensive references are available[3]. One example, the Predator UAV, is shown in the figure below.

Figure 5.2-1 The Predator UAV.

The Predator has a low cruise speed of 70 kts, range 725 km, fuselage dimensions 8.2m X2.1 m, and 500 kg payload capacity. Most UAVs are fixed wing though low flying speeds are available in some. One UAV, the Fire Scout resembles a helicopter and has the capability to hover[7]. Its payload is 1400 kg and a picture of it is shown below.

Figure 5.2-2 The Fire Scout

A more comprehensive, though dated, summary of military UAVs is also available[8] and it projects developing technology going forward. A more up to date and comprehensive summary of vehicles and their capabilities was published in three years ago[9].

5.3 Underwater screening

Screening a vessel at sea below the waterline can be accomplished by launching an Autonomous Underwater Vehicle (AUV) from a surface ship, from a submarine, or dropped from the air. This vehicle would carry an interrogation source and a detector array, or the detector array could be carried in a separate partner AUV. It would approach the suspect vessel from below and would maintain its position against the hull as the suspect vessel continues underway. For this purpose the AUV must be capable of maintaining the speed of the target vessel while maintaining its location within ~ 1 m of the ship's hull. It would then navigate along the length and breadth of the target vessel to carry out an interrogation of all regions considered to be important. Screening data could be transmitted back to the host vessel or stored on board for later recovery. Very few AUVs presently available have adequate speed capability and so some further development will be required.

5.4 Underwater platforms- tractors

Tanks and pipelines may be inspected using underwater robots that attach themselves to a metal wall with magnetic treads and they negotiate the hull or tank wall just as a tractor with sticky treads would do. The navigation is either autonomous or these robots may be tethered to receive power and instructions from a remote control vehicle. Generally, these vehicles are small and carry only a simple acoustic sounder or small x-ray machine. However, given the highly capable navigation systems carried by these platforms it would be relatively straightforward to develop a sturdier version capable of carrying larger payloads. In that case an interrogation system could be attached to the hull of a ship and would be used to expeditiously scan the cargo hold from below the waterline. Examples of these tractor systems may be found in a variety of sources[10-16] and several of these systems are summarized in a web page[17].

These systems are part of a well-developed and highly successful commercial technology for inspection of metal structures including those underwater. The principal task in this implementation is to provide adequate space and power for active interrogation systems and for detector arrays. Then appropriate navigational protocols would provide the scanning methodology.

5.5 Underwater platforms- freely navigating

Autonomous underwater vehicles (AUV) have been developed for a wide variety of purposes from deep-sea research to inspection of tanks and hulls[12-15, 18-20] to detect cracks or for automated searches of harbors and channels for military mines. Summaries of the various AUV platforms are available[21, 22]. Some of these vessels are large with substantial payload capabilities in both volume and mass and on-board energy storage is available up to ~ 200 MJ. The latter can supply a 10 kW load for up to 5 hrs. A recent issue of Science[23-26] was devoted to robotic vehicles including AUVs and this provides an up to date review of the technology. Pictures of several large AUVs are shown below.

Figure 5.5-1 Large AUVs available for underwater interrogation platforms.

AUVs currently available have been used over a long period of time and have been found reliable and their navigation systems are highly capable for autonomous operation. While their speed is less than needed in many cases this could be improved. These vehicles have useful range 20-1000 km, and they have dimensions up to 10 m long and 2.5 m diameter. Many of them are operated at depths up to 4000 m though that is not required in the screening application.

6. Physics limits

6.1 Measurements in air

Substantial development has been carried out to detect SNM buried in thick cargo at a detection range of R=1-2 m from the near surface of the cargo. Some are based on neutron interrogation[27-38] with detection of fission neutrons[27-31], some with detection of fission product γ-radiation[32-34] while others rely on detection of delayed neutron emission by fission products[36-44]. Some systems utilize intense beams of high-energy photons to induce fission[39-41, 45-47].

Interrogation beams are reduced in intensity with distance as the beam diverges and as air scatters and/or absorbs the beam. The flux at the entry wall of the target vessel is reduced by both of these effects as described in the equation below.

$$\frac{\Phi(R)}{\Phi_o} = \left(\frac{R_0}{R}\right)^2 e^{-\frac{R-R_o}{\lambda}} \qquad 6.1\text{-}1$$

where Φ_o is the flux at distance R_o, Φ_o the flux at distance R, λ is the mean free path in air and R_o is the distance at which systems described above have been shown successful in detecting SNM buried in cargo materials. The figure below shows a plot of Eq. 6.1-1.

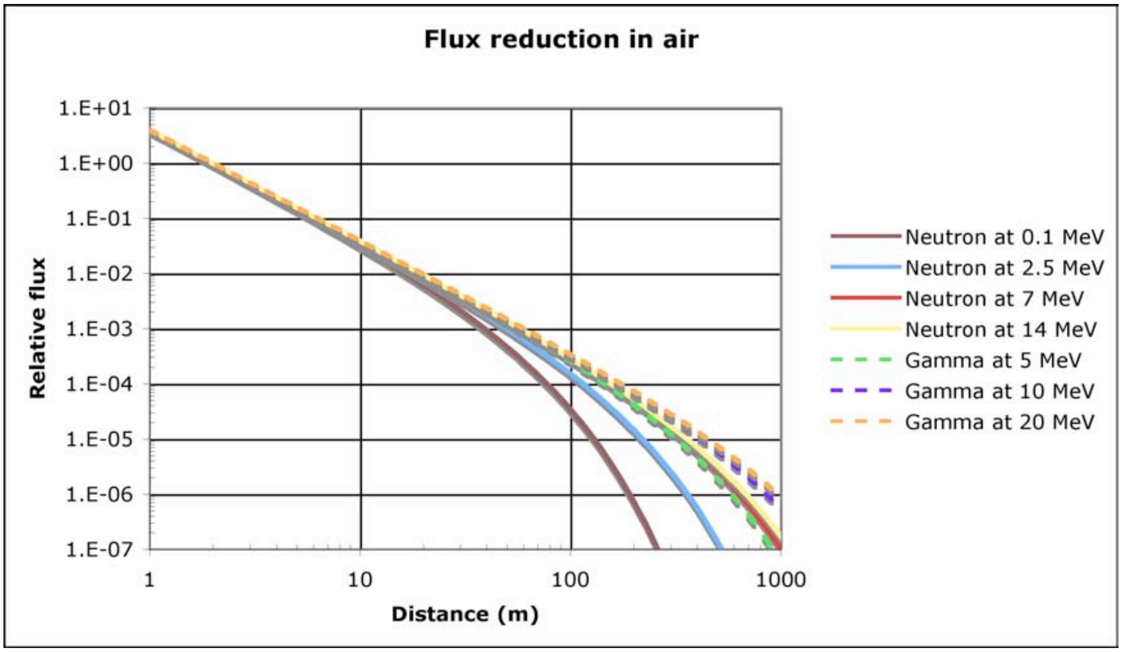

Figure 6.1-1 Intensity reduction due to air attenuation and beam divergence compared to proven systems at distance R= 2 m. Neutron intensity reduction is shown in the solid curves at several energies and γ-ray intensity reduction is shown in the dashed curves at several energies.

The figure above shows the intensity reduction in air due to beam divergence and to air attenuation. The solid curves show reduction in neutron beam intensity while γ-ray beams are shown in the dashed curves. It is clear that over distances of 10's of meters the intensity is primarily affected by beam divergence as indicated by the relatively straight lines. Air attenuation begins to be important only at ranges beyond R≥ 100 m. Air attenuation begins to be significant for neutrons at ranges R≥ 50 m at low energy and R≥300 m at high energy. For γ-radiation air attenuation only becomes important at R ≥ 300-1000 m with the highest energy γ-rays suffering the least attenuation. Generally, γ-ray beams penetrate air better than neutron beams.

Interrogation at high intensities provides a robust fission signature that can accommodate intensity reductions of order 10^{-4} to 10^{-5}. This would require development of suitable high intensity interrogation sources suitable for use in the field. Taking that assertion as a physical limit on effective detection range the data in the figure may be used to conclude that neutron beams have useful standoff range R ≤ 80-400 m depending on neutron energy and which limit is taken. A "ballpark estimate' indicates that neutron beams perform adequately at R ≤ 200 m. Interrogation by γ-ray beams can provide useful standoff ranges R ≤ 150-500 m depending on their energy and which limit is taken. Using the same criteria as for neutrons it could be assumed that γ-ray beams perform adequately at R ≤ 400 m.

It is important to consider that fission signature radiation is also reduced in the same way as the interrogation beam. In the likely event that the detectors and interrogation beam are at the same distance then the intensity reduction factor is the same for both. In this case the useful standoff range may be only half as large as shown in the figure. For this important case the <u>effective standoff range is roughly R ≤ 100 m for neutrons and R ≤ 200 m for γ-ray beams and signature</u>s. On the other hand it may prove impractical to confidently screen cargos when attenuation factors are as large as 10^{-4}.

In some cases there are major advantages to separate the source and detector if either can be placed close to the target. Then strong attenuation applies only for one leg of the interrogation trip. In short, we must pay careful attention to the outbound trip of the interrogating radiation and the return trip of the fission signature radiation. In all cases it is important to acknowledge the reduced standoff distances when source and detector are co-located, and when the tolerable attenuation is smaller than asserted above.

6.2 Underwater measurements

Water is three decades more dense than air and has mean free path three decades shorter and similar reduction in effective range. An evaluation of Eq. 6.1-1 for water can be used to show the sensitivity of interrogation intensity to distance. That result is plotted in the figure below.

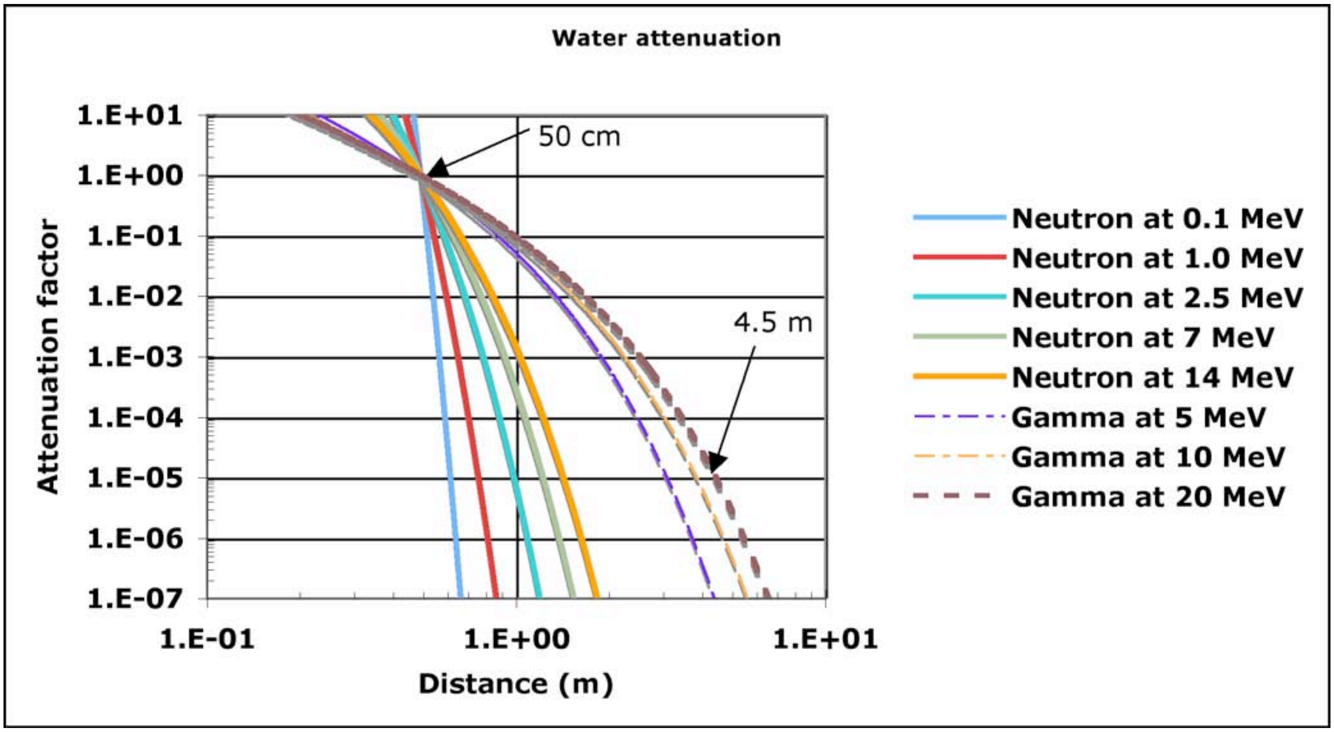

Figure 6.2-1 Intensity reduction in water for neutrons (solid curves) and γ-rays (dashed curves) at several energies.

In the data plotted the intensities have been normalized at R=50 cm. It is clear from the figure that beam divergence is unimportant compared to attenuation in water at the ranges of interest. Using the criteria of the previous section it is clear neutron beams are effective in water only to standoff distances R ≤ 70-150 cm. On the other hand high-energy g-ray beams can be effective at standoff distances R ≤ 250-500 cm. Just as before the detected signal also undergoes attenuation and, if co-located with the interrogation source the attenuation is significant. If 2.5 MeV neutrons are used for interrogation and fission neutrons are utilized as the detected signal then the effective standoff is only half of the indicated distance so that <u>the useful range is R ≤ 0.5 m when neutrons are utilized both for the outgoing and returning radiation</u>. On the other hand, using the same criteria, high-energy γ-radiation has a useful interrogation range in water of R ≤ 2.5-5.0 m. <u>When the source and detectors are co-located then useful range is then R ≤ 2.5 m</u>. It is clear from this result that an underwater platform must approach the hull of a suspicious very closely to be effective.

6.3 Summary of maximum standoff distances

Discussions and graphical data presented in the previous two sections are summarized below in a table. It is important to distinguish the efficacy of single ended systems, i.e. those with co-located source and detector, from those where either the source or detectors are placed relatively close to the threat target.

Table 6.3-1 Maximum viable standoff distances (m) based on beam divergence and attenuation.

Maximum tolerable attenuation	**14 MeV neutrons**	**20 MeV γ-rays**
Attenuation in air		
One way 10^{-1}	6.2	6.2
One way 10^{-2}	19	20
One way 10^{-3}	55	61
One way 10^{-4}	150	165
One way 10^{-5}	340	440
Two way 10^{-1}	3.1	3.1
Two way 10^{-2}	9.5	10
Two way 10^{-3}	28	30
Two way 10^{-4}	75	83
Two way 10^{-5}	170	220
Attenuation in water		
One way 10^{-1}	0.23	1.28
One way 10^{-2}	0.46	2.55
One way 10^{-3}	0.68	3.8
One way 10^{-4}	0.9	4.9
One way 10^{-5}	1.2	6.6
Two way 10^{-1}	0.11	0.64
Two way 10^{-2}	0.23	1.3
Two way 10^{-3}	0.34	1.9
Two way 10^{-4}	0.45	2.5
Two way 10^{-5}	0.6	3.3

Examination of the table shows that neutron interrogation has poor penetration in water, as does detection of neutron signatures. However, high-energy γ-radiation penetrates water much better. Even if source and detector are co-located the useful standoff range is ~ 60 m in air and ~ 4 m in water if the technology can accommodate 10^{-3} attenuation in the round trip. This is NOT an insurmountable goal. If the source or detector can be placed near the threat target these distances are doubled. If the technology employed can tolerate greater attenuation then the useful stand off distance improves correspondingly. In the most optimistic case considered here with a system able to accommodate 10^{-5} attenuation in a round trip the useful detection range is ~ 200 m in air or ~ 3.3 m in water. Both are practical ranges given the platforms described below.

7. Interrogation sources

7.1 Photon interrogation

SNM detection utilizing a bremmsstrahlung photon source is a technique developed over the past two decades or so[39-41]. The photon source is relatively small and portable as shown in the figure below.

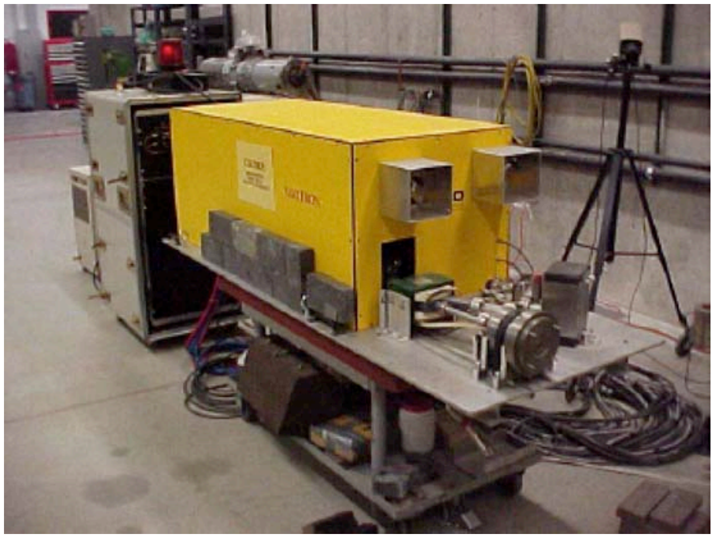

Figure 7.1-1 Bremsstrahlung x-ray source with endpoint Ee=9-15 MeV[48].

The photon interrogation beam has an angular width $\Delta\theta \sim 1/\gamma$ or ~ 30 mrad at E_γ=15 MeV. This technique requires large photon fluxes since the (γ,f) cross section is small, as seen in the figure below.

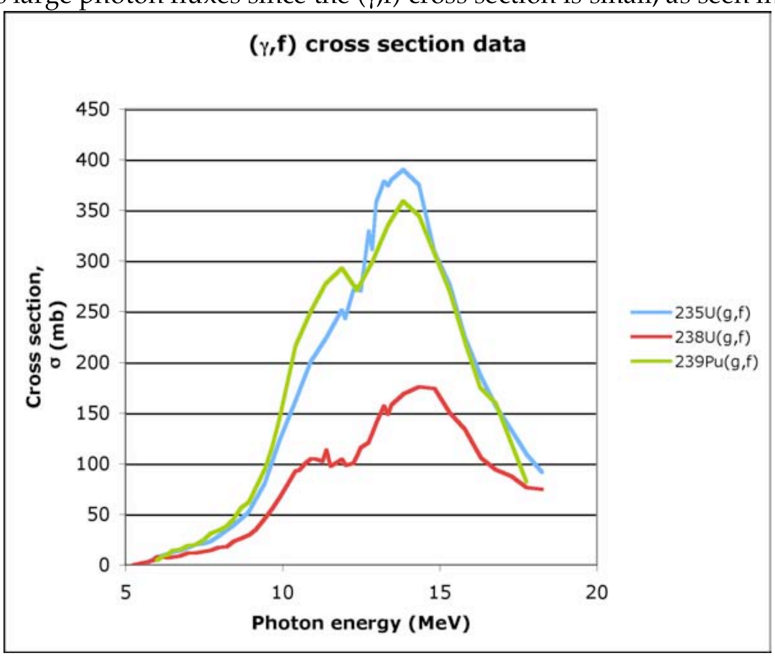

Figure 7.1-2 Fission cross section for SNM isotopes for photon-induced fission.

Note in the figure that the (γ,f) cross section peaks at σ ~ 150-400 mb as compared to a neutron thermal fission cross section of σ ~500-800 b so that g-ray fluxes must be ~ 1000X larger than neutron fluxes to produce the same number of fissions. At the higher fluxes the radiation dose to the target is ~ 10X higher to produce the same number of fissions as a neutron beam. In addition, the (γ,f) cross section is resonant with a reaction threshold $E_{min} \geq 5.6$ MeV and the peak reaction rate occurs at $E_\gamma \sim$ 14 MeV. Bremmsstrahlung sources must have high endpoint energies so that a significant part of the beam is capable of producing fission. Nevertheless, these systems have proven viable at detection of small amounts of SNM deeply buried in a variety of commercial cargo materials, albeit at short range (R < 25 m). These systems are small enough to be flown in a UAV without the surrounding shielding that would be required on the ground.

7.2 Neutron interrogation

Neutron sources have been effectively deployed to induce fission in hidden SNM. Two high power versions are shown below where both utilize a Radio Frequency Quadrupole (RFQ) to produce a kinematically directed beam forward at high intensity. These are shown below.

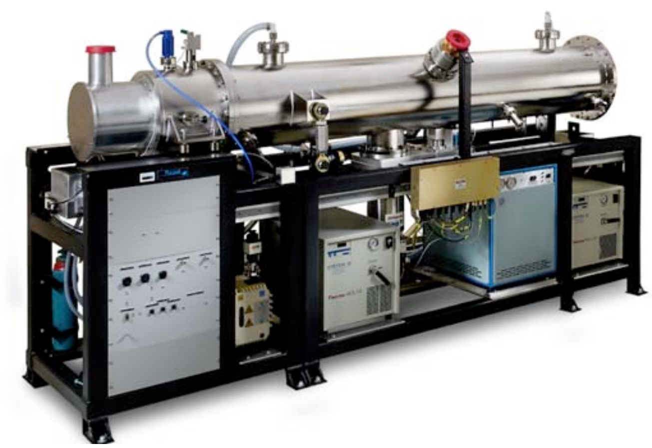

Figure 7.2-1 Left, a 2 MeV proton RFQ that generates neutrons at E_n~ 60 keV by the $^7Li(p,n)$ reaction into a small spot in the forward direction. This unit can be transported in two modules of mass ~ 100 kg each. Right, a 4 MeV deuteron RFQ that generates neutrons at E_n=3-7 MeV by the D(d,n) reaction into a small spot in the forward direction.

The 4 MeV RFQ generates neutron fluxes on the order $\Phi \sim 2x10^7$ n/cm^2/sec at a distance R ≥ 1 m, comparable to an isotropic source with total output I=2x10^{12} n/s[49]. Lower intensity neutron sources are available commercially from several suppliers. They are smaller and more portable but provide only marginal neutron fluxes on a remote target.

8. Proposed CONOPS for many venues

Detection of SNM in vessels at sea would rely on either airborne (UAV) or submerged (AUV) platforms. These platforms could be launched from surface ships or submarines, and they could be dropped into the sea from a C-131 or other suitable aircraft. The platforms, either a pair with the interrogation source on one and detector arrays on another, or a single platform carrying the whole interrogation system would be brought within the appropriate range of the suspicious vessel. Airborne systems would require the ability to orbit the target vessel at close range for as long as it takes to make a survey. This could be minutes or an hour or longer. Underwater vessels could be launched from a submarine and brought up under a vessel's keel without knowledge of the crew, thus providing undetected surveillance. Submerged platforms could also be launched from surface ships. In all cases the interrogation would provide sufficient flux on target to detect a threat object within a few meters of the hull whether it is below the waterline or near the keel or high up in the cargo. Maximum viability would be for threat objects where the vessel's overall cargo dimensions are small enough so that penetration of a few meters beyond the hull is sufficient to scan most or all of the cargo. This is the case for vessels smaller than 1000 tons or so. Observation times up to an hour or so would improve the delectability for threat objects in larger vessels.

A surface vessel or submarine or aircraft would monitor the scanning process and interpret results. If further action were required these vessels would call for help as appropriate.

9. Summary

The capability to scan vessels at sea for the presence of nuclear weapons or their component parts is extremely important to US national security. This problem is very broad in scope covering many possible venues. Any venues left unattended will become the pathway of choice for a terrorist smuggler so it is important to cover all possible pathways. Many of these are extremely difficult to provide adequate coverage but it has been shown in previous sections that extensions of existing active interrogation technology can provide minimally viable standoff range for this screening. The challenges are extraordinary so that even extensions of existing technology will not succeed in all venues or with all target threats. But, for smaller vessels of ~ 1000 tons or less there are extensions of known technologies that may prove viable for these threats. That would provide screening for a substantial part of the vessel fleet now utilized by international smugglers and this is an important goal and one warranting high-risk R&D to solve this problem.

10. References

1 J. Medalia. 2002.

2 M.-A. Descalle, D. Manatt, and D. Slaughter, "Analysis of recent manifests for goods imported through US ports", UCRL-TR 225708, Lawrence Livermore National Laboratory, Livermore, CA, October 31, 2006,

3 Wikipedia, "Unmanned aerial vehicle", 2008, http://en.wikipedia.org/wiki/Unmanned_aerial_vehicle.

4 GeneralAtomic, "General atomics GNAT", 2008, http://en.wikipedia.org/wiki/GNAT-750.

5 Wikipedia, "MQ-1 Predator", 2008, http://en.wikipedia.org/wiki/MQ-1_Predator.

6 Wikipedia, "RQ-4 Global Hawk", 2008, http://en.wikipedia.org/wiki/RQ-4_Global_Hawk.

7 Wikipedia, "MQ-88 Fire Scout", 2008, http://en.wikipedia.org/wiki/MQ-8B_Fire_Scout#MQ-8B 300kg payload 8hrs.

8 C. A. Jones, "Unmanned aerial vehicles (UAVs): An assessment of historical operations and future possibilities", Thesis Air Command Staff College, US Air Force, March, 1997, http://www.fas.org/irp/program/collect/docs/97-0230D.htm.

9 Intelligence, "Unmanned aerial vehicles", 2008, http://www.globalsecurity.org/intell/systems/uav.htm.

10 NDT, "Large structure inspection (LSI) automated ultrasonic inspection system", 2006, http://www.ndtautomation.com/index.aspx?go=products&focus=/Portable%20Systems/LSI.htm.

11 MAUS, "Mobile Automated Scanner (MAUS)", 2008, http://www.ndts.net/htm/maus.htm.

12 SeaBotix, "Combo swimmer and crawler for ship hull inspection", 2006, http://robotgossip.blogspot.com/2006/06/combo-swimmer-and-crawler-for-ship.html.

13 VideoRay, "HulsFest report", 2006, http://www.hulsfest.com.

14 C. Gibson, "VideoRay releases comprehensive analysis of navy hull inspection benchmark", 2006, http://www.videoray.com/Press_Room/hulsfest-060806.htm.

15 SeaEye, "SeaEye Falcon ROV", 2006, http://www.seaworks.co.nz/Text/rovfalcon.htm.

16 SonicWorks, "SonicWorks waterside facilities security and inspection", 2006, http://sonicworks.com.

17 Shark, "Remotely operated vehicles -ROVs", 2006, http://www.sharkmarine.com/rov.htm.

18 SeaBotix, "The most comprehensive line of Mini-ROVs in the world", 2006, http://www.seabotix.com/index.htm.

19 desertstar, "Ship hull inspections with AquaMap", 2006, www.desertstar.com.

20 S. Tetlow, "Hull inspection ROV", 2006, http://www.cranfield.ac.uk/sims/marine/research/other.htm.

21 U. R. Zimmer, "Autonomous underwater vehicles", 2008, http://www.transit-port.net/Lists/AUVs.html.

22 Wikipedia, "Autonomous underwater vehicle", 2008, http://en.wikipedia.org/wiki/Autonomous_Underwater_Vehicle.

23 R. F. Service, "Oceanography's third wave", Science **318**, 1056 (2007).

24 A. Cho, "Robotic cars tackle crosstown traffic- and not one another", Science **318**, 1060 (2007).

25 M. S. Lavine, D. Voss, and R. Coontz, "A robotic future", Science **318**, 1083 (2007).

26 J. G. Bellingham and K. Rajan, "Robotics in remote and hostile environments", Science **318**, 1098 (2007).

27 K. A. Jordan and T. Gozani, "Neutron differential die away analysis for detection of nuclear materials", Nuclear Instruments and Methods in Physics Research B **261**, 365 (2007).

28 K. A. Jordan and T. Gozani, "Detection of ^{235}U in hydrogenous cargo with differential die-away analysis and optimized neutron detectors", Nuclear Instruments and Methods in Physics Research **A579**, 388 (2007).

29 K. A. Jordan and T. Gozani, "Pulsed neutron differential die away analysis for detection of nuclear materials", Nuclear Instruments and Methods B **B261**, 365 (2007).

30 K. A. Jordan, J. Vujic, and T. Gozani, "Remote thermal neutron die-away measurements to improve differential die-away analysis", Nuclear Instruments and Methods in Physics Research **A579**, 407 (2007).

31 K. A. Jordan, J. Vujic, E. Phillips, et al., "Improving differential die-away analysis via the use of neutron poisons in detectors", Nuclear Instruments and Methods in Physics Research **B579**, 404 (2007).

32 D. R. Slaughter, M. R. Accatino, A. Bernstein, et al., "The nuclear car wash: A system to detect nuclear weapons in commercial cargo shipments", Nuclear Instruments & Methods in Physics Researchs A **579**, 349 (2007).

33 J. M. Hall, S. Asztalos, P. Biltoft, et al., "The nuclear car wash: Neutron interrogation of cargo containers to detect hidden SNM", Nuclear Instruments and Methods in Physics Research B **261**, 337 (2007).

34 J. Church, A. Bernstein, M.-A. Descalle, et al., "Study of signal interferences in the nuclear car wash", Nuclear Instruments and Methods in Physics Research B **261**, 351 (2007).

35 D. R. Slaughter, M. R. Accatino, A. Bernstein, et al., "Preliminary results utilizing high-energy fission product γ-rays to detect fissionable material in cargo", Nuclear Instruments and Methods B **241**, 777 (2005).

36 R. C. Byrd, J. M. Moss, W. C. Priedhorsky, et al., "Nuclear detection to prevent or defeat clandestine nuclear attack", 2004, IEEE, IEEE,

37 C. E. Moss, C. L. Hollas, G. W. McKinney, et al., "Comparison of active interrogation techniques", 2005, IEEE Nuclear Science Symposium, San Juan, Puerto Rico, 23-29 October, IEEE,

38 C. E. Moss, M. W. Brener, C. L. Hollas, et al., "Portable active interrogation system", Nuclear Instruments and Methods B **241**, 793 (2005).
39 J. L. Jones, B. W. Blackburn, D. R. Norman, et al., "Status of the prototype pulsed photonuclear assessment (PPA) inspection system", Nuclear Instruments & Methods in Physics Research **A579**, 353 (2007).
40 J. L. Jones, B. W. Blackburn, S. M. Watson, et al., "High-energy photon interrogation for nonproliferation applications", Nuclear Instruments and Methods in Physics Research B **261**, 326 (2007).
41 D. R. Norman, J. L. Jones, B. W. Blackburn, et al., "Time-dependent delayed signatures from energetic photon interrogations", Nuclear Instruments and Methods in Physics Research B **261**, 316 (2007).
42 C. E. Moss, C. A. Goulding, C. L. Hollas, et al., "Linear accelerator-based active interrogation for detection of highly enriched uranium", 2002, Conference on Accelerator Applications in Research and Industry, Denton, TX, 12 November,
43 G. R. Keepin, "Nuclear safeguards research and development", LA 4368-MS, Los Alamos National Laboratory, Los Alamos, NM, October-December, 1969,
44 G. R. Keepin, "Nuclear safeguards research and development", LA- 4457-MS, Los Alamos National Laboratory, Los Alamos, NM, January-April, 1970,
45 J. L. Jones, W. Y. Yoon, K. J. Haskell, et al., "Pulsed photonuclear assessment (PPA) technique: CY04 year-end progress report", INEEL/EXT 05-02583, Idaho National Laboratory, Idaho Falls, ID, February, 2005,
46 J. L. Jones, W. Y. Yoon, D. R. Norman, et al., "Photonuclear-based, nuclear material detection system for cargo containers", Nuclear Instruments and Methods B **241**, 770 (2005).
47 D. R. Norman, J. L. Jones, W. Y. Yoon, et al., "Inspection applications with higher electron beam energies", Nuclear Instruments and Methods B **241**, 787 (2005).
48 J. L. Jones, "Photofission-based nuclear material detection: Technology demonstration", INEEL/EXT 02-1406, Idaho National Engineering Laboratory, Idaho Falls, ID, December, 2002,
49 D. R. Slaughter, S. Asztalos, J. A. Church, et al., "A 7 MeV neutron interrogation system to detect well shielded SNM: the final report", UCRL-TR 236521, Lawrence Livermore National Laboratory, Livermore, CA, 30-September, 2007,