LA-UR-15-26068

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Intended for: Report

Issued: 2015-07-31

A new method of passive counting of nuclear missile warheads -a white paper for the Defense Threat Reduction Agency

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Abstract Cosmic ray muon imaging has been studied for the past several years as a possible technique for nuclear warhead inspection and verification as part of the New Strategic Arms Reduction Treaty between the United States and the Russian Federation. The Los Alamos team has studied two different muon imaging methods for this application, using detectors on two sides and one side of the object of interest. In this report we present results obtained on single sided imaging of configurations aimed at demonstrating the potential of this technique for counting nuclear warheads in place with detectors above the closed hatch of a ballistic missile submarine.

The problem

Both the United States and the Russian Federation have deployed the bulk of their strategic nuclear weapons on missiles that have the capability to deliver multiple, independently targeted warheads. This poses a difficult problem for verification of the number of warheads mounted in each missile. For instance, an Ohio class ballistic missile submarine, Figure 1, has 24 Trident C4 SLBMs with up to 8 MIRVed nuclear warheads on each missile.

The current method of verification is visual inspection. Inspectors are allowed to visually inspect the shrouded payload region of a small set of missiles in order to count the number of reentry bodies. START allows the use of radiation detection equipment to verify that an object declared to be non-nuclear is non-nuclear. This inspection procedure is complicated and expensive. The missile launch tubes need to be opened, nose cones and heat shields need to be removed. All of the steps involve complicated procedures that protect classified data while insuring that all treaty partners are meeting their obligations. Stringent safety requirements must be met during these inspections.

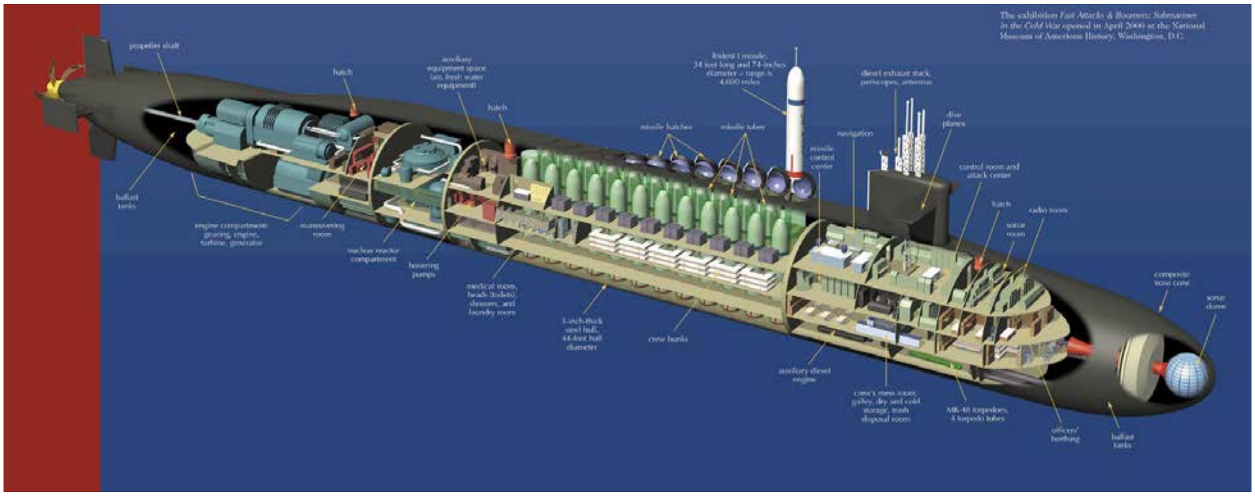

Figure 1) Cutaway view of an Ohio class ballistic missile submarine.

Here we demonstrate a potential method that allows imaging of active warheads using passive signals obtained from cosmic radiation. This technique uses single sided neutron tagged muon imaging. We demonstrate that this technique can see through 2.5 cm of steel and provide images of sufficient quality to count warheads in situ. This method of warhead verification can considerably simplify and reduce the cost of the inspection regime while providing accurate verification data and protecting sensitive weapons design information.

Tagged muon imaging

Tagged imaging uses the incoming trajectory of neutron-tagged cosmic rays to create an image of material below a set of muon tracking detectors using a technique called laminography. The flux of cosmic ray muons at the earth's surface is composed of both positively and negatively charged muons. Muons are slowed down and eventually stopped as they move through matter. Free muons decay into positrons or electrons, depending on their charge, and neutrinos. In matter negatively charged muons are captured into bound atomic states by the Coulomb force, like electrons, but with much smaller radii. In nuclei heavier than magnesium the predominant decay becomes muon capture on a bound proton, producing a neutron and a neutrino. In fissionable material this decay leaves an excited nucleus that subsequently fissions and produces more neutrons. In fissile assemblies, such as a nuclear warhead, there is additional gain due to neutron amplification. The neutrons can be detected and used to tag their parent muon. Both the muons and the neutrons are highly penetrating radiation that can pass through layers of steel. Even scattered neutrons are useful for the tagging so considerable steel overburden should not affect this technique much.

The positions where the tagged muon trajectories intersect a plane at the location of the warheads can be tallied (histogrammed) in two dimensions to produce an image that is very sensitive to the fissile material in the warheads, as shown schematically in Figure 2. The position resolution is not sufficient to reveal classified details of the weapon. Also, the strength of the image should be distinctive of a specific weapon type but should not reveal classified information because it depends on both the mass of fissile material and its geometry in a way that cannot be disentangled without further information. The information barriers are inherent to this technique make it especially well-suited to international arms verification efforts.

This concept has recently been demonstrated using the mini muon tracker (MMT) in Los Alamos[1] with a single neutron counter and a muon tracker in a geometry optimized to detect tagged events. Here we present the results from some recent tests approaching the geometry needed for warhead counting in a missile submarine, list the remaining risks, and estimate the costs of a deployable system.

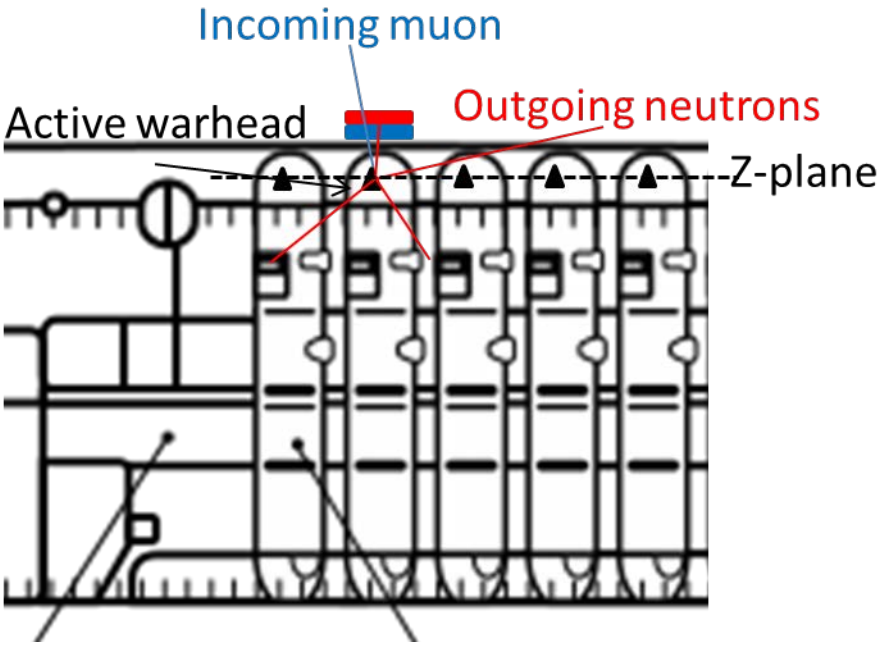

Figure 2) Sample geometry for counting warheads. An incoming negative muon(shown as a blue line) stops in a warhead and initiates a neutron cascade resulting in some number of outgoing neutrons (shown as red lines). The incoming trajectory is tracked in the blue detectors and the trajectory is tagged by an outgoing neutron detected in the red detector.

Results

We show data taken in several configurations including in a shielded box and in a geometry approximating the one needed for imaging the MIRVed warheads in the nose cone of a missile in its launching tube through a closed hatch. Data were taken using 20 kg cubes of both depleted (DU) and low enriched uranium (LEU) as surrogates for the fissile material in a missile warhead. One of the setups is shown in Figure 3. In Figure 4 we show the tagged muon rate as a function of the distance between the detectors and the LEU cube. The solid line is a prediction of rate made using the MuonEstimator tool previously provided to DTRA. The prediction is high at small distance because we have not taken the finite detector sizes into account but assume that the distances from all points at the detectors to the cube are equal to the normal distance between the detector planes and the cube.

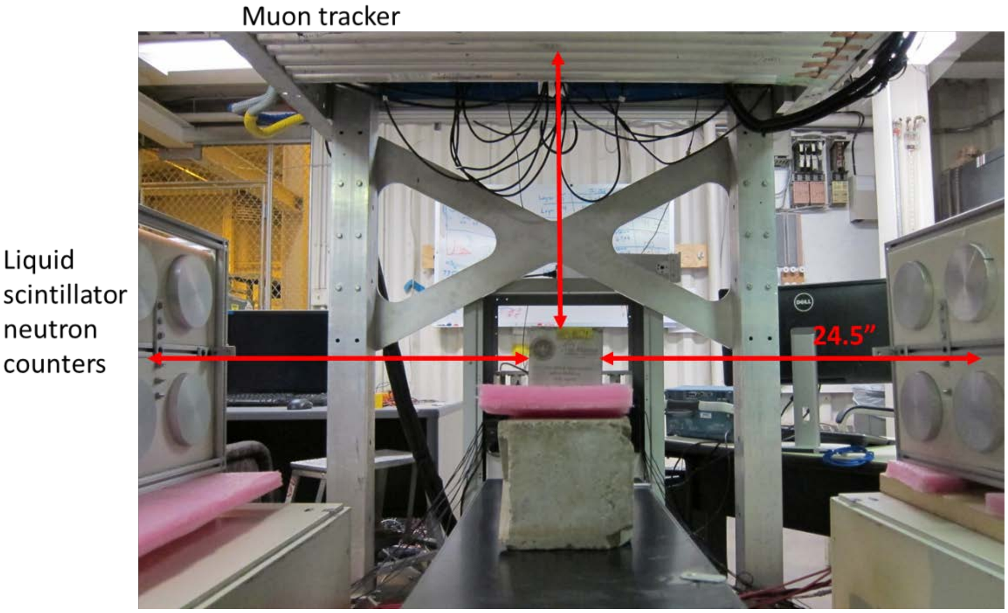

Figure 3) Photograph of one of the setups used to test the MuonEstimating tool. The EJ301 neutron detectors are to the left and right, the bottom of the muon tracking detector can be seen at the top and the LEU cube is in the center of the photograph.

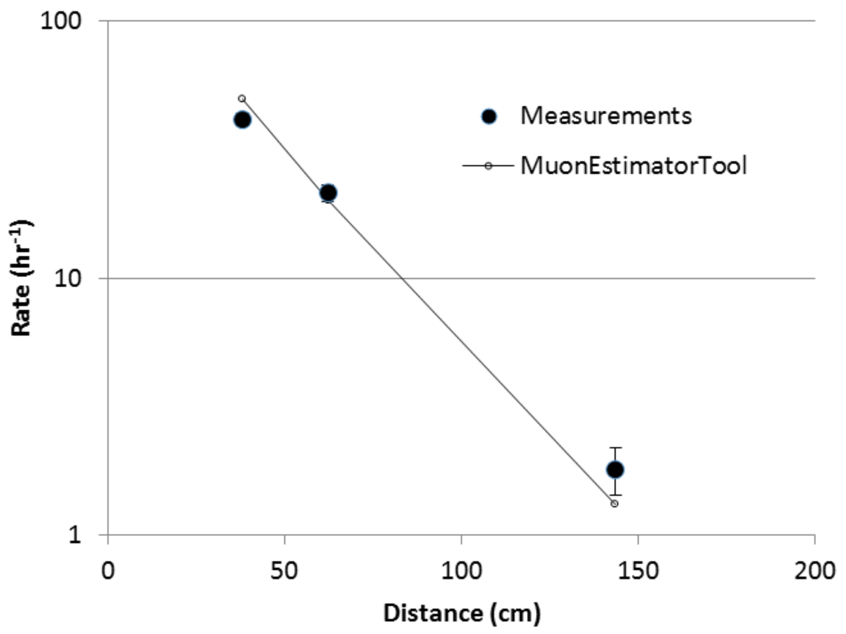

Figure 4) rate vs distance from the detectors. Distances are from the nearest face of the cube to the front of the tracking detector and the front of the neutron detectors. During this measurement campaign the muon detector and the neutron detectors were kept at the same distance from the uranium cube.

In the next test the cube was placed inside of a shielding box with a three inch layer of polyethylene and a 1 inch layer of lead surrounding the cube on all sides. This shielding would be sufficient shielding to defeat any passive neutron or gamma detection of a similarly sized piece of weapons grade uranium. Data were taken with both an empty shielding box (20 hours) and with the uranium cube in the shielding box (61 hours). The normalized rate was measured to be lower without the uranium but more data are needed to completely quantify the difference. It is important to note that a significant quantity of highly enriched uranium (HEU) or plutonium would generate many more neutrons than the cubes used here. This technique may provide an entirely passive method to inventory or search for shielded nuclear weapons or special nuclear materials (SNM).

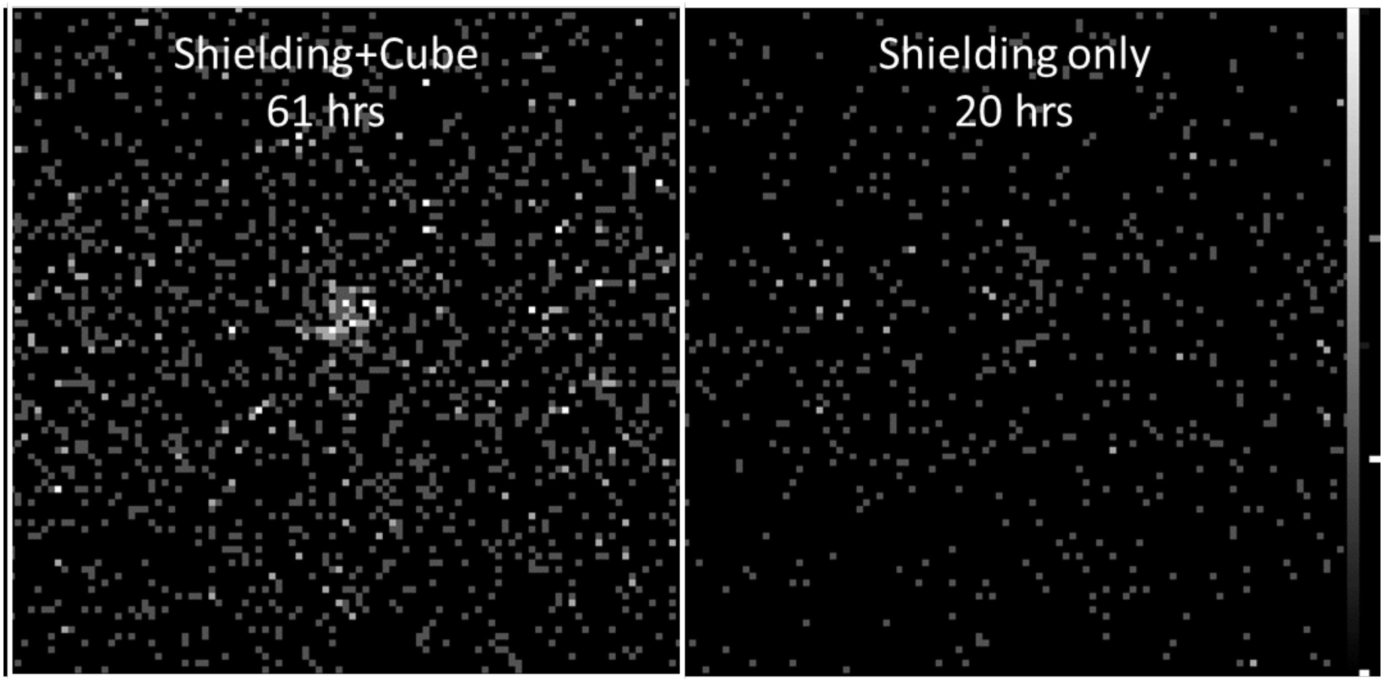

Figure 5) a 61 hour image of the shielded uranium cube (left) and a 20 hour image of only the shielding (right).

Imaging war heads through a missile hatch

In order to test imaging through overburden, like that expected in submarine, we constructed the setup shown in Figure 6. Three 20 kg uranium cubes were placed on the concrete floor about 160 cm under the tracker. The neutron detectors were placed on the floor approximately the same distance from the centroid of the cube positions. Steel was placed on a table just below the upper tracking detector to mockup the missile hatch. The thickness of steel was chosen based on the assumption that the hatch would be as light as possible based on the pressure requirements for the submarine. The cut away drawing, Figure 1, lists the diameter of the hull as 10 m and the thickness as 7.6 cm. The missile hatches appear to be spherical with a diameter of 2 m. The missile hatch could be as thin as 0.76 cm and still hold the same pressure as the hull. A thickness of 2.5 cm of steel was chosen as a conservative estimate of the missile hatch thickness for these measurements. More research on the specifics of submarine design is needed to find the actual thickness.

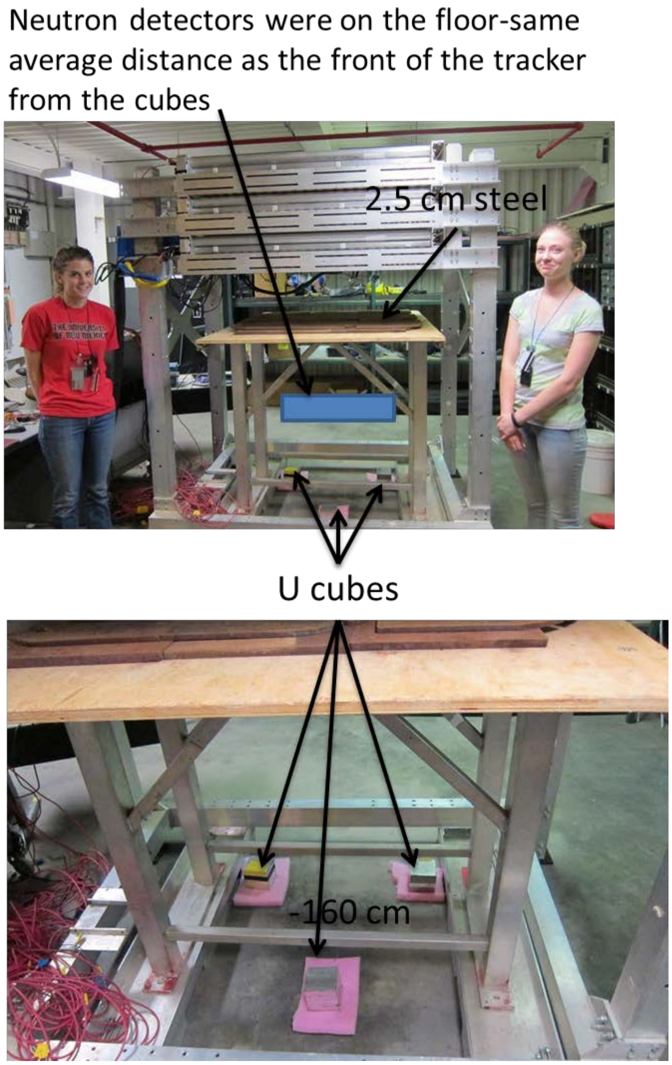

Figure 6) Set up used to mockup warhead counting with detectors above a missile hatch. The hatch was assumed to be about 1” of steel in thickness. The neutron detectors were on the floor, so were not shielded by the steel, but this is estimated to have a minimal effect on counting rates.

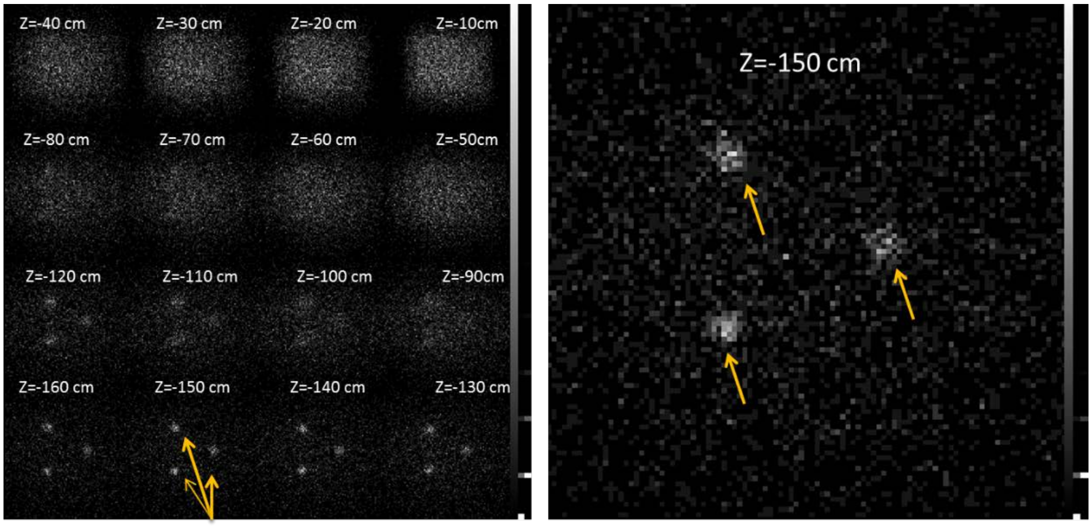

Figure 7) Left) the laminograph of 93 hours of exposure for the setup shown in Figure 6. The slices are labeled by the distance below the face of the tracking detector. Right) A single slice near the best focus of the objects. The field of view for reach slice is 2 m×2 m. the orange arrows mark the locations of the uranium cubes.

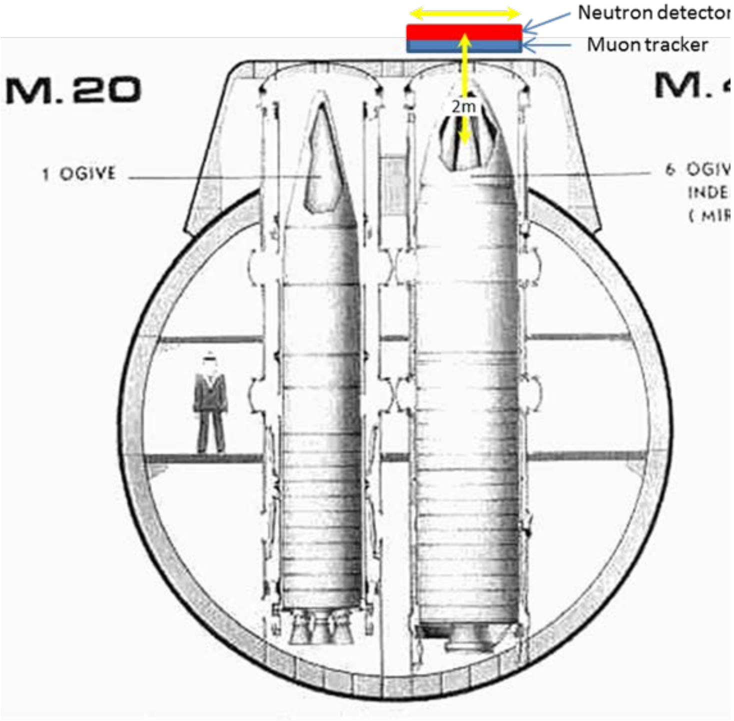

Figure 8) Cross section view showing MIRVed missile in a French ballistic missile submarine.

A sample counting geometry is illustrated in Figure 8. The detectors are mounted on top of the closed hatch. The diameter of the missile tube is 2 m. Although the accuracy of these figures may be dubious, it appears that a two meter standoff should allow the warheads to be observed from the top of the hatch. (It appears this is a French submarine).

Remaining Risks

- The geometries could be different from the studies here, reducing the counting rates to an impractical level.
- The neutron background expected from thermonuclear devices with plutonium pits could produce large accidental coincidence backgrounds and obscure the signal.
- The safety issues involved in mounting detectors above the submarine hatch could be insurmountable.
- The assumptions that the information from real systems is unclassified could be incorrect.

Path forward

- More research into the actual geometries encountered in treaty verification needed to verify the geometries used in this experiment.
- Further measurements are needed using neutron sources to simulate the neutron background expected from thermonuclear devices with plutonium pits.
- Large area neutron detectors that do not use low flashpoint solvents need to be tested.
- Data should be taken in a realistic geometry with weapon trainers to ensure the data are unclassified.

A rough estimate of the cost of this effort is $600k-6 months of the P-25 threat reduction team. This work can be completed in 1 year.

Cost of a deployable system

A 1.8×1.8 m^2 muon tracker used with a set of 100, 10 cm diameter, 10 cm long stilbene neutron detectors would provide rates about 40 times larger than in this experiment. This would allow warhead imaging with sufficient statistical precision to count active warheads in place in times on the order of an hour. Since stilbene is an organic crystal, it poses no safety hazard.

The current price for a tracker is about $250 k (est.). A set of 100 neutron detectors would cost about $600 k (est. based on quote for 100 bare stilbene crystals of $474 k). A rough estimate of the total cost of a scanner with data acquisition and mechanics is about $1M. An additional $550k is needed for engineering, construction and testing. This work can be completed in 1 year.

Submarine Demonstration

Demonstration of warhead counting requires access to a submarine in port. Assuming that both access and the costs associated with obtaining authorization and access are provided, this demonstration could be performed for about $450K. A demonstration could be made using the existing scanner and the results could be scaled to the larger detectors described in the previous section.

Pentagon demonstration

The current system could be used for a demonstration at the Pentagon. Travel and set up would cost approximately $66k.

Summary

We have performed an experiment to evaluate tagged muon imaging for counting warheads in a MIRVed missile system in a submarine. It appears from this simple experiment that sufficient rate can be obtained to identify and count warheads with about an hour of exposure without opening the missile hatch using equipment currently commercially available.

1. Guardincerri, E., et al., *Detecting special nuclear material using muon-induced neutron emission.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2015.

2. Morris, C.L. and A. Saunders, *NewDisplay*, in *Los Alamos Computer Code*. 2004.