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Optimization of the Army's Fast Neutron Moderator for Radiography

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PREFACE:

This paper details ARDEC's continuing efforts to construct advanced equipment in the neutron radiographic inspection method for use at smaller sites, specifically those within the Department of Defense. The complimentary information obtained using neutron inspection provides a higher degree of reliability, safety, and product assurance for the end user of the item under investigation.

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SUMMARY:

This paper expands upon the previous work done in the field of neutron radiography by the ARDEC radiographic laboratory, in an effort to establish a baseline for the inspection method within the Department of Defense (DoD). Multiple experiments were done to achieve the highest possible thermal neutron flux from a commercially available high-energy D-T neutron generator. This paper details the steps taken to increase exposure rates and reduce exposure times by optimizing target orientation and increasing neutron beam quality with filters of varying material thickness and type. Overall, these tests showed the promise of the inspection technique and its viability for research and development purposes. Specimens of aluminum, lead, brass, steel, clay, sponge, and tungsten, whose thicknesses ranged from 0.31 cm to 3.8 cm, could be viewed within the same image. Corresponding data obtained through the use of the American Society for Testing and Materials (ASTM) image quality indicators showed reasonable results. The experiment also demonstrated the test source's limitations when compared to images taken with high-yield sources such as reactors, due to the inherently low yield of the presently available commercial generators. It was determined that higher strength electronic neutron sources would be required. The latest technological developments in high-output electronic neutron sources (that are also small in size) are transitioning to the US Army for testing and use in the specialized radiographic applications of munitions and weapon inspection. These new generators are expected to bring high quality neutron images with shortened exposure times that will make low-rate production sampling possible. Some of the initial testing included in this paper points towards further investigation and experimentation into the development of a complete neutron radiographic system that is applicable to a variety of facilities, for items that cannot otherwise be inspected non-destructively.

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ABSTRACT:

Early experiments in neutron radiography have been demonstrated at the US Army Armament Research, Development, and Engineering Center (ARDEC). From the early 1970s through the 1980s, neutron imaging was done using Californium-252 (Cf-252), and showed significant potential for expansion into an NDT method that would be viable to inspect munitions and weapon systems. However, due to the inherent issues involved with the use of radioactive sources, and the high costs and numerous requirements for operating a reactor or research accelerator, little progress has been made since that time. Neutron radiography has not been widely implemented for use within the DoD, mainly due to the limitations of available neutron producing sources. Current commercially available electronic sources and generators are impractical for imaging due to low outputs, which require exposure times measured in days, not minutes, as is typical for x-ray imaging. These conditions were shown in the initial baseline experiments performed at ARDEC with a commercial source. The early tests showed promise in the method, but reinforced the need for a high-output, small-size, easy-to-use neutron source. This paper presents a more in-depth investigation into the optimization of a laboratory neutron radiographic (NR) imaging system, and its potential for nondestructive inspection directly applicable to defense components. This upgraded NR setup uses a moderator and collimator specifically designed for use with the 14.1 MeV neutrons from a deuterium- tritium (D-T) generator. The field of view (FOV) was also increased for more practical use with standard 35 cm L x 43 cm W (14 in L x 17 in W) radiographic cassettes and film. The goal of this experiment was to have increased thermal neutron flux rates and shorter exposure times than previously achieved. Additional technology developments are also underway to build state of the art neutron sources for the Army. Their intent is to bring this method into common use within the defense community. An example of the initial imaging setup for one of these novel systems was included to show the progress made in the NR field.

KEYWORDS:

Neutron, radiography, high yielding, electronic sources, munitions, nondestructive testing, NDT, NR.

INTRODUCTION:

Past Work

Early results from a commercial-off-the-shelf (COTS) ThermoFisher P385 neutron generator provided direct data on the current state of technology for relatively small and easily obtainable neutron sources (Ref 1). Initial image studies showed that neutron radiographs could be generated for small inspection items using COTS sources, but the image quality was low and required more than a full week of exposure to acquire. The images that were previously taken also had a field of view no larger than 15.24 cm in diameter, making them impractical for real-world inspections. The best image acquired during these early experiments also lacked the quality necessary for accurate measurement of its image quality indicators (IQI's), as specified in ASTM E 545 (Ref 2). In most cases, the images required digital processing to pull information from the exposure, information that was otherwise invisible using conventional film review techniques.

The biggest detriment to the outcome of these early tests was the use of a moderating assembly originally designed for a neutron producing isotope, specifically Cf-252. This particular isotope produced a peak neutron energy of 2.35 MeV, which is significantly lower than the peak energy of 14.1 MeV produced by the chosen COTS generator utilizing the D-T fusion reaction. This reduced the thermalizing efficiency of the moderator at higher energies, resulted in a large loss of neutron flux at the image plane, and negatively impacted the exposure times required. Other variables that adversely affected the image quality and exposure time of the initial experiments were asymmetric self absorption within the generator itself and the lack of beam filters to reduce scatter and noise.

OPTIMIZING THE SYSTEM:

Moderator Changes

In order to increase the flux at the imaging plane more neutrons need to find their path into the collimator. This requires more neutrons to be thermalized within the moderator, without the capability of increasing the yield coming from the source. The D-T energies produced by the chosen generator are so high that precisely calculating specific interactions is inherently difficult to perform. Therefore rough estimates were used based off of thermalizing lengths for specific materials, in this case high density polyethylene (HDPE). These estimates were completed to determine what size moderator would be beneficial. The calculations were completed by using the general thermal neutron attenuation coefficients and attenuation equations found in references 2 and 3 (Ref 2, 3). It was estimated that nearly two times the thickness of HDPE was needed to optimize the moderator for the P385 generator. This amount accounted for the difference in energy from previous work with isotopes. The adjusted size also ensured minimal neutron loss would occur, by reducing the number of fast neutrons that could exit through the sides of the moderator. The change in geometry was also designed to not increase the thickness of moderator material beyond the limit where too many neutrons would be captured. A result in excessive activation products can occur if this consideration is not made. In most cases the impact of increasing gamma scatter and contamination through neutron capture is an easier issue to compensate for rather than having to deal with escaping neutron scatter. By adding masking and beam filters, which are heavy attenuators to gamma photons, most contamination can be removed while allowing the added thermal neutron flux through the collimator. Modeling with Monte Carlo N-Particle (MCNP) transport code is the most effective way of predicting material thicknesses, thermalizing lengths, and other variables involved in neutron interactions. However, this software was not readily available. Therefore a general trial and error method was used instead during these experiments.

In the early design and testing with the P385, multiple inserts were tested to assist in knocking down the energy of the fast neutrons in a shorter distance. Several combinations of HDPE and low carbon steel were used. Due to the number of changing variables, the set of inserts used were in the same combination throughout this optimization experiment. The images taken within the setups presented later in this paper included an all steel insert placed directly against the generator. The steel insert was 4.4 cm thick, and can be seen in the Figure 1.

Figure 1:
Low-carbon steel insert used to slow the high-energy D-T neutrons over a shortened distance.

Collimator changes

The main issue that was seen with the previous collimator was the small FOV it produced. A simple redesign was completed to allow for modular lengths and collimator openings to vary the FOV if necessary. The idea behind this change was to match the size of a common 35.6 cm L x 43.2 cm W radiographic cassette and film size. Since the ratio of the length to aperture diameter (L/D ratio) was incredibly low to begin with, an increase in the diverging angle was seen as negligible in terms of added parallax. Due to the fact that the exposures were so long during the early experiments, it was seen as more beneficial to gain added knowledge per image. The length of exposures varied between 25 and 60 hours initially.

The upgraded collimator was a simplified lead cone that was removable and allowed for adjustments in the length of the beam line and the FOV at the imaging plane. The aperture started at the same 5.1 cm diameter as before, but also allowed for variation to smaller diameters if necessary. The length of the collimator could be adjusted from 30.5 cm up to 53.3 cm, or L/D values between 6 and 10.5, if the image plane was directly against the assembly. The half angle of the cone was 14-degrees. The FOV was now able to be adjusted in sizes ranging from 21.4 cm in diameter up to 33 cm.

The thinnest section of lead that any one x-ray or gamma ray photon could pass through was 1.27 cm thick in the direction of the image plane. This was enough to remove unwanted gamma rays created in the activation of the hydrogen within the HDPE. Figure 2 shows the collimator assembly as it was being constructed.

Figure 2:
The collimator assembly during construction (left), installed in the moderator (center), and covered with lead sheeting to shield the image plane (right).

Generator placement

This new design for the moderator and collimator are illustrated in Figure 3 below. The HDPE moderator was a cube roughly measuring 121.9 cm on each side. The generator here was oriented perpendicular to the floor, mainly to maximize the number of thermal neutrons that could be retained and used for imaging. In the early design the generator was parallel to it. This exploited the design of the P385, where the source head has fewer internal parts and lower material thicknesses on the sides, perpendicular to the target plane. This geometry created a small bias of increased neutron yield coming from the sides rather than the top of the generator. The manufacturer specifications estimate that up to 30% more neutron yield can be ejected from the sides. In the original experiment (Ref 1), the top of the generator was pointed towards the imaging plane. During this experiment, the top of the generator was pointed down into the moderator, towards the direction of the floor. The expectation was that this would allow the main flow of thermalized neutrons a more probable chance of exiting through the collimator due to the inherent directional biased created by the source. This can be visualized by considering the collimator aperture to be a water faucet and the flow of neutrons exiting the collimator to be the direction the water is moving in. If the main flux is from the sides of the generator, a higher output or pressure directly towards the collimator occurs. This concept is analogous to the water flowing straight out through the faucet opening without any impedance. However, if the main flow is pointed away from the aperture the water will more likely be disrupted; i.e. the neutrons will be more likely to be lost, absorbed, or otherwise removed within the moderator. This results in a loss of available neutrons that can exit through the collimator and reach the image plane. The general expectation was to increase the thermal flux at the imaging plane by at least a few percent, which will help reduce the exposure time and increase image quality through an increase in the signal to noise ratio (SNR) as seen by the film.

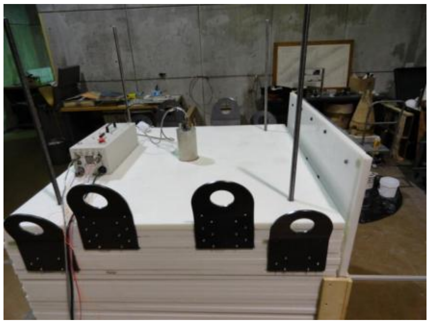

Figure 3:
The complete upgraded moderator and collimator assembly with the generator placed vertically.

RESULTS AND DISCUSSION:

Image Quality Achievements

With the changes made to the moderator/collimator assembly, the P385 generator produced positive results, but also continued to show extreme shortfalls of the current technology. The images taken with this setup had exposure times of 28.1 to 52.5 hours, with Hurter and Driffield measurements (H&D) of 0.46 to 0.66. The first image was taken with AGFA brand D3SC film, but the bulk of images taken with this system employed the faster D4SC film. This allowed an increase in the throughput during refinement of the setup. The original intent was to keep a comparative baseline with what is done in production at nuclear reactor facilities, but the time needed for exposures with the slower film made this unfeasible. The gains that were achieved by using faster D4SC film were worth more than the small loss of resolution caused by switching film types. This loss was negligible compared to the already high geometric unsharpness and parallax that occurred during imaging. During this set of optimization experiments, the major variables adjusted included the thickness of gadolinium (Gd) paint that was put onto the exterior of the lead (Pb) collimator cones, the L/D ratio, and the thickness of inline beam filters. These adjustments resulted in the reduction of neutron scattering events, reduced parallax (by a change in L/D), and a lessening of gamma- and x-ray pollution directly in the beam line.

Figure 4 below shows the image with the best overall quality generated by this experimental setup and technique. This image used D4SC film, a 0.64 cm bismuth (Bi) beam filter, a beam length of 101.6 cm, and an L/D of 20. A significant increase in resolution, penetration, contrast, latitude and overall clarity is shown. The exposure time for the image was approximately 52.5 hours and produced an H&D of 0.46. The achieved field of view was roughly 34.3 cm (13.5 in) in diameter. From this experiment, it was easy to distinguish the boron nitride (lower set) and lead discs (upper set) on the beam purity indicator. The ability to discern masking tape, adhesive tape, and a 0.32- to 3.8 cm-thick lead step wedge in the same exposure was also evident.

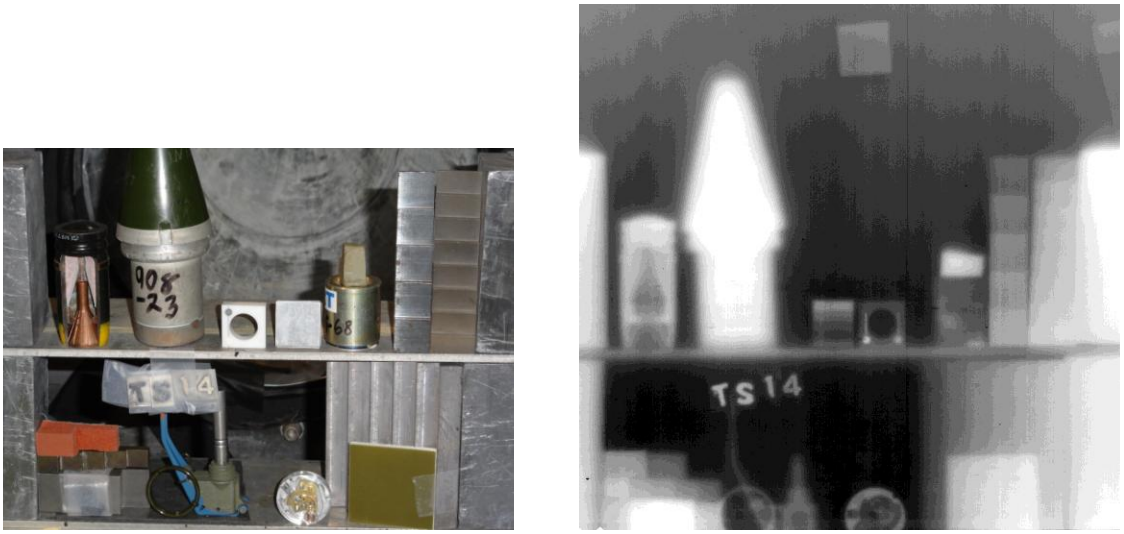

Figure 4:
An example of a neutron radiograph using the P385 generator with the upgraded moderator/collimator assembly (right); and the visual setup of the inspection items (left).

The biggest takeaway from these optimization trials was the ability to detect very low physical density components that were placed directly in line with very high density pieces. In conventional radiography using x-rays, there are physical difficulties in penetrating through lead and tungsten (W) because of their high densities. Depending on thickness, purity, and other variations of a given material, penetration can be accomplished if a high enough photon energy is achieved. However, in doing so, materials low in density are “washed away” or “burned through” and cannot be detected, since the attenuation length of the material is very low in comparison to the surrounding high density material. This is where neutron radiography has its greatest application. In Figure 5 it is easily seen that the information obtained in the neutron radiograph supplies a different array of knowledge about the parts under investigation when compared to a standard radiograph made with x-rays. The images show the obvious attenuation differences by comparing the beam purity indicator (BPI) and sensitivity indicator (SI) found in both images, as well as the increased detection in the neutron image of a piece of carbon fiberboard directly behind the lead step wedge (bottom right). The fiberboard is practically undetectable in the high energy x-ray image, while in the neutron image it is very easy to see. Other variations between the images are also apparent, but this particular one shows the importance of how multiple NDT methods widen the range of inspection capabilities.

A practical example of how neutron radiography can add to the inspection of defense items is visible in the lower left corner of the images. An inert version of a M213/M228 hand grenade fuze was imaged, where the simulated delay column was clearly defined and could be accurately measured. Even with some of the best digital x-ray detectors available today, using image processing and program filters, the delay is difficult to detect and measure. The length of this column is a critical inspection criterion for the fuze, as it determines the amount of time delay between initiation of the fuze and its detonation of the hand grenade.

The height of this column is difficult to detect consistently with x-ray inspection due to the density difference between the delay and the surrounding material of the fuze body that envelops it, especially in the threaded region of the fuze assembly. The density difference and sharp thickness changes has less of an effect in the neutron image, resulting in the delay column being clearly defined against the image of the fuze body.

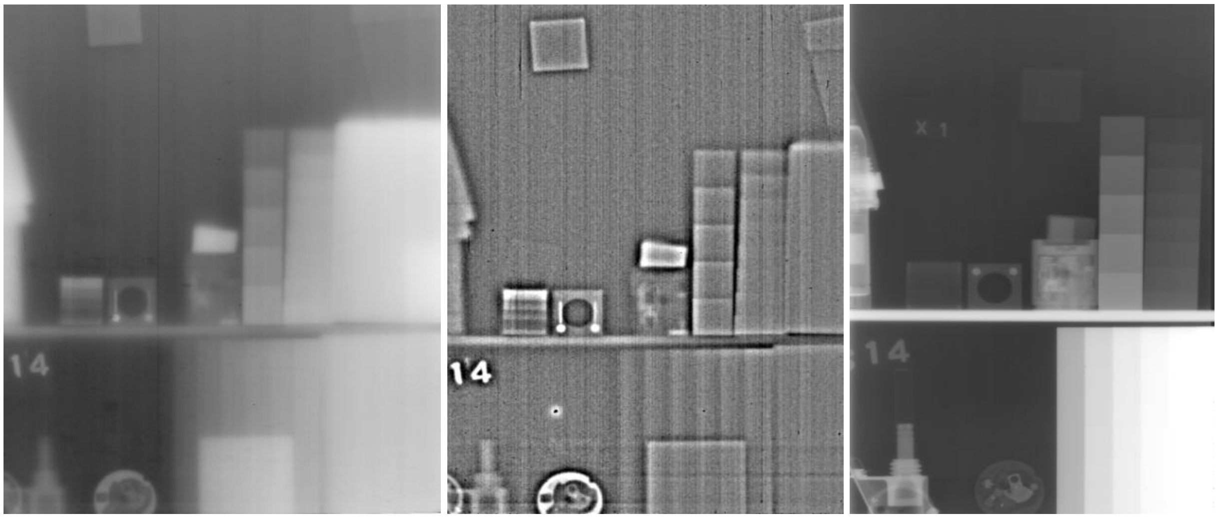

Figure 5:
Partial view of the raw neutron radiograph (left), the same image with an applied band pass filter (middle), and a high-energy 3 MeV x-ray comparison image (right).

Figure 6 provides a similar comparison with other objects in the original image. It shows how two overlapped pieces of tungsten, with a combined thickness of 2.5 cm, can cause detection problems when using x-ray inspection. In the very bottom left of each image in Figure 6, directly in the center of the tungsten, there is a small 0.32 cm thick piece of ceramic behind the thickest portion. The ceramic is undetectable in the x-ray image. As the photon energy increases to better penetrate the thickest region of the tungsten, the attenuation caused by the ceramic decreases, reducing contrast and making the detection of even the edges of the ceramic unlikely. However, in the neutron image, the ceramic is easily seen. The digitally filtered image (middle) clearly shows its presence. This illustrates situations where certain part configurations may not favor the use of x-ray inspection, and can only be inspected using neutrons. Conversely, certain inspections will always need to be done with conventional radiography. For instance, the inert artillery fuze (upper middle) showed much more internal structure using x-rays. Its exterior body material is one that highly attenuates neutrons, preventing them from adequately penetrating through the fuze.

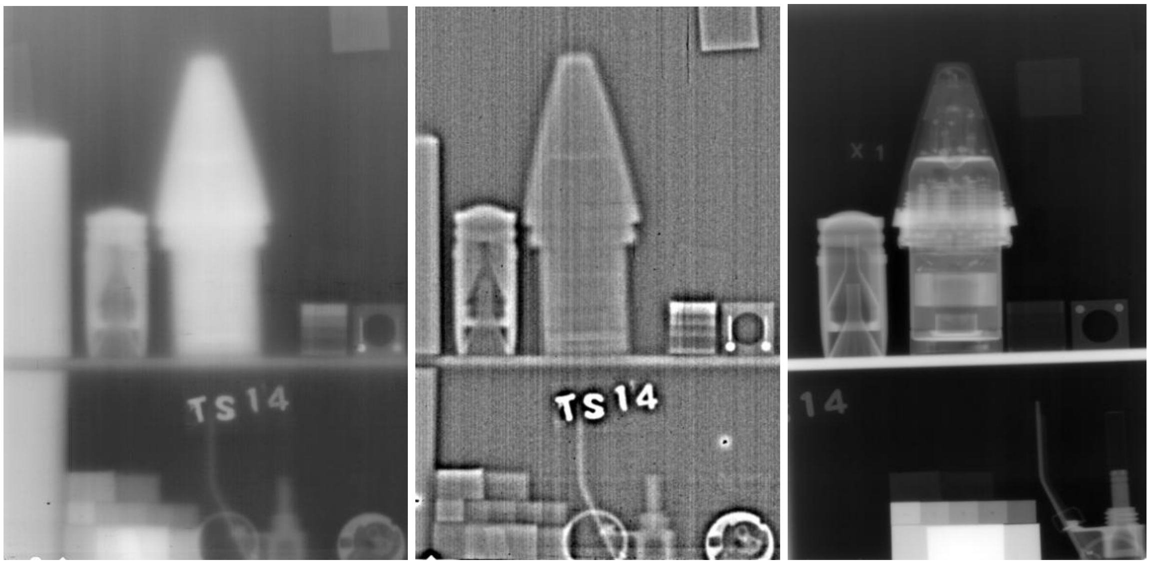

Figure 6:
Second half of the raw neutron radiograph (left), applied band pass filter image (middle), and x-ray comparison image (right).

Overall, this project illustrates the added benefits that neutron radiography can bring to the world of inspecting munitions and weapons systems. However, it also shows its current impracticality, due to the overall resolution achieved, the reduced H&D measurements obtained, and the extremely long exposure times required. The quality that can be achieved with the COTS neutron generator tested will always be poor when compared to images taken with sources as powerful as a research reactor or accelerator. This project has shown, though, that electronically-generated neutron radiographs are viable within a laboratory setting, and are a real possibly for production use. Pending an increase in thermal neutron production is achieved, and a higher flux/fluence can be produced at the film plane. This could potentially broaden the ability of NDT to inspect parts, configurations, and materials not otherwise inspected. It may also be viable for parts that cannot be inspected at a reactor facility; for example, muntions and weapon systems that contain energetic materials.

TECHNOLOGY DEVELOPMENTS:

PNL Generator / Moderator Design

As briefly discussed in the previous paper (Ref 1), the latest technology that is in development for the US Army by Phoenix Nuclear Lab (PNL) has been manufactured, delivered, and installed (Ref 4). This neutron generator uses the broader and lower peak neutron energy spectrum (2.35 MeV) produced by the deuterium-deuterium fusion reaction. This system is capable of reaching a 1E11 n/s yield when in operation at its maximum power output (9 kW). This electronic source was delivered to the ARDEC radiographic laboratory in December 2012, and placed inside an imaging cell that measured 8.53 m L x 8.53 m W (28 ft L x 28ft W).

The cell consists of concrete shield walls 4.57 m high that were designed and configured to contain high flux commercial x-ray sources with a maximum peak photon energy of 450 keV. The thinnest section of standard-density concrete on any one wall is 68.6 cm. The imaging cell does not have a ceiling, due to the explosive-safety design of the laboratory building, which can result in radiation safety issues when using neutron sources. Figure 7 shows the new generator as it appeared both prior to and after the addition of moderating material around the target.

Figure 7:
The initial setup of the PNL neutron generator system at ARDEC, without moderator (top left), with added graphite, concrete, and boron shielding (top right), and the first design of the beam port (bottom).

PNL used MCNP simulations to determine that the generator gained the most advantage in thermalizing neutrons through the use of high-grade graphite. Nuclear-grade graphite was used for the moderator, with additional HDPE and lead surrounding the assembly. However, due to its high cost, the thickness of graphite needed to achieve the highest thermal flux rates for the system could not be acquired. It was decided to postpone this upgrade until later in the project, after preliminary data had been obtained. The minimum thickness of graphite in any direction from the target chamber was 61 cm. During assembly, some areas of the moderator contained air gaps where the square graphite bricks could not conform to the shape of the generator target. This lack of complete uniformity was considered insignificant for initial testing purposes. The overall configuration allowed for multiple beam ports and for variation of the collimator assemblies during testing.

This initial setup also included added layers of boron-infused materials to reduce the overall neutron dose rates experienced by personnel outside of the exposure room, as required by both Army and Occupational Safety and Health Administration (OSHA) radiation safety guidelines and regulations. The imaging port was covered in lead to reduce x-ray or gamma-ray contamination at the imaging plane.

Early testing is now underway to ensure the robustness of the prototype system. During this timeframe, a series of test pieces will be imaged that have previously been inspected by neutron radiography at various reactor sites. These items will provide an excellent comparison. The items of interest include the 120mm tank primer assembly and the M84 stun hand grenade. Once the system in running at full capacity, we will document the applicability to various munition programs and attempt to transition this technology to eventual production use.

CONCLUSIONS:

This second stage of experiments to optimize a low-yield off-the-shelf neutron generator for neutron imaging was considered to be a success. These experiments and tests yielded an increase in overall image quality with slight reductions in exposure times. The images obtained also showed an increase in latitude over previous experiments. Ceramic and carbon fiber materials could be detected behind tungsten and lead blocks, respectively. This could not have otherwise been accomplished through imaging with x-rays or gamma-rays. Several comparisons were developed to show the added benefits provided by the neutron radiographic inspection method, particularly in regards to the inspection of DoD munitions and weapon systems. Where fragmenting liners, high-density shaped charge materials, organic compounds and other specialty materials impede the use of standard radiography or other non-destructive test methods. These areas, as well as many others, are where a direct application of neutron radiography is necessary for product assurance.

Using the Army's latest high-output long-lifetime neutron generator, developed by Phoenix Nuclear Labs, exposure times are expected to drop significantly. Sub-shift timeframes under eight hours for full exposures (1.5 to 2.0 H&D) in the area of interest are possible. The image quality is also expected to increase, with the ability to use L/D ratios much higher than those achieved with the COTS system. Preliminary calculations indicate ratios in the range of 35 to 60, with a 5.06 cm diameter aperture, now seem feasible. Testing with this system is underway and imaging is expected to demonstrate its applicability to various munition programs.

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LIST OF SYMBOLS, ABBREVAITIONS AND ACRONYMS:

A	Amp
ALARA	As Low As Reasonable Achievable
ARDEC	Armament Research, Development, and Engineering Center
ASTM	American Society of Testing and Measurement
c	centi-, 1E-2
Cf-252	Californium isotope 252
COTS	Commercials off the shelf
D-D	Deuterium – Deuterium
DoD	Department of Defense
D-T	Deuterium – Tritium
eV	electron-volt
FOV	Field of View
H&D	Hurter and Driffield
HDPE	High Density Polyethylene
IQI, BI, SI	Image Quality, Beam Purity, and Sensitivity Indicators
k	kilo-, 1E3
L/D	Length to Diameter ratio
M	Mega-, 1E6
m	meter
MCNP	Monte Carlo N-Particle transport code
n	neutron
NDT	Nondestructive Testing
NR	Neutron Radiography
OSHA	Occupational Safety and Health Administration
OEM	Original Equipment Manufacturer
PNL	Phoenix Nuclear Labs, LLC
s	second
SNR	Signal to noise ratio
u	micro-, 1E-6
V	Volt
W	Watt
γ	gamma