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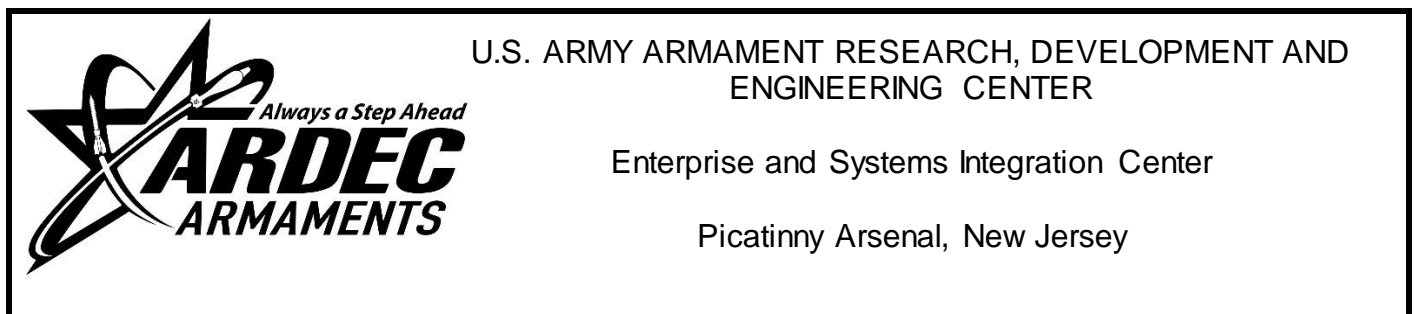
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Technical Report AREIS-TR-16005

**APPLYING PRACTICAL NEUTRON RADIOGRAPHIC INSPECTION TO THE
DEPARTMENT OF ARMY**

Stephan C. Zuber

November 2016



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14. ABSTRACT Over the last five years, the radiographic laboratory within the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, has been working to increase the viability of neutron radiography for the inspection of munitions and weapon systems. The project began by base-lining images obtained with a low-yield electronic generator and comparing them to the image quality and exposure time capability of nuclear reactors, research accelerators, and neutron producing isotopes. During this phase, two new deuterium-deuterium fusion based state-of-the-art neutron generators were under construction, designed to be small in size, high-yield (>1E10 n/s), have long life spans under continuous use, and be easy to operate in an industrial environment. This report describes the initial tests' exposures and experimental setups performed with a commercial off-the-shelf system. The preliminary work showed the short falls of the inspection method and how far the technology has progressed toward final development of a practical neutron radiographic system. The end goal of this project was to produce quality neutron images with exposure times that are acceptable for low-rate inspection of production components that are used by the U.S. Army and Joint Services.					
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PREFACE

The work documented in this paper is a direct team effort of the Radiographic Laboratory at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ. Without all the parties involved, this concept would not be on the path of realization for added quality inspections of munitions and weapon systems to support the warfighter and the U.S. Army. The people listed in the acknowledgments provided the biggest impact on the project. They allowed the time to perform the experiments outlined herein by procuring supplies, installing contracts, assisting in equipment development, providing in-depth technical input and instruction, and providing the original concepts necessary to apply practical neutron radiography for defense applications.

It is intended that this paper, project, and work will continue to build the technology and expand the neutron radiographic inspection method into smaller sites. This accomplishment would allow production applications to take full advantage of another inspection method, one that would provide knowledge to make safer, more reliable components and increase their overall effectiveness.

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SUMMARY

This report is a compilation of the internal work completed by the U.S. Army Armament Research, Development and Engineering Center's (ARDEC), Picatinny Arsenal, NJ, Radiographic Laboratory and shows the recent developments in technology that may further expand the capabilities of neutron radiographic inspections. Various areas of deficiencies exist when using nuclear reactors, research accelerators, and radioactive isotopes to image. The overall problem is not having more practical neutron radiography (NR) sites available, specifically for use in defense applications and the inspection of munitions and weapon systems. Currently available commercial off-the-shelf (COTS) electronic neutron generator technology is not viable since excessive exposure times result from their low yield and flux capabilities. This report presents baseline experiments that show the abilities and inabilities of these types of neutron producing devices. The overall results outlined in this report will demonstrate that it currently takes several day-long exposures to obtain readable images, which reinforces the need for viable neutron generator technology. An additional summary of the two latest developments in generator technology that have been completed or are in the final stages of completion will be briefly reviewed. These new technologies have the potential to bring NR into common place use with higher neutron outputs. Further progress on both an optimized setup using this current system and on high-output generators will be presented in later reports.

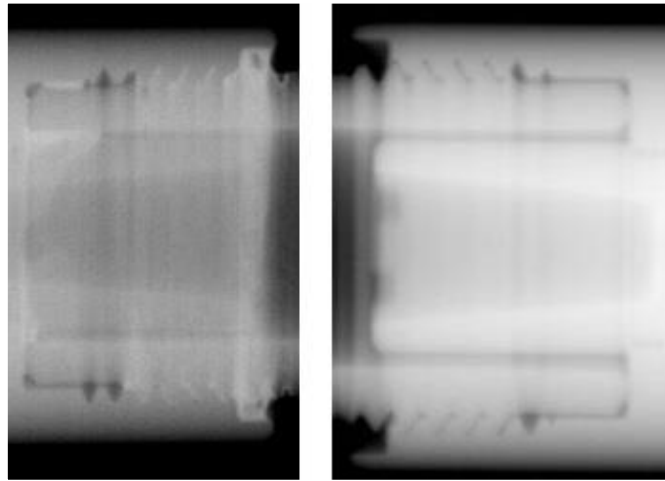
INTRODUCTION

Reduced Availability of Neutron Radiography

Starting in 2007, the ARDEC Radiographic Laboratory found that the U.S. Army lacked an entire field of testing for both development and production inspections of defense munitions and components. Up until that point, only select items had been inspected using NR, and all were handled at specific reactor sites across the country. For many of the current and latest defense systems, new materials (composites, plastics, rubbers, epoxies, etc.) are being used in their construction and are constantly changing. This has reduced the overall inspection reliability and capability available through x-ray or gamma-ray radiographic inspections. The inspection of organic materials (and other low density materials) assembled inside the high density casings used in munitions creates physical combinations that hamper the effectiveness of x-ray imaging. In addition to unique material combinations, some components also contain various geometric designs that cause a high level of internal scattering (i.e., fragmenting liners, shaped charge liners, etc.). These types of items have made standard radiographic inspection difficult and, in some cases, physically impossible. Since NR is a complimentary inspection that is specifically designed for inspections of low density materials, it is surprising that there is not a more practical means for producing neutron images, especially for use within the Department of Defense (DoD).

With NR, the inspection is no longer based directly on the physical density of the part that is under investigation but on its nuclear makeup. Neutrons interact with the nuclei of the atoms and their attenuation is based on nuclear cross section (relative size of a given nucleus as seen by the incoming particle) rather than by interaction with the atoms' electrons as x-ray or gamma-ray photons do (based on physical density within a given photon energy level). This is why materials that contain large amounts of hydrogen atoms attenuate neutrons, since hydrogen has a large nuclear cross section. Materials such as glues, plastics, and rubbers contain large amounts of hydrogen but are also low in physical density, thus reducing the ability to use x-ray inspection. In the inspection of certain munitions, the x-ray energies needed to penetrate through the part are high (in the MeV range) due to exterior cartridge cases, high density penetrators, and thick steel liners. This causes low density materials that are inside of the part to be over exposed and, therefore, not visible in the radiographic image. Figure 1 shows the differences between a radiograph produced by using neutrons (fig. 1a) and one using x-rays (fig. 1b). There is glue present between the threads that

holds the assembly together. The glue is not discernible in the x-ray image because of the penetrating photon energy needed to image inside of the steel.



(a)

(b)

Figure 1
Distinct differences between types of radiographs

In most cases where this occurs, there is no other method of testing that can be used without causing harm to the inspection piece. This is why NR is a complimentary inspection to the commonly known radiographic test method. In some instances, part design, construction materials, and overall internal configuration will benefit the use of x-ray inspection, while others will favor neutron inspection. Combined, these two methods vastly increase the overall detection of part placement or presence, the ability to reverse engineer, the finding of suspect or defective conditions, and the determination of the final assembly quality. The NR also helps to increase the overall production quality of a given item. Considering the high level of quality control detail generally placed in military specifications, the NR inspection method would provide additional oversight on the entire production process. All of the aforementioned areas show why NR is a beneficial inspection for munitions and weapon systems and why a more practical means of performing the inspection needs to be developed.

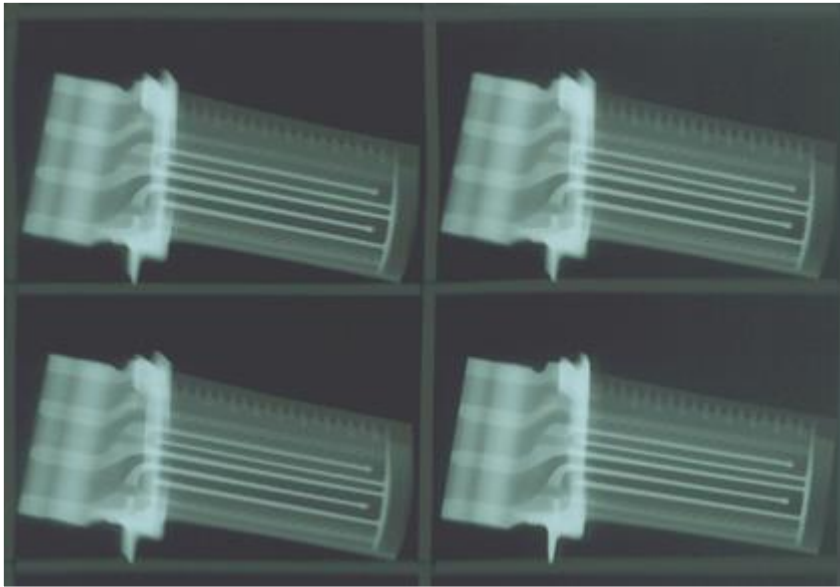
BACKGROUND ON TYPES OF SOURCES FOR NEUTRON RADIOGRAPHY

Reactors/Research Accelerators

With most NR inspection images that can be seen on the internet or in publications, one thing remains consistent: the need to use a nuclear reactor or research accelerator. A major issue with this is the need to acquire or have in place a large infrastructure, a high number of operational personnel onsite, and Nuclear Regulatory Commission (NRC) permits and oversight. Additionally, all of these requirements result in a high cost of initial construction, implementation, and sustainment for using and maintaining such systems. However, the sites that use these types of systems have the advantage of achieving neutron yields greater than $1E14$ n/s and are generally not concerned with losses involved in the moderation and collimation required for imaging. In cases where conventional radiographic film is used in combination with a reactor or accelerator, exposures can be completed in several minutes to tens of minutes (with optical densities of 2.0 or greater). These systems are also designed to have high quality beam content that increases clarity and image resolution (less than $200 \mu\text{m}$). The images presented in figure 2 represent the image quality that is

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achieved at many of these NR sites. With the initial base-lining that was done at the ARDEC Radiographic Laboratory, it will be easy to see why this gap in NR technology has existed for multiple decades.



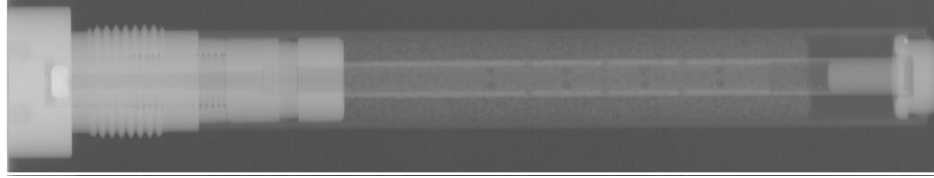
Note: These are graphite, aluminum, or nickel turbine blades with enhanced image contrast using gadolinium (Gd) coatings inside of their cooling channels.

Figure 2

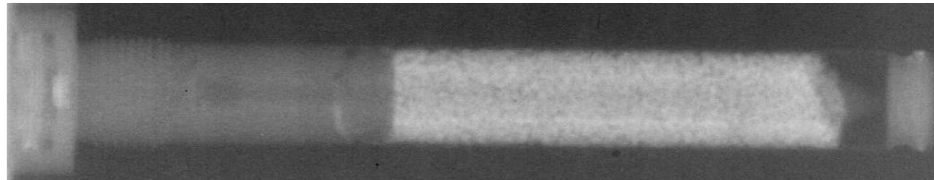
Achievable image quality from a nuclear reactor or research accelerator

Neutron Producing Isotopes

An alternative to performing NR with a reactor or an accelerator is to use neutron producing isotopes such as Californium-252 (Cf-252), Americium-Beryllium, or Radium-Beryllium. The benefits of using them are similar to those of using a gamma source over an x-ray source in that they are portable, can be used in very tight spaces, and can have medium yields for some of the larger sources (up to $1E12$ n/s for milligram/curie-size sources). The disadvantages are: constraints and licensing that exists with all radioactive materials, they cannot be turned off, high cost of replenishment or replacement, not easily stored, difficult disposal, lack of availability, fast neutron speeds, and reduced beam characteristics from the total radiation output (i.e., low neutron to gamma ratios, added scattered radiation, increased film fogging, etc.). The images in figures 3 and 4 show a representative sample of what level of image quality can be obtained using a Cf-252 source. The specific source was 10 mg (5 curies), which equates to a neutron yield of approximately $2.3E10$ n/s with a peak neutron energy of 2.35MeV. These images were taken in the early 1970s at the ARDEC Radiographic Laboratory and are accompanied by comparative x-ray samples.

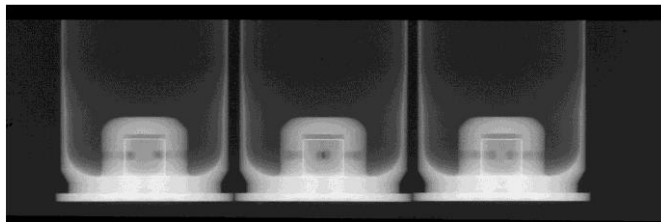


(a)
X-ray radiograph

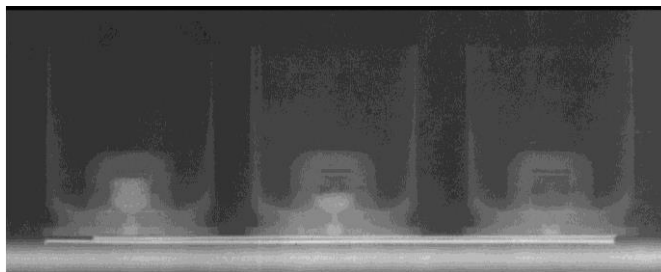


(b)
Neutron radiograph

Figure 3
M299 ignition cartridge radiographs



(a)
X-ray radiograph



(b)
Neutron radiographs

Figure 4
40-mm cartridge case and primer cup radiographs

Although neutron producing isotopes can be used for laboratory or production use, the related safety/administrative requirements render them impractical for use within the U.S. Army and DoD. Also, the full-strength source that produced the images in figures 3 and 4 required exposure times in the multi-hour timeframe. The natural decay of these sources over time reduces their output and can lengthen exposures to more than 24 hr. The Cf-252 isotope half-life is just over 2.6 years,

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which means the neutron output is cut in half over that time period. With conventional films, the relation of exposure time and optical film density is logarithmic, so that exposure times can increase substantially in a short period when using radioactive isotopes.

Electronic Neutron Generators

Neutron generators are electronic devices that can produce neutron radiation; they are similar in operation to a pulsed or constant-potential x-ray generator. The main differences lie in the processes by which neutrons are created and the average peak energy of the neutrons produced. Unlike an x-ray source which can change the penetration energy of the photons by changing the voltage, neutron generators can only vary the yield or output (n/s). The physical process in which a neutron is produced directly controls the energy (peak, average, etc.) that is created and is constant for a given source. Certain betatrons (magnetic induction x-ray sources) and linear accelerators can be converted to specifically produce neutrons; they can also generate photo-neutrons from the creation of high energy x-rays. Unfortunately, these types of sources have low yields (below $1E9$ n/s) and are not easily retrofitted.

Fusion types

For this discussion, neutron generators that are feasible for radiographic imaging use isotopes of hydrogen and the fusion reaction process to create neutrons. The fusible isotopes of hydrogen are deuterium ($2H$ or D) and tritium ($3H$ or T). When any combinations of the two are accelerated into one another above their threshold energies, they fuse together, resulting in the production of a neutron and certain byproducts.

Tritium is radioactive and tends to increase the logistics of buying, operating, and disposing of the generator. For that reason, the T-T reaction will not be reviewed since the amount of tritium required negates its benefit over a standard neutron producing isotope. The Deuterium-Tritium (D-T) reaction is unique in that it produces a neutron for every fusion event, which means the efficiency of production versus power input is very high. However, the constraint on using this reaction is that the high energy neutron produced is approximately $14.1MeV$. At this energy, the neutron is attenuated very little by most common materials; it requires significant shielding, induces measurable levels of activation, and is difficult to use for imaging. The initial studies discussed later involve a generator that uses this reaction but will require additional research to determine if generators using this reaction are viable.

The Deuterium-Deuterium (D-D) reaction is a main area of interest due to the energy level it produces of $2.45MeV$, which is very close to the energy output of the Cf-252. The D-D reaction creates a neutron half of the time a fusion event occurs. The other half produces a triton, which becomes embedded in the target area after the reaction. This means reduced efficiency in neutron production versus power input in comparison to the D-T type. In practical terms, D-D sources are 100 times lower in yield than an equivalent D-T source of the same generator type and power input.

The benefits and constraints of each type of fusion reaction may at first appear to make them equally viable, but the driving factor for radiographic imaging is practicality. In general, a D-T source contains a small amount of tritium. However, it is considered a sealed source and still requires some NRC oversight from the beginning. In a D-D source, the amount of tritium created internally is in such minute amounts that it would take decades of continuous use to produce enough material to require disposal needs of a radioactive source. Because of this, D-D sources are generally favored and that was the direction the ARDEC Radiographic Laboratory took regarding equipment development.

HOW TO IMAGE USING NEUTRONS

Creating Thermal Neutrons for Imaging

Neutron Energy Ranges

The neutron sources mentioned previously all produce so-called “fast” neutrons. “Fast” refers to a neutron that is ejected from the source with relatively high energy or kinetic temperature. Fast neutrons are generally listed as being above 1 electron-volt (eV), although this definition is not universally accepted. “Thermal” refers to neutrons with energies that are approximately the same as air molecules at room or ambient temperature, around 0.025eV, but can range from 0.01 to 0.05eV (ref. 1). For radiographic purposes, neutrons interacting with matter are converted into ionization products, which are then detected by the imaging media. The energy of these ionization products is directly proportional to the energy of the original neutrons. Imaging can be done with any neutron energy, but the thermal range is the best option for ease of use and efficiency in production. When using neutrons in the fast energy range, the part under inspection attenuates the incoming neutron radiation very little. The conversion materials that expose the imaging media also become transparent to the impinging fast neutrons. This makes converting fast neutrons into an image difficult, which generally causes poor image quality for investigation. Neutrons that are lower in energy, such as thermal, “cold” (<0.01eV), or “epithermal” (>0.5eV) neutrons, are more easily absorbed within the part, and this attenuation is better for imaging. The energies above and below the thermal range each have their advantages; cold neutrons give increased contrast, and epithermal and fast neutrons allow thicker parts to be inspected. However, to use these energies for imaging, additional constraints must be applied, and a loss in neutron flux occurs. This results in increased exposure times. The goal is to minimize these times using small neutron generators, so only thermal energies are being considered for this project. If the flux rates generated during this project are found to be adequate for imaging using thermal neutrons, additional studies will be attempted using cold and fast neutrons with their own reports.

Moderating Neutrons

To create neutrons with energies lower than those produced by a given source, the neutron beam must be passed through a moderator. Materials ideally suited for moderation have high neutron scattering cross sections and small absorption cross sections. A given material's total cross section is the combination of these values. Materials such as heavy water, high grade graphite, beryllium, high density polyethylene (HDPE), lithium wax (Li-6 enhanced), and water extended polyester are commonly used. The factors of thermal efficiency, thicknesses needed, available equipment space, purchase price, machining costs, activation byproducts, and availability determine which material is chosen. Other materials are also feasible; pressurized helium can be used, but extensive planning is needed in order to reduce neutron losses in its containment vessel.

The most effective moderating materials conform to the source design at the neutron generation target. The closer it is to the source target where neutron production occurs, the more efficient the moderator will be by minimizing air gaps and complex shapes. A moderator does not have to be a homogeneous material. It can be made up of different layers to moderate the neutrons in less time or distance. Depending on the neutron energy spectrum of the source, other materials with a larger cross section for the given energy range may be necessary such as low carbon steel for the 14 MeV range. For a D-T source, a layer of low carbon steel can thermalize neutrons more quickly and over a shorter distance than a material such as HDPE alone. However, more complex designs require computer simulations using Monte-Carlo n-particle transport code to determine how much of each material is advantageous. To reduce cost and time for this project, one or two materials were used within the moderator assemblies.

Moderators can also assist in multiplication of neutrons by the (n,2n) reaction. Materials such as lead, beryllium, and uranium can produce additional neutrons through multiplication, but each one has a threshold energy at which this occurs. Machining of these materials can be costly and difficult, and simulations are generally needed to determine their position, shape, and size within the moderator. A moderator can also use reflectors that direct the isotropic neutrons toward one side. Beryllium, methane, and hydrocarbons shaped into plates, cavities, or other shapes can be used to reflect neutrons, but each type has a resonance at specific energy ranges where they are most effective.

The main concept of a moderator is to thermalize neutrons as close to the source as possible and/or in the shortest distance possible without the moderator absorbing the neutrons itself. Moderator materials that contain hydrogen can produce very good thermalization, but an increase in activation will occur if the material is too thick. Hydrogen releases a prompt 2.2MeV gamma photon upon capture of a neutron, which can become a large source of activation contamination within the neutron beam if it is not accounted for. Although no moderator will completely eliminate the production of activation products, insufficient shielding and/or masking will significantly degrade image quality. If the level of activation products become excessive, additional protective shielding of personnel will also be required. In some designs, the level of activation produced scattered gamma rays can cause as much radiation dose to personnel as the neutrons themselves. The total dose to personnel (gamma and neutron combined) may then be above acceptable limits once the design is put into place and tested, resulting in a safety hazard. Figure 5 shows a moderator assembly that can be used for NR (fig. 5a) and an HDPE assembly that can be used with a Cf-252 isotope (fig. 5b). Figure 5b has an outer layer of lead to improve image quality.

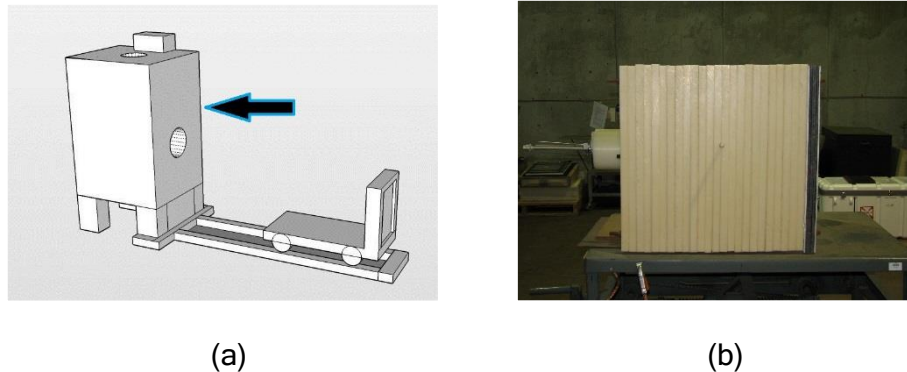


Figure 5
Depiction of a moderator assembly and an HDPE assembly

Collimation of Neutrons

After the neutrons coming from the source are thermalized by a moderator, they need to be directed toward the test subject and image media. Neutrons produced isotropically (in all directions equally) at the generator target become scattered inside the moderator and create a particle cloud with no means for them to escape. The neutrons can move in any direction inside the moderator, and collimation is required for a useful imaging beam. A collimator is an opening within the moderator assembly that allows the neutrons to pass through in a beam-like manner. It provides the neutrons with a focused trajectory toward the inspection items and image media. Without a collimator, the neutron flux ($n/cm^2/s$) will radiate through a 4π solid angle (essentially in all directions), yielding a significantly reduced flux at the image plane of the detector. The flux at the detector will also not be perpendicular to the image plane, resulting in excessive parallax, mottled or blurred images, and exposure times lasting weeks or months. The collimator can form the neutrons into a cone beam or other useful shape; it can control the divergence of the beam; it can dictate the

level of geometric unsharpness seen in the image; it can also adjust the level of neutron flux at the image plane. The consequence of this collimation, however, is that the total number of usable neutrons that pass through the collimator will be drastically less than the original number produced at the generator target. For example, a design using HDPE will typically have a loss factor of 100-to-1. The level of loss will be dictated by the thermalizing efficiency of the moderator and the size of the collimator. The main design factor controlling this variable is the size of the aperture, which is the collimator opening nearest to the neutron source.

The collimator can be enhanced by incorporating materials that are effective at shielding and blocking unwanted side effects created by the moderator. These effects include neutrons from outside of the beam path, x-rays given off by the source, and gamma rays from within the moderator generated by neutron capture and activation. Different combinations of Gd and lead layers are commonly used to cancel out these effects. Additional components can be added to the collimator assembly to reduce unwanted radiation in the beam path, including beam filters placed at the aperture, which further reduce unwanted x-ray and gamma ray contamination. Beam filters such as sapphire (Al_2O_3) also have the added benefit of “hardening” the beam by removing neutrons with energies above and below the desired thermal range. There are wide arrays of different collimator designs available, but this project used a common diverging beam type since it reduces the neutron flux the least. The only beam filters used in this early experiment were types made of bismuth. Figure 6 shows a collimator assembly made of Gd coated bismuth rings, a lead cone, and an HDPE tube of ARDEC’s design.



(a)
Unassembled collimator assembly



(b)
Completed collimator assembly
placed within the ARDEC Cf-252
moderator

Figure 6

Collimator assembly made of Gd coated bismuth rings, a lead cone, and a HDPE tube of ARDEC’s design

RADIOGRAPHIC, IMAGE QUALITY, AND SAFETY RESOURCES

Performing Radiographic Imaging with Neutrons

This project made the best attempt to follow the guidelines set by the American Society of Testing and Materials (ASTM) for image quality and standard practice in making neutron radiographs, specifically guides E-545, E-748, E-1742, E-2003, and E-2023 (ref. 2). A valuable source of information regarding test exposure variables versus effects was found in “Practical

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Neutron Radiography” (ref. 3). It contained data detailing the changes in exposure for different conversion screen types and fluences (n/cm^2) needed to properly expose various types of conventional radiographic film. The sensitivity indicator (SI) in figure 7a is used to determine penetration, latitude, and other characteristics of a neutron beam. The beam purity indicator (BPI) in figure 7b provides quantitative values of thermal neutron content, gamma content, edge sharpness, and other imaging values in relation to the quality of the neutron beam.

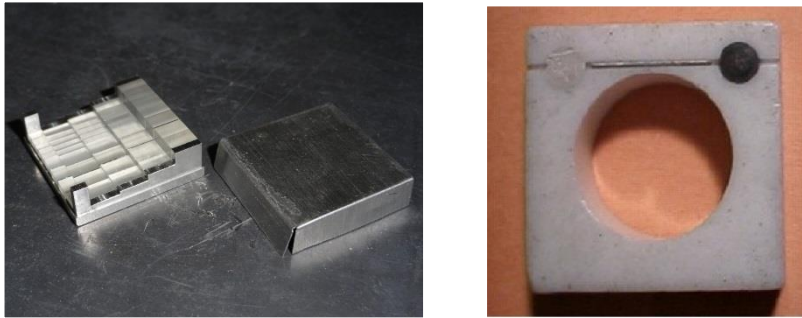
(a)
SI(b)
BPI

Figure 7
Image quality indicators listed in ASTM E-545

Neutron Radiation Safety

When using any type of radiation source, personnel safety is a primary concern. Two resources that contain data and information specific to neutron radiation from electronic generators are National Council on Radiation Protection and Measurements (NCRP) report no.72 and NCRP report no. 38 (refs. 4 and 5). Dose rate quality factors for the varying neutron energies can be found as well as shielding information specific to concrete structures. During this project, ARDEC personnel wore neutron-gamma-alpha-beta- sensitive thermo-luminescent dosimeters, gamma/x-ray pocket dosimeters, and gamma/x-ray ring dosimeters. To ensure all occupied areas met federal dose rate limits for personnel, neutron and gamma/x-ray survey meters were used at all times. Gamma/x-ray area alarms were also present inside the shielded exposure room to produce an audible alarm when photon radiation was present. All required permits and approvals were obtained prior to operations, and a formal standard operating procedure was put into place after early testing established operational parameters.

INITIAL BASELINE TESTING AND IMAGING

Using a Commercial Off-the-shelf Low Yield Generator

For D-D neutron generators, there are different ways to accelerate the deuterium ions together. As of mid-2012, the most common commercially available generators were of the Cockcroft-Walton type. This design uses a cascade accelerating device to accelerate D^+ ions into a solid target impregnated with deuterium (or tritium for D-T) held at ground potential. Many of these target designs have very short life spans ($<1,500$ hr), which is directly related to the use of zirconium or titanium within their targets. Both of these materials present problems when the target undergoes heat loading. Over time, these targets decay and the impregnated hydrogen isotopes are permanently released, resulting in the loss of neutron production. Other factors detrimental to radiographic use include low yields ($<1E7$ n/s), limitations on input power ($<160kV$, $<150uA$, $<24W$), and limited reliability during continuous operations.

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To accurately assess the short falls of the available low yield COTS neutron generators, a practical approach was taken. A COTS generator was used to construct an imaging system, and multiple experimental images were produced to achieve the best image quality possible. These images were then analyzed for overall quality through a side by side comparison with known examples of neutron radiographs previously obtained using a nuclear reactor, research accelerator, and radioactive isotope. The generator that was chosen for these baseline experiments was the Thermo Fisher Scientific P385. This particular generator uses the D-T reaction, has a nominal yield of $3E8$ n/s, a maximum yield of $5E8$ n/s, and a specified lifetime of 1,000 to 1,500 hr of operation, depending on the power input used. Its neutron yield, life span, small size (~91 cm long by 10 cm in diameter), low power requirements (130kV, 70uA, 9W maximum), and reasonable cost (~\$100k) made it a good candidate for this project. Figure 8a shows the ThermoFisher Scientific P385 neutron generator, and figure 8b shows the first neutron radiographic setup used at ARDEC with the generator in place inside of the moderator assembly.



(a)



(b)

Figure 8
Neutron generator

Imaging Setup

From previous work performed at the ARDEC radiography laboratory in the early 1970s, a great deal was known about the use of Cf-252 for imaging. This early work also provided a readily available moderator assembly (HDPE cube) that was made to handle a Cf-252 capsule and exposure device. Prior to experimentation, it was determined that more moderating materials would be needed for the P385 so the existing assembly was modified. The modifications to the assembly can be seen in figure 9 with the added HDPE tube that held the P385 in place. The initial setup, however, excluded the plug, the added HDPE at the rear of the assembly, and the HDPE discs and rings shown.

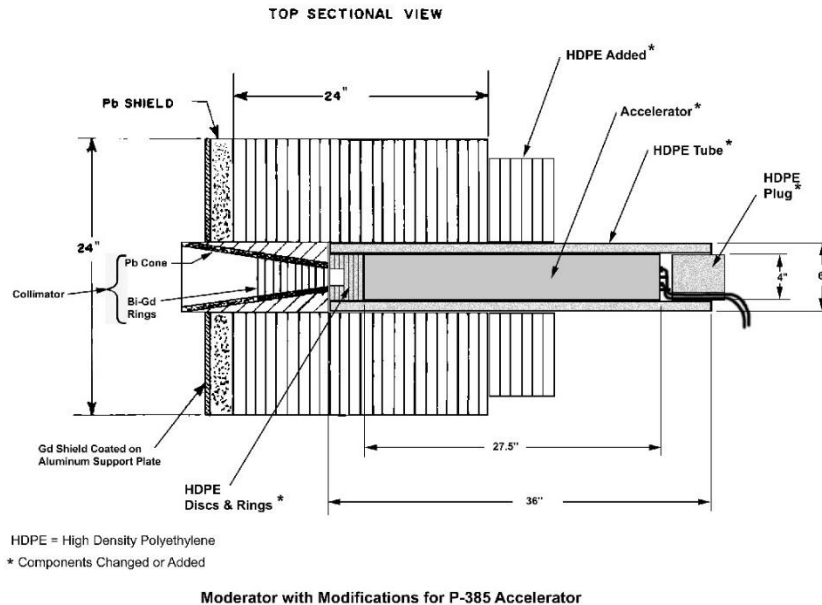


Figure 9

Modifications made to the original Cf-252 moderator to fit the P385 neutron generator

The two main conditions that adversely affected this project from the beginning were the known low output of this particular generator and the major loss of neutrons that occurred during thermalization. With the chosen setup and design, the flux rates reaching the end of the collimator were between $1E2$ and $2E3$ n/s/cm² for a collimator with a length-to-aperture width or diameter (L/D) ratio of approximately 6 [beam length 30.5 cm (L), aperture 5.1 cm (D)]. With a fluence of $1E9$ n/cm², this equates to calculated exposure times of 140 to 2,700 hr, necessary to achieve an optical film density of 2.0, when using AGFA D3SC film (ref. 3). The AGFA D3SC film is the type that is most commonly used within the NR community. It provides very high resolution images due to the small size of its silver bromide (AgBr) crystals. This film type also reduces "noise" in the film image through its single emulsion layer design. Films with dual emulsions produce two images: one from neutrons impinging the conversion screen (in one emulsion) and a second (in the other emulsion) exposed by any gamma or x-ray contamination in the beam line. Exposure times are, however, decreased significantly with a double emulsion film. For this project, AGFA D3SC was used to provide a solid image quality baseline. Also, a single back screen was used to convert the neutrons, which is common practice at most reactor sites. The use of a front screen has been shown to provide very little added benefit, as the front screen causes more attenuation than additional exposure to the film. It acts as a shield rather than an intensifier.

These conditions combined to influence the need to move the image plane as close to the collimator opening as possible. Figure 10a shows an aluminum backed conversion screen with a 15- μ m thick vapor deposited Gd layer and a neutron cassette next to it that contains a front screen of 0.08 cm of lead, a magnesium face, and 0.03 cm of lead on the back (to reduce scatter). Figure 10b shows the Gd screen, film, and cassette are placed as close to the source as possible.



(a)

(b)

Figure 10

Conversion screen and cassette that were used along with their placement against the moderator and collimator

RESULTS AND DISCUSSION

First Neutron Exposures with P385

The first series of exposures taken with the P385 generator used three combinations of inserts. The first image used a solid tube of HDPE, the next used an all steel insert, and the rest used the configuration shown in figure 11, which was used to decrease the thermalization distance of the D-T neutrons. It was a multi-layer design; the inserts provided a very small air gap between the generator and the first set of three low carbon steel sleeves, which had a combined thickness of 0.95 cm. Next came two plastic sleeves (0.64-cm thick) followed by a final steel sleeve (0.64-cm thick). This complete assembly was then placed within a solid 61-cm length by 30.5-cm width by 30.5-cm height HDPE moderator. All the images taken with this setup used an L/D of 6, contained no beam filters, and only varied by changes in film type and conversion screens. Figure 11a shows the generator and inserts in place inside the moderator. Figure 11b is of the set of five remaining inserts.



(a)

(b)

Figure 11

Initial images used several combinations of low carbon steel and HDPE inserts

The moderator used had a 3.8-cm thick layer of lead with a 0.64-cm thick faceplate of aluminum on the collimation side of the moderator. This was to reduce the gamma contamination seen on the imaging side of the system. With this setup, the exposure times were between 26 and 37.5 hr in length, running the generator at full output. The Hurter and Driffield (H&D) optical film

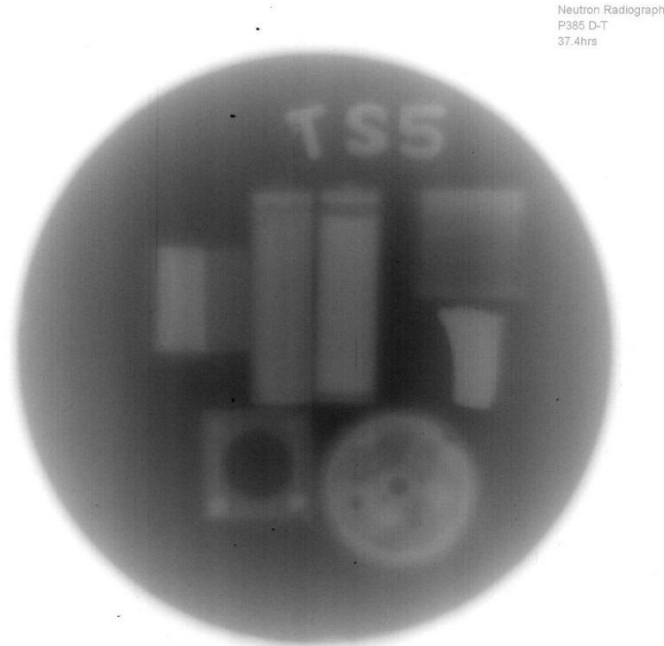
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densities ranged from 0.28 to 0.50 using AGFA D3SC. In a comparison test, an H&D of 1.7 to 2.25 was obtained using Kodak AA400, a high-speed film with larger AgBr crystals and a double emulsion. However, due to its exposure characteristics and the equipment configuration, the AA400 images contained a low neutron to gamma ratio (n/γ). This meant the second emulsion layer contained a large gamma-ray induced image to the detriment of the desired neutron image. This film type is also much more susceptible to scattered radiation than the D3SC. This was visibly confirmed with the BPI. Its boron nitride ceramic discs could be seen but were faint and had low contrast in comparison to its lead disc that showed a much higher attenuation in the image. High-speed film was therefore not seen as advantageous, and AGFA D3SC remained the film type of choice for the baseline.

The first series of test images were acquired using techniques with the following conversion screen combinations: the Gd back screen only, a ZnS (Li6) front screen with a Gd back screen, and a 0.04-cm thick indium (In) foil front screen with the Gd back screen. Different combinations of double loaded film (two sheets of film per cassette) were also used during this series. This allowed a comparison of the different combinations and their effect on gamma/x-ray contamination versus neutron imaging. Most of these early exposures were too low in H&D to take accurate measurements and assign an ASTM E-545 film category, which provides quantitative values in regards to image quality. This neutron exposure was the highest quality image obtained with the P385 generator in the Cf-252 moderator and collimator assembly. Of all the test images, the one shown in figure 12 was the best in terms of achieved image quality. It showed the highest n/γ ratio, the most latitude, and a large difference in the level of attenuation between lead and ceramic. The exposure time was approximately 37.5 hr and produced a 0.5 H&D with a field of view that was 15.2 cm in diameter. The image shown was digitally scanned and processed to increase brightness. In this exposure, the BPI's boron nitride discs are visible as bright dots, but the lead disc near the top of BPI is not (bottom left corner of the photograph). The variation in attenuation is also apparent when viewing the other test items in the image: two layers of lead (far left), a piece of ceramic (far right/middle), and an aluminum and steel M739 Safe and Arm Device (bottom right). The SI (far right/top) shows a good range of latitude over the thickness differences of each step. The remaining items on the image are a nickel-cadmium battery (center right) and a lithium-ion AA battery (center left).



Neutron Radiograph
P385 D-T
37.4hrs

Figure 12
Highest quality image of neutron exposure obtained

When compared to the photographic and x-ray images shown in figure 13, the test exposure shown in figure 12 was promising, despite the extremely low flux used and long exposure time needed to acquire it. Additionally, the moderator was not optimized for thermalizing the high energy neutrons created by the D-T reaction. However, the neutron image quality achievable in this test is well below that shown in figures 2, 3, and 4 produced by conventional neutron sources. This illustrates the significant gap in available technology when using a small neutron generator as compared to a reactor, research accelerator, or isotope. Figure 13a shows a photograph of the items neutron-radiographed in figure 11, and figure 13b shows a standard x-ray image of the same set of objects.



(a)



(b)

Figure 13
Photographic and x-ray images of same set of objects

LATEST CONCEPTS IN NEUTRON GENERATORS

Phoenix Nuclear Labs Design

Recently, two state-of-the-art electronic neutron generators have been designed and constructed for ARDEC by outside vendors. The first design was built by Phoenix Nuclear Labs, LLC, Madison, WI (contract no. W15QKN-08-C-0515), and it uses an elongated target chamber that is filled with deuterium gas (ref. 6). This particular generator is designed to input a maximum of 9 kW of power at 300 kV to the accelerator section and can produce up to $2E11$ n/s. Unlike most other conventional neutron generators that produce neutrons isotropically at the target, this design has a long cylindrical target chamber that creates a neutron flux with a teardrop shaped distribution. Previous work in NR has suggested that a point source was the ideal size and shape of a neutron source. This follows the principles of conventional radiography where an x-ray source with a smaller focal spot size produces less image parallax and higher resolution than a larger focal spot. However, in the case of neutron imaging, the materials surrounding the source heavily dictate the beam characteristics and the overall amount of parallax and resolution. The type and configuration of moderating materials is particularly important so that given the same general conditions, a point source and a larger diameter target source could potentially produce the same image quality. The added advantage of a larger source, such as this one from Phoenix Nuclear, is a potential increase in flux ($n/s/cm^2$) at the imaging plane through an increase in thermalizing efficiency (slowing fast neutrons to thermal energies). Simply put, even though the neutrons are slowed over a larger area, more may be available for imaging.

Starfire Industries Design

The second neutron source is a newly-designed generator under construction by Starfire Industries, LLC, Champaign, IL (contract no. W15QKN-08-C-0516) (ref. 7). Their design uses innovative targets and ion sources beyond those commercially available to improve neutron output and increase operational lifespan. The design also maintains the compact size typical of the semi-portable x-ray sources used for nondestructive testing. Starfire's target consists of a specialized hydrogen-retaining layer on a grounded copper backer mount. Often found in conventional x-ray tubes, copper is one of the best materials for heat conduction and allows the target to be cooled easily, permitting higher power inputs and an increased radiation output in a small size. Current achievements have shown neutron yields close to $2E10$ n/s (D-D reaction) in the base design with an accelerator power input of 7.5 kW at 200 kV. Planned upgrades will increase system power to 12 kW and further improve target cooling for higher neutron output.

CONCLUSIONS

These results confirm that currently available commercial off-the-shelf (COTS) neutron generators are not sufficient to produce interpretable neutron radiographs in their current form. Their long exposure times, due to low neutron flux output, also prevent their widespread use as a diagnostic tool in most production environments. This preliminary work is a step toward further research with the potential to increase both thermal neutron flux and overall neutron image quality from electronic neutron sources.

The legacy moderator used in this project was designed for 2.45MeV neutron energies. It was less than ideal for the thermalization properties inherent to 14.1MeV neutrons produced by the Deuterium-Tritium reaction. This likely resulted in reduced thermal flux that further increased exposures times. Also, this initial test did not factor in the internal geometric properties of the P385 generator where a small directional bias might occur that could affect the flux rates reaching the image plane. Changes to the moderator and accelerator configuration (beyond the scope of this

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experiment) may be the path forward for a COTS generator to produce quality images with reasonable exposure times (i.e., not measured in days).

Additional investigations will commence when the two new neutron generators are fully installed, tested, and verified as operational at the Radiographic Laboratory at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ. Further tests with the new units are expected to quickly show the benefits that result from high neutron yield designs.

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REFERENCES

1. MacGillivray, R., Nray Services Inc. Training Program, Dundas, ON, Canada, 2009.
2. Bailey, Sean J., et al., "Annual Book of ASTM Standards," volume 03.03, Nondestructive Testing, American Society for Testing and Materials, West Conshohocken, PA, 2011.
3. Domanus, J.C., "Practical Neutron Radiography," Kluwer Academic, Dordrecht, Netherlands, 1992.
4. Roesch, W. C., "Radiation Protection and Measurements for Low-Voltage Neutron Generators," NCRP reports, volume XI, report no. 72, National Council on Radiation Protection and Measurements, Bethesda, MD, 1983.
5. Rossi, H.H., "Protection Against Neutron Radiation, National Council on Radiation Protection and Measurements," NCRP reports, volume IV, report no. 38, National Council on Radiation Protection and Measurements, Bethesda, MD, 1971.
6. Radel, R., "High Flux Thermal Neutron Source," ARDEC SBIR Phase II Enhancement contract no. W15QKN-08-C-0515, Phoenix Nuclear Labs, LLC, Madison, WI, 2012.
7. Jurczyk, B., "High-Efficiency Long-Lifetime Neutron Generator for Radiographic Munitions and IED Inspection," ARDEC SBIR Commercial Pilot Program contract no. W15QKN-08-C-0516, Starfire Industries, LLC, Champaign, IL, 2012.

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LIST OF SYMBOLS, ABBREVAITIONS, AND ACRONYMS

A	Ampere
ARDEC	Armament Research, Development, and Engineering Center
ASTM	American Society of Testing and Materials
BPI	Beam purity indicator
c	centi-, 1E-2
Cf-252	Californium isotope 252
COTS	Commercial off-the-shelf
D-D	Deuterium - Deuterium
DoD	Department of Defense
D-T	Deuterium - Tritium
eV	electron-volt
H&D	Hurter and Driffield
HDPE	High density polyethylene
k	kilo-, 1E3
M	Mega-, 1E6
n	neutron
NR	Neutron radiography
SI	Sensitivity indicator
u	micro-, 1E-6
V	Volt
W	Watt
γ	gamma

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