Advanced Neutron Radiographic Equipment within the US Army

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LIMITED USE OF THE NEUTRON RADIOGRAPHIC INSPECTION

Neutron radiography (NR) is a unique inspection method that can inspect for complex part placements, inclusions of organic materials, and numerous other conditions that no other method is able to detect. It is a complimentary inspection with standard radiography using x-rays or gamma rays and increases the information known about a given item. However with the addition of so many new plastic, synthetic, and composite materials, standard radiography alone is not enough to cover every inspection requirement. The academic world has been progressing in perfecting reactors and research accelerators (spallation sources) to produce high purity beams and build digital neutron detection. However, most of it is only applicable for scientific purposes. Direct application for industrial use of NR is limited to only a few facilities across the country and still requires the use of conventional film. Availability, overall costs, and logistics of onsite energetic storage have also limited the use of NR in the defense sector. This is why the US Army has been in development of technology that brings high output electronic neutron sources into realization. This paper discusses new advances in generator technology that allow small devices to have outputs that are viable for shorten exposure times comparable to reactors and accelerators. Initial base line tests show what current commercial systems can and cannot do, and recent progress made using these advance NR systems is provided.

The Path to Bridging the Gap for Practical NR Systems

A program was implemented at the radiographic lab within the Army's Armament Research, Development, and Engineering Center (ARDEC) located at Picatinny Arsenal, NJ to investigate more practical neutron sources. With the help of the small business innovation research (SBIR) program, several deliverables have been completed and are in the early stages of being tested.

For direct applications of NR, several key attributes have been used for development of two new deuterium-deuterium (D-D) fusion type neutron generators. These generators both have a small footprint, high neutron production, exclusive target geometries to allow high thermalizing efficiencies, and are robust for use in industrial environments. The present goal in these new technologies is to push the NR inspection method into the common place, allow them to be used by small teams, and implemented with the infrastructure that is already in place at radiographic sites across the joint services within the Department of Defense (DoD).

EARLY IMAGING & BASELINE METHOD TO COMPARE SOURCES

The first step taken to show the added benefits that these two new generators bring to the NR field was to create a base line comparison between them and other commercial off the shelf (COTS) low yield generators. Imaging experiments were setup and completed at the ARDEC radiographic laboratory to show the progress made during early testing of these new technologies.

To start, a ThermoFisher P385 D-T generator was purchased, which can achieve up to the 5E8 n/s (neutrons per second) range. This COTS generator uses tritium within a solid target, which produces fast neutrons at an average peak of 14.1 MeV. The peak energy of this generator is much higher than the 2.45 MeV energies that come from the D-D reaction. This generator was then placed into a moderator assembly made mainly of high density polyethylene (HDPE), with a collimator that was a gadolinium (Gd) coated lead cone with an aperture of 5cm (2-inches). To make an even comparison images were made using conventional film (D3sc and D4sc), and a direct gadolinium conversion screen that is identical to what is commonly used at production reactor sites. Initial images

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14. ABSTRACT
Neutron radiography (NR) is a unique inspection method that can inspect for complex part placements, inclusions of organic materials, and numerous other conditions that no other method is able to detect. It is a complimentary inspection with standard radiography using x-rays or gamma rays and increases the information known about a given item. However with the addition of so many new plastic, synthetic, and composite materials, standard radiography alone is not enough to cover every inspection requirement. The academic world has been progressing in perfecting reactors and research accelerators (spallation sources) to produce high purity beams and build digital neutron detection. However, most of it is only applicable for scientific purposes. Direct application for industrial use of NR is limited to only a few facilities across the country and still requires the use of conventional film. Availability, overall costs, and logistics of onsite energetic storage have also limited the use of NR in the defense sector. This is why the US Army has been in development of technology that brings high output electronic neutron sources into realization. This paper discusses new advances in generator technology that allow small devices to have outputs that are viable for shorten exposure times comparable to reactors and accelerators. Initial base line tests show what current commercial systems can and cannot do, and recent progress made using these advance NR systems is provided.

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were taken with a setup using an L/D of 6 which provided valuable data on such things as achievable image quality, changes that adversely affect the content of the neutron beam, and achievable exposure times. On average, each exposure with this setup was completed at the maximum power output of the generator (~9 W) in a timeframe of 37.5 hours, which only provided a range of 0.3 to 0.5 in film densities (H&D). These images were digitized for further review and showed promising information towards the neutron to gamma ratio, contrast sensitivity, latitude, parallax, and overall properties related to image quality.

Noting that all the NR inspections performed in this project attempted to follow the applicable standards outlined by ASTM, including E748, E545, and E1742 [1]. These experiments also used pertinent data to adjust imaging characteristics found in the "Practical Neutron Radiography" book [2]. Reference 2 is also a great introductory resource for learning the fundamentals on understanding the application of NR.

COTS Results

The image seen in figure 1 was an average sample that was achieved from the initial setup with the COTS generator. Overall the baseline experiments achieved low quality images that also required long exposure times to acquire. The optical densities of the resultant images also required digitization for review. However, when considering the low output of the P385 generator the images obtained were not that unsatisfactory. The thermal flux reaching the film plane was only on the order of 3E2 n/cm²/s (neutrons per centimeters squared per second) at 30.5 cm (1-foot). Full results of these initial experiments can be seen in reference 3 [3].

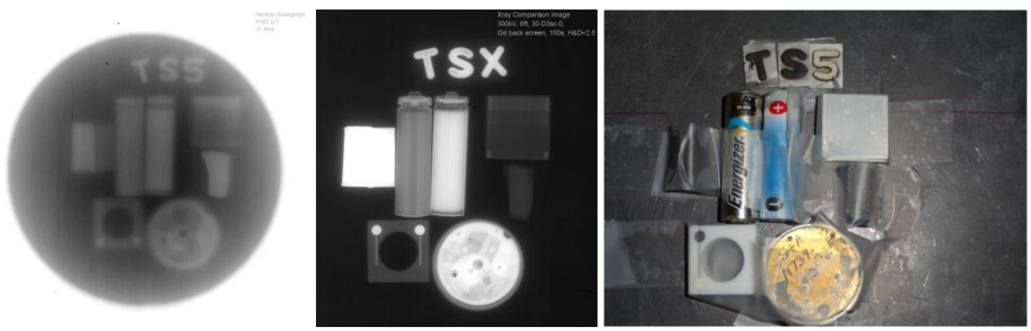

Figure 1:
Early P385 Neutron Image vs. a comparable X-ray radiograph and visual setup

Further steps were taken to optimize the entire setup to push the COTS generator to the limits. A larger moderator, extended collimator, and re-orientation of the target plan allowed for L/D's that exceeded 20. These changes also reduced exposure times by roughly 15%. There was a significant gain in the image quality, but it was still significantly poor compared to a radiograph made using x or gamma radiation. Additional information on these optimizing experiments can be seen within reference 4 [4].

Although great progress was made with a low yielding, fast neutron producing device. The overall exposure times were in excess of 24 hours, and the image quality was nowhere near good enough for even low scale production inspection, which is the main goal for the upcoming technology.

NEW NR TECHNOLOGY & RECENT PROGRESS IN SOURCES

The biggest hurdle in having a facility that can perform NR is a neutron source that has a high enough output of neutrons. The highest yielding transportable electronic source that is commercially available can only achieve up to the1E7 n/s range using D-D for proven systems. Whereas yields of greater than 1E14 n/s can easily be achieve when using a reactor or research accelerator. In most cases, transportable electronic sources are the Cockcroft-Walton design and are heavily limited in the amount of power that can be put on target. These types of sources are also restricted in lifetime from the use of solid targets which decayed within 1000 to 2000 hours of operation.

First Neutron Generator Design

The first of the two new neutron generators developed for ARDEC was built and delivered by Phoenix Nuclear Labs (PNL) located in Madison, WI. Figure 2 below shows the system just after its completed assembly onsite. This neutron generator is currently capable of reaching 1E11 n/s if operated at its maximum power (9 kW) [5]. This system uses a microwave ion source to produce D+ ions that are focused and accelerated into a symmetrical cylindrical target chamber that contains deuterium gas. The design of this generator takes an approach that is against conventional thought that a smaller point like source is more advantageous. Since most neutron sources produce neutrons isotropically (in all directions equally), a small point source like the neutron producing isotope Cf-252 is dependent on the type of moderator materials, its size, and the dimensions of the collimation device. This is why this particular generator technology was examined since its target can accept higher currents for high yields. In addition, by utilizing the correct geometries for the moderator and collimator a significant increase in the thermal flux rates and fluence are possible compared to previous electronic sources. Current projections show that this system may exceed 1E6 n/cm²/s thermal neutrons at 1-meter, which is approaching the interaction or flux rate that several x-ray radiographic digital detector arrays (DDA's) can operate with.

Figure 2:
Prototype Neutron Generator from Phoenix Nuclear Labs

Second Neutron Generator Design

The second generator design developed for ARDEC was built by Starfire Industries, LLC located in Champaign, IL and has achieved 3E9 n/s during preliminary testing [6]. Its design however is very much capable of achieving close to 2E10 n/s at full power and a simple target upgrade, which is available. Figure 3 shows the system during the final installation at ARDEC. Their system is no larger than a common 450keV x-ray unit including the generator head, power supplies, transformer, and controls. The distinctiveness of this second system is how it uses an approach of internal design that is very similar to a conventional x-ray head. However, instead of accelerating electrons into copper or tungsten, it accelerates D+ ions into materials that contain deuterium. In addition to its increase in yield, its expected lifetime and overall industrial robustness are expected to exceed existing COTS electronic neutron generators. It was designed with the intent to be equivalent to current high grade x-ray systems on the market. This system is in the verification and testing stages of development and is currently being put through a thorough shakedown to ensure long term reliability.

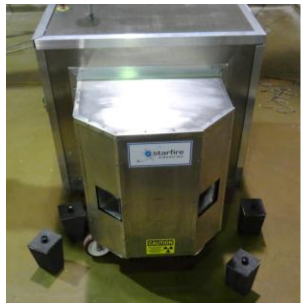

Figure 3:
Prototype Neutron Generator System from Starfire Industries

PRELIMINARY NEUTRON RADIOGRAPHS AND RESULTS

During the hardware and software testing of the PNL neutron generator several test shots were collected in order to show preliminary data on the functioning and capability of the system. These early setups used a crude version of an enclosed beam port made with various slabs, bricks, sheets, and foils of materials containing lead, boron, and HDPE. This port merely functioned as a scatter reducer from the surrounding walls, floor, and objects close to the image plane. In the application of using any neutron producing device some activation products (prompt and delayed) will occur, which may cause unwanted radiation (neutron, x-ray, and gamma) to travel into the image plane. The effect of scatter was grossly apparent from the start and continues to be an area of improvement which can be seen in the neutron radiographs in Figures 4 and 5.

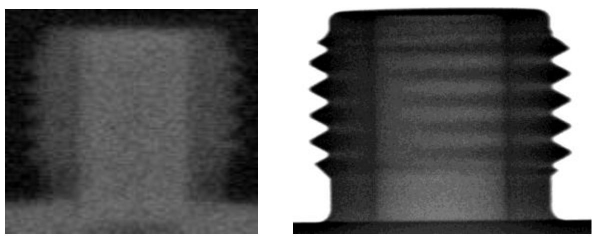

Figure 4:
Initial Radiograph Comparison at ARDEC Showing Penetration through Tap/Die Regions
(Left – Neutron, Right – X-ray)

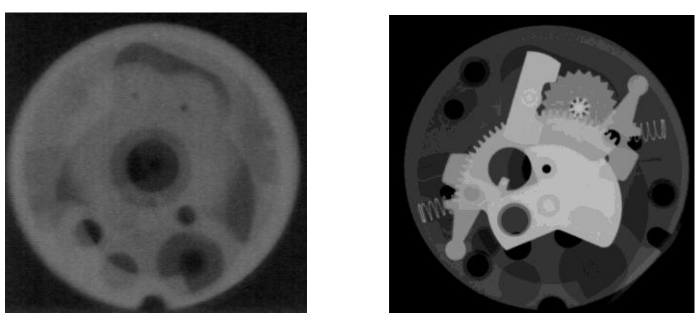

Figure 5:
Radiograph Comparison Showing Two Similar Mechanical Devices with High Density Components
(Left – Neutron, Right – X-ray)

The bulk of these test setups attempted to achieve L/D ratios of 35, which is the minimum criteria listed within ASTM E 748 when using the beam purity indicator (BPI) [7]. The moderator used to slow the fast neutrons was made entirely of high grade graphite, while the collimator was a series of conical inserts made of HDPE, lead, and Gd infused paint.

The trial experiments have shown that with the system running at its designed maximum power, an eight to ten hour exposure is possible. Even faster exposures may be produced with the use of more than one beam port, faster neutron sensitive phosphor scintillators or conversion screens, and with the addition of higher speed film types. Further investigation is necessary to determine the systems fixed geometries for the moderator and collimator, but the initial results are promising. Other future ventures expected to surface during this program are high efficiency neutron sensitive scintillators that may be combined with current digital detector panels to solidify the application for production use. An important note to make regarding Figures 4 and 5 is that the x-ray images were taken digitally with a 200um spot size source and increased physical magnification. On the other hand, the neutron images contained no physical magnification, were digitally scanned films, and digitally magnified for the purposes of reporting.

OVERALL REVIEW AND ASSESSMENT

By using a COTS neutron generator for baseline radiographic inspection tests, a confirmation was made to show limitations and downfalls of the current technology available on the market. Low yields and shorten target lifetimes make the production of even low quality radiographs difficult. New technology being developed by the Army is expected to be able to increase yields by over a thousand times, while reducing the footprint, large sustainment costs, and inability to be used practically.

Additional developments are underway at ARDEC to take this generator technology and show its ability to be directly applied to munition and weapon system examinations. Pending the results of current studies it is intended that the system will be open for use on R&D samples and potentially available for low rate production services across the Army within calendar year 2014. Further investigation is expected to be performed to determine detection applications on various materials such as composites, rubbers, plastics, and glues while also confirming its use on complex geometries or interfaces like shape charges and fragmenting liners. At this time, these new technologies cannot yet touch the exposure times of a reactor or be implemented for full up production rates. The near future however does show promise for these smaller, more easily sustained and controlled neutron radiographic systems. The potential for their viable use in the defense sector as well as for commercial or private sector is continually growing along with advances in new materials and quality requirements.

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