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## ABSTRACT

A test campaign was undertaken during April 16-19 in LaHonda, California to match the operational performance of the Idaho National Engineering and Environmental Laboratory (INEEL) Varitron accelerator to that of an ARACOR Eagle accelerator. This Eagle-matched condition, with the INEEL Varitron, will be used during a concept demonstration test at Los Alamos National Laboratory (LANL). This operational characterization involved the use of similar electron beam energies, similar production of photoneutrons from selected non-nuclear materials, and similar production of photofission-based, delayed neutrons from an INEEL-provided, depleted uranium sample. Then using the matched operation, the Varitron was used to define detector performances for several INEEL and LANL detectors using the depleted uranium target and Eagle-like, bremsstrahlung collimation. This summary report provides neutron measurements using the INEEL detectors. All *delayed neutron data* are acquired in the time interval ranging from 4.95 to 19.9 ms after each accelerator pulse. All *prompt neutron data* are acquired during 0.156 to 4.91 ms after each accelerator pulse. Prompt and delayed neutron counting acquisition intervals can still be optimized.



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# ARACOR Eagle-matched Operations and Neutron Detector Performance Tests

## 1. INTRODUCTION

A test campaign was undertaken during April 16-19 in LaHonda, California to match the operational performance of the Idaho National Engineering and Environmental Laboratory (INEEL) Varitron accelerator to that of an ARACOR Eagle accelerator. This Eagle-matched operation of the INEEL Varitron will be used to support a concept demonstration test at Los Alamos National Laboratory (LANL) during FY02.

The ARACOR Eagle is a mobile cargo inspection imaging system used by the US Customs Service at ports-of-call to perform cargo manifest verifications. Presently, a CRADA has been established between ARACOR, INEEL, and LANL to assess the addition of a nuclear smuggling detection system with the Eagle inspection system.

The Eagle-matched operational assessment involved the use of similar electron beam energies, similar production of photoneutrons from selected non-nuclear materials, and similar production of photofission-based, delayed neutrons from an INEEL-provided, depleted uranium sample. Then using the matched operation, the Varitron was used to define detector performances for several INEEL and LANL detectors using the depleted uranium target and Eagle-like, bremsstrahlung collimation. This summary report provides neutron measurements using the INEEL detectors. All *delayed neutron data* are acquired in the time interval ranging from 4.95 to 19.9 ms after each accelerator pulse. All *prompt neutron data* are acquired during 0.156 to 4.91 ms after each accelerator pulse. Prompt and delayed neutron counting acquisition intervals can still be optimized. It is expected that a LANL report will be generated to provide the LANL detector results.

### 1.1 Experimental Configuration

ARACOR provided a “nominal” 6-MeV accelerator operation encased in an Eagle-like photon shield assembly (See white “box” in the upper right of Figure 1). To support another on-going project, ARACOR has modified the actual Eagle collimator assembly design to include a cylindrical hole (10-cm diameter, 41-cm long). The hole is axially centered on the electron beam centerline. Despite the shield modification, the goal to match the delayed neutron output was not compromised. Positioned on the beam centerline, and relative to the accelerator’s photon source, was an air ionization chamber at 1-m and a 4.4-kg depleted uranium (DU) target at 1.05-meter (Note, tabular data results list this DU position as 1-m nominally). INEEL deployed four cylindrical, neutron detectors (see lower right portion of Figure 1) located at 1-m from the DU. Each INEEL detector weighs about 12 kg and consists of a 76-cm long, 2.54-cm diameter, helium-3 tube individually encased in a custom moderator and shield configuration. Specifically, Detector #0 was positioned at 90-degrees (perpendicularly aligned with the beam centerline at the DU) while Detector #1 was located at about 45-degrees off beam-axis. Between these two detectors, Detectors #2 and #3 were equally positioned with the position of #3 closest to Detector #0. LANL deployed one 2.4-m long, helium-3 detector (See left portion of Figure 1). The LANL detector was positioned parallel to the beam centerline at a distance of 1.34-m and opposite the INEEL detectors. It had its closest end positioned such that it was aligned with the front face of the ARACOR shield assembly.

## 1.2 Background Measurements

Many tests were performed over the three-day test campaign. These tests included different detector locations and accelerator operations (i.e., X-ray ON and OFF). Results showed the average neutron background at La Honda, California to be  $0.11 \pm 0.03$  counts per second for each INEEL detector using the above-indicated delayed neutron acquisition window. Since the prompt count is dependent on the specific experimental configuration and accelerator operation, no average prompt neutron background was determined.

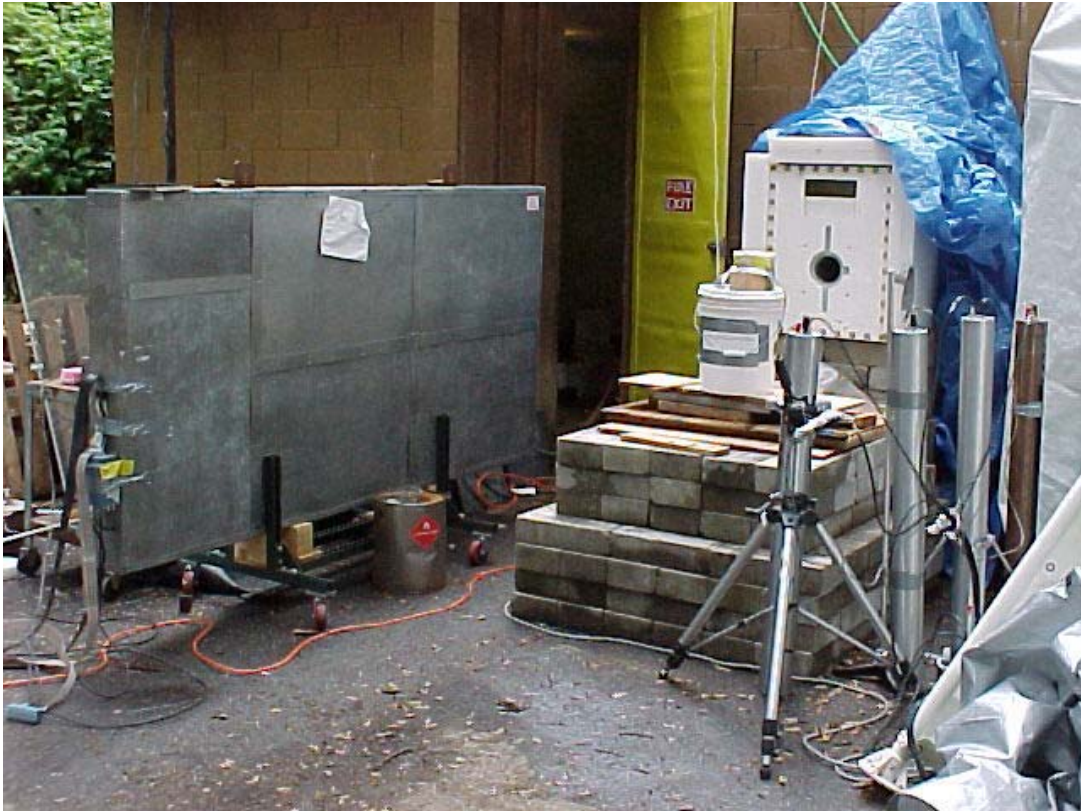


Figure 1. Experimental configuration of the neutron detectors, the depleted uranium target, and the ARACOR “nominal” 6-MeV accelerator and modified shield assembly.

## 1.3 “Nominal” 6-MeV ARACOR Experiments

Using the experimental configuration described above, an operational assessment was made to optimize the electron beam energy for a 50-Hz operation of ARACOR’s “nominal” 6-MeV accelerator in order to obtain a maximum delayed neutron output from the DU target. Maximizing the magnetron power and reducing the accelerator’s electron gun filament voltage from 0.85 to 0.67 iteratively determined this maximum delayed neutron output. This optimized operational performance remained within the Eagle’s operational requirements. The corresponding photon dose rate was about 80 R/min at one meter.

With this operational condition determined, several key characterization experiments were performed with DU. Some of these experiments involved the addition of a 30-cm long beryllium (Be) bar (0.93 kg) or a 20-cm long heavy water (D<sub>2</sub>O) container (1.8 kg) **inside the hole** of the ARACOR shield assembly. Beryllium and D<sub>2</sub>O was chosen to help characterize/identify any differences in the



bremsstrahlung produced by these accelerators at photon energies less than the DU photonuclear threshold energy ( $\sim 5.8$ -MeV). Be and D<sub>2</sub>O were selected since they have very low photoneutron threshold energies: 1.7- and 2.2-MeV, respectively. When one of these materials was added, the added material was positioned at the ARACOR's electron/photon converter and aligned with the beam centerline. The delayed and prompt neutron detection results for these cases are given in Tables 1 and 2, respectively, along with detector sum and the corresponding one-sigma uncertainty.

Table 1. Net delayed neutron counts per second for the four INEEL detectors positioned at one meter from the DU target and using the ARACOR “nominal” 6-MeV accelerator.

Case	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
Du-Only	1.36	0.11	1.22	0.11	1.06	0.10	1.00	0.10
DU + Be	0.13	0.04	0.15	0.05	0.12	0.04	0.11	0.04
DU+ D2O	0.67	0.08	0.62	0.08	0.57	0.08	0.55	0.07

Table 2. Total prompt neutron counts per second for the four INEEL detectors positioned at one meter from the DU target and using the ARACOR “nominal” 6-MeV accelerator.

Case	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
Du-Only	6.20	0.23	5.76	0.22	4.60	0.20	4.33	0.19
DU + Be	465.72	1.97	455.31	1.95	404.68	1.84	362.50	1.74
DU+ D2O	572.80	2.18	581.07	2.20	543.74	2.13	510.69	2.06

## 1.4 INEEL Varitron Matching Experiments

With the exception of a symmetric reflection of the INEEL and the LANL neutron detectors about the beam centerline, a similar detector configuration was established using the INEEL Varitron instead of the ARACOR accelerator. This test configuration is shown in Figure 2. No photon shielding was used forward of the Varitron’s bremsstrahlung convertor for this test series.

After several iterations it became clear that while the delayed neutron response from DU could be matched, it was not possible to completely match the photon dose at a meter. It appeared that some differences in the detailed acceleration processes of these two accelerator waveguides exist. Hence, it was decided to match the DU target delayed neutron response and see what the additional Be and D2O material responses would indicate. Tables 3 and 4 present the net delayed and total prompt neutron count rates, respectively, for this series of tests. Figure 3 presents the energy spectrum of the Varitron’s accelerated electrons for this operational condition having an average beam current of 3.3  $\mu$ A.



Figure 2. Matching experimental configuration using the INEEL Varitron.

Table 3. Net delayed neutron counts per second for the four INEEL detectors positioned at one meter from the DU target and using the INEEL Varitron.

Case	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
Du-Only	1.16	0.10	1.23	0.11	1.10	0.10	1.35	0.11
DU + Be	0.30	0.06	0.36	0.06	0.29	0.06	0.45	0.07
DU+ D2O	0.62	0.08	0.56	0.07	0.69	0.08	0.70	0.08

Table 4. Total prompt neutron counts per second for the four INEEL detectors positioned at one meter from the DU target and using the INEEL Varitron.

Case	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
Du-Only	7.14	0.24	6.17	0.23	5.22	0.21	5.80	0.22
DU + Be	391.11	1.81	303.02	1.59	236.19	1.40	206.42	1.31
DU+ D2O	535.49	2.11	432.03	1.90	349.41	1.71	327.68	1.65

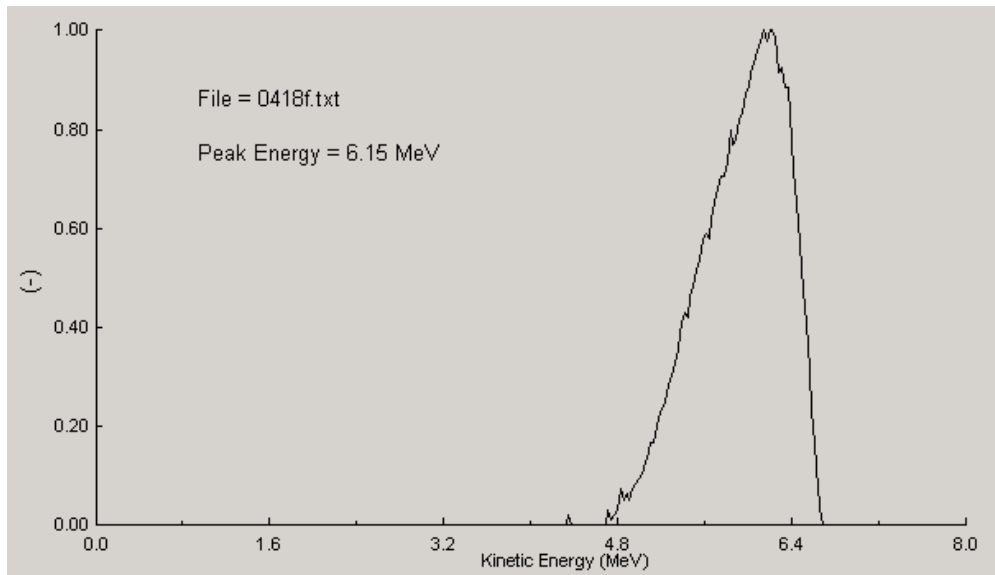


Figure 3. The Varitron’s accelerated electron beam energy spectrum (normalized) used to match the delayed neutron response of the ARACOR Eagle.

For the “DU-Only” cases, note the similar delayed and prompt neutron detection responses of the four INEEL detectors with their corresponding responses for the ARACOR data shown in Tables 1 and 2. Note, only 24 R/min was produced at one meter with an open-end bremsstrahlung converter indicating some difference in the shape of the bremsstrahlung output for these two machines. [For reference, the Varitron’s converter is a 0.993-cm diameter, 0.178-cm thick composite material of 80% tungsten and 20% copper brazed onto a 1.91-cm diameter copper plate that is 0.152-cm thick.] Similar trends are seen when comparing the detection responses with the addition of the D2O material. In this case, the prompt response appears to slightly decrease with increasing detector-to-converter distance. This is because the Varitron did not use a large mass shield forward of its converter (as with the ARACOR accelerator). However, a match is not observed when the lowest energy threshold material (Be) is added. In this latter case, the Varitron’s summed (all detectors) delayed neutron results is nearly 2.7 times that of the ARACOR accelerator, but shows correspondingly lower prompt neutron detection responses. No valid explanation of this anomalous behavior has yet been determined, but it must be related to the photon/neutron scattering within the Be and the ARACOR shield assembly and the correspondingly lower Varitron photon dose output.

## 1.5 Detector Performance Tests Versus Distance

Using the identified “matched” performance condition, the Varitron accelerator was used to characterize the prompt and delayed neutron detection responses of all the neutron detectors using the DU target. Figure 4 shows the detector positions of the four INEEL detectors and the single LANL detector. Tables 5 and 6 show the delayed and prompt neutron detection responses, respectively, for an uncollimated Varitron accelerator operation as the DU target is move from 1 to 3 meters away from the photon source. The net delayed neutron counts range from 1.04 to 0.08 counts/second over background per detector and show the highest count in the detector closest to the DU placement. The total prompt count is shown with and without DU so that an estimate of the photonuclear effect can be realized. For example, at a DU placement of one-meter from the Varitron, a net prompt count rate is over 3 counts/second per INEEL detector at one-meter from the DU (i.e.,  $6.18 - 2.89 = 3.29$  cts/s).

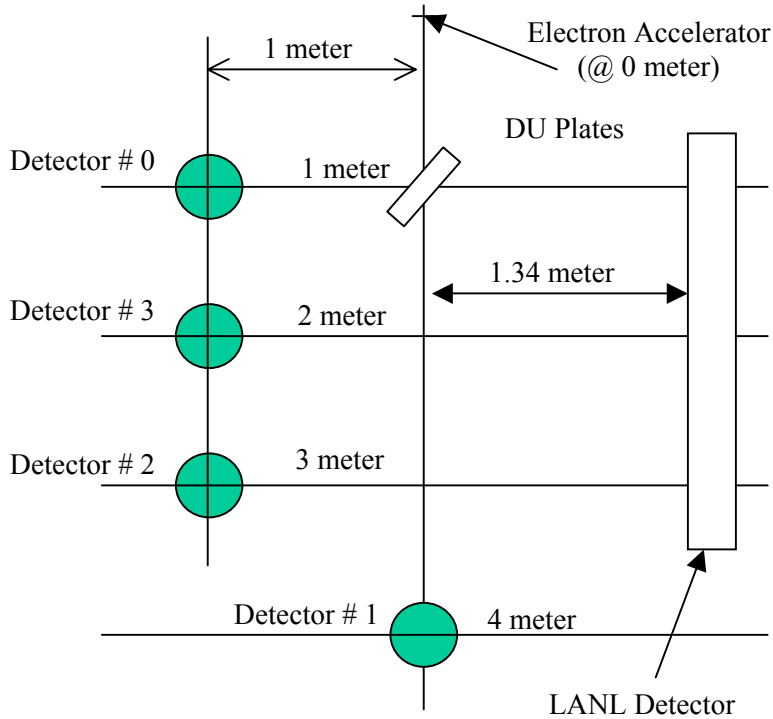


Figure 4. Experimental configuration for the performance tests.

Table 5. Net delayed counts per second for the four INEEL detectors versus DU placement using an unshielded Varitron.

DU Loc.(m)	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
No DU	-0.01	0.03	0.08	0.04	0.03	0.03	-0.08	0.02
1	1.04	0.10	0.80	0.09	0.43	0.07	0.26	0.06
2	0.19	0.05	0.42	0.07	0.23	0.05	0.15	0.05
3	0.08	0.04	0.16	0.05	0.17	0.05	0.21	0.05

Table 6. Total prompt counts per second for the four INEEL detectors versus DU placement using an unshielded Varitron.

DU Loc.(m)	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
No DU	2.89	0.16	1.28	0.10	0.89	0.09	0.58	0.07
1	6.18	0.23	4.06	0.18	2.42	0.14	1.33	0.11
2	4.08	0.18	2.91	0.16	1.63	0.12	1.23	0.10
3	2.78	0.15	2.04	0.13	1.46	0.11	0.98	0.09

## 1.6 Eagle-like Collimation Tests

The final experimental assessment involved the configuration presented in Figures 2 and 4 but used an additional tungsten (W) collimation forward of the Varitron bremsstrahlung source. This W-assembly is shown in Figure 5. It was 35-cm long, had a 7.5 mm-wide slit opening, and included the “pencil” beam collimation section with the normal Varitron collimator assembly. The resulting photon dose at one meter was about 4 R/min.

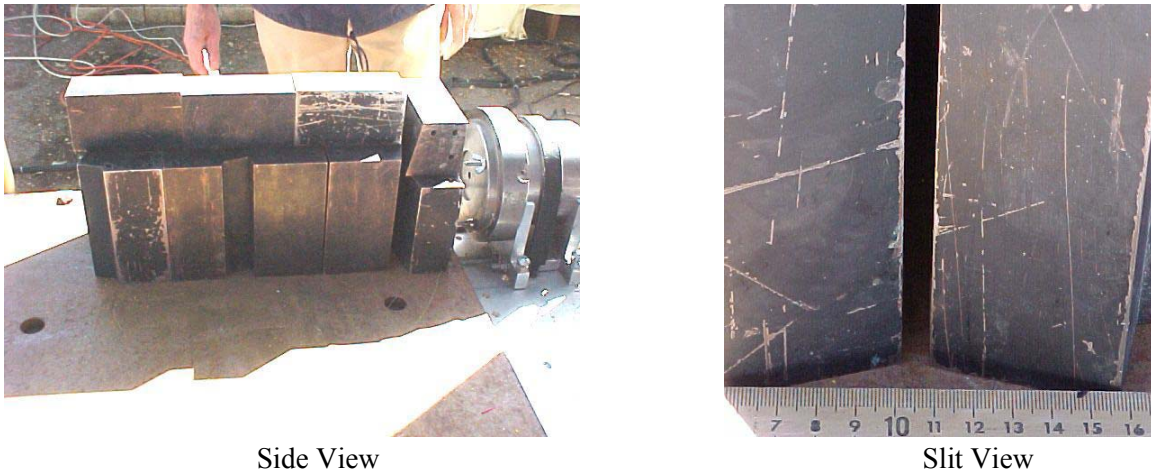


Figure 5. The tungsten collimation assembly used to approximate Eagle-like conditions.

Tables 7 and 8 shows the detection responses for the “nominal” 6-MeV Varitron operation without DU, when DU is positioned on the beam axis at 1.05-meters (i.e., one meter nominally), and finally, when DU is placed at one meter but off-axis; just outside the slit opening (i.e., shielded by the tungsten). Note, in Table 7, the similarity of the “No Du” and “DU off-axis” cases. This result indicates the effectiveness of the tungsten collimation. Also note, that even with DU present at one-meter and positioned on the beam axis, only a segment of the entire object is illuminated. Only the closest detector, Detector #0, has any significant delayed neutron counts.

Table 7. Net delayed counts per second for the INEEL detectors using an ARACOR-like, tungsten collimation at the photon source.

DU Loc.	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
No DU	0.04	0.04	-0.04	0.03	0.01	0.03	-0.02	0.03
DU @ 1 m	0.12	0.04	0.01	0.03	0.02	0.03	0.01	0.03
DU off axis	-0.01	0.03	0.03	0.03	-0.04	0.03	0.04	0.04

Table 8. Total prompt counts per second for the INEEL detectors using an ARACOR-like, tungsten collimation at the photon source.

Case	Detector Number with Error							
	0	Sigma	3	Sigma	2	Sigma	1	Sigma
No DU	2.47	0.14	1.13	0.10	0.67	0.07	0.50	0.06
DU @ 1 m	3.19	0.16	0.63	0.07	1.02	0.09	0.63	0.07
DU off axis	3.33	0.17	1.31	0.10	0.70	0.08	0.61	0.07

## 2. SUMMARY

Using the measured delayed neutron output for a 4.4-kg depleted uranium target at one meter from each accelerators bremsstrahlung source, the operation of the INEEL Varitron was successfully matched to the operation of an ARACOR Eagle. Relying on the operational repeatability of the Varitron and its transportability, a technology demonstration at LANL using an Eagle-like accelerator operation is now possible.

When using the Eagle-matched operation, the uncollimated Varitron was able to provide a maximum net delayed neutron count rate between 1.04 to 0.08 cts/s per INEEL detector depending on the 1- to 3-meter DU target positioning, respectively (See Table 5). Net prompt neutrons emissions for this same scenario range from 6 to about 1 counts per second per detector, indicating that prompt counting, in conjunction with imaging, might be used to assist in identifying nuclear materials. Additional attention will be focused on assessing the advantages/disadvantages of prompt neutron counting with the Eagle inspection scenario.

Use of an Eagle-like photon shield assembly, such as shown in Figure 5, shows about an order-of-magnitude decrease in the counting rate (e.g., 1.04 cts/s [Table 5] and 0.12 cts/s [Table 7]) for a similiary placed target-to-detector configuration. For the same scenario, the prompt count shows only a factor of two decrease (i.e., 6.18 cts/s [Table 6; 1 m] to 3.19 cts/s [Table 8; 1 m]).

The successful imaging operation of the ARACOR Eagle requires the movement of the accelerator relative to the cargo container. This movement must be at least 0.5 mph, or 22.4 cm/s, to operate within a predetermined operational safety envelope. With a 50 Hz pulse rate operation, this results in each accelerator pulse imaging 0.45-cm of the container per pulse. If a 5 kg sphere of uranium is assumed, having a 4-cm radius, a complete interrogation of this uranium shape would require at least 18 pulses, or 0.36 s at 50 Hz.

At the “nominal” 6.0-MeV Eagle operation, Table 7 results would indicate that only 0.043 net delayed neutron counts (0.12 cts/s \* 0.36 s) would be obtained for one INEEL detector positioned at one meter from an unshielded, 4.4-kg uranium target. Use of shielded highly enriched uranium will futher increase the expected detection responses. Yet, a net prompt count of ~0.3 counts ((3.19 – 2.47)\*0.36 s) per detector would be expected.

Based on these results, several options are possible to integrate a photonuclear detection scheme with the ARACOR Eagle:

Option 1: Using the existing Eagle inspection scenario and an optimized photonuclear accelerator operation, continue to increase and/or maximize the delayed neutron detection. Candidate items include larger area detectors (i.e., LANL's detector), increase the number of INEEL detectors, and optimize the acquisition region-of-interest between pulse to optimize the signal-to-noise ratio (S/N).

Option 2. Using the resulting Eagle imaging capability, along with prompt/delayed neutron measurements, identify candidate objects in the container. Once objects are identified, dwell on the selected object with sufficient accelerator pulses to provide nuclear material verification. This option may mean repositioning the Eagle at the location of the suspect item. Another version of this option may be the use of the prompt signal measurement as a flag for performing real-time delayed neutron measurements (i.e., method to enhance S/N).

Option 3: Increase the electron beam energy to 8-MeV. Laboratory experiments with the Varitron have already shown an overall increased detection response by a factor of ~20 per accelerator pulse compared with a similar 6-MeV operation. This higher energy operation will allow increased penetration into a loaded container and will considerably reduce the number of detectors required.