**PULSED PHOTONEUTRON INTERROGATION:
THE GNT DEMONSTRATION SYSTEM**

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Westinghouse Idaho Nuclear Company, Inc.
Idaho Falls, Idaho 83403

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J. L. Jones

Y. D. Harker

W. Y. Yoon

J. M. Hoggan

G. J. McManus

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Idaho National Engineering Laboratory
Idaho Falls, Idaho

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EXECUTIVE SUMMARY

The Idaho National Engineering Laboratory (INEL) has developed and tested an active photon interrogation technique to support the Department of Energy's (DOE) Office of National Security and Nonproliferation (NN) mission related to verification technologies development. The INEL concept, referred to as the Gamma-Neutron Threshold (GNT) technology, uses a transportable, field-deployable, selective-energy (2 to 10 MeV), pulsed, electron accelerator to produce energetic X-rays having a bremsstrahlung spectrum. The energetic X-rays induce neutrons in many proliferation-limited items via direct photoneutron/photofission interactions. The time-dependent neutron response, as a function of the electron beam energy, is measured with a tripod-mounted, detector assembly and a portable data acquisition system. The portable detector assembly has been specifically designed to operate in very intense, pulsed X-ray environments. The GNT technique measures both the prompt and delayed neutron emission after each accelerator pulse. This report fully describes each component of this system and presents various signature results based on these emissions.

The prompt and delayed neutron emission responses are used to identify the presence of nuclear and critical non-nuclear materials in various forms, to discriminate between conventional and nuclear weapons, and to differentiate between nuclear weapon classes. The emission response reveals no information regarding weapon configuration or component shapes.

A demonstration system has been built and tested. Results of these tests are described which show operational design performance, beam energy profile measurements, and representative individual, and combined nuclear and non-nuclear target signatures requiring less than six minutes to acquire.

An experimental assessment, using various nuclear and non-nuclear materials, showed that the GNT demonstration system can detect less than 1 gram of critical non-nuclear weapon material in a configuration where both the X-ray source and the detector are positioned one meter from the target. In a similar configuration, less than 50 grams of uranium is detectable. Smaller quantities may be detected by decreasing the accelerator X-ray source-to-target distance or increasing the target-to-detector distance.

The test results have also shown the potential of using the photon interrogation technique for applications outside weapon material verifications, for example, assay of nuclear wastes containing uranium or plutonium and measurements of neutron doses in high gamma radiation fields.

1. INTRODUCTION

The DOE has for several years supported the investigation and characterization of many verification technologies, related to nuclear weapon counting, identification, and component verification. Most of these technologies have focused on the use of commercially-available components. The requirements of the verification system were largely based on a "reciprocity principle." For a given treaty agreement, the principle provided for full technical and operational disclosure of a verification technology for compliance deployment by any involved party. Hence, DOE emphasized technologies which optimized compliance issues while preventing the release of potentially classified data. This report describes one of these verification technologies.

The GNT technology is an active, pulsed interrogation technique that uses a transportable, selective-energy (2-10 MeV) electron accelerator to generate energetic X-rays. The X-rays will induce a target neutron signature which is measured by a portable neutron detection system. A schematic describing this concept is presented in Figure 1.1.

The X-rays, produced from the interactions of electrons with a high-Z material (material having a high atomic mass number), have a bremsstrahlung spectrum with a maximum energy equal to the maximum electron beam energy as indicated in Figure 1.2. These energetic X-rays have high penetrability in most materials and will interact within specific targets to produce neutrons via the photoneutron and/or photofission interactions. As indicated in Figure 1.3, the X-rays are primarily forward-directed and the intensity versus angle becomes more forward peaked as the energy of the electrons is increased. For example, the photon intensity for a 8 MeV electron beam operation decreases to 50 percent of maximum at $\pm 10^\circ$, whereas the corresponding decrease occurs as $\pm 5^\circ$ for 15 MeV electrons.

An X-ray collimator, made of tungsten, is used to help define the maximum angular divergence of the bremsstrahlung photons. Different collimator designs can be used to selectively illuminate specific target components. By selecting an electron beam energy (i.e., maximum photon energy) above the photoneutron/photofission thresholds of a material present in the interrogated item, photoneutron/photofission interactions will occur generating neutrons. The stimulated neutrons, detected as a function of electron beam energy, is the basic signature which characterizes the critical material content in a given interrogated object but does not reveal any geometric component data due to the broad energy neutron spectra of multiple emitting material.

Figure 1.1. Schematic description of the GNT technology.

Figure 1.2. Calculated bremsstrahlung X-ray spectra for various electron beam energies. (Taken from Reference 1)

Figure 1.3. X-ray intensity distributions for various electron beam energies.
(Taken from Reference 1)

Table 1.1 lists the threshold energies of various materials important to the verification application of this technique. In this table, most structural materials have photoneutron thresholds in the range of 8-10 MeV. Typical photofission thresholds for nuclear materials are about 6 MeV, and many critical non-nuclear weapon related materials have thresholds less than 6 MeV. Hence, the neutron signature response of the specific electron beam energies can be used to differentiate critical nuclear materials from structural materials.

Based on the successful results of the proof-of-concept² and follow-on tests³, a demonstration system has been developed and functionally tested. The demonstration system includes a customized, selective-energy, electron accelerator unit and a neutron detection system. The customized electron accelerator system was constructed for this application from commercial components and includes an electron beam energy and beam current measurement assembly. The accelerator uses a Varian, Inc. 3000A accelerator wave guide and was custom built by High Energy Services Corporation (HESCO) of Redwood City, California. The completely transportable accelerator is referred to as the VARITRON. The VARITRON design has been successfully transferred to private industry (VARIAN Associates, Inc.) for enhanced X-ray radiography applications.

The GNT neutron detection system includes a tripod-mounted, multiple detector (helium-3) assembly and a portable data acquisition system. The detection system uses an INEL-fabricated double differentiation signal amplifier circuit to enable rapid recovery of the detection system response following an X-ray flash. The system can detect stimulated neutrons as early as 10 microseconds after each accelerator pulse. Photon shielding requirements are minimal. The rapid recovery capability, coupled with a neutron moderator around the detectors, allows the detection of the prompt neutron emission as well as delayed neutron emission.

Section 2 presents a complete system description of the GNT demonstration system. The basic accelerator design specifications are presented in Appendix A. Section 3 discusses the two primary operation modes for signature acquisition. System tests, described in Section 4, characterize both the accelerator design and detector operations. Representative signatures from selected nuclear and non-nuclear materials are included. Finally, minimum detection limits for selected target materials are presented in Section 5.

TABLE 1.1. REPRESENTATIVE PHOTONEUTRON/PHOTOFISSION PRODUCTION
NUCLIDES

<u>Element/Isotopes</u>	<u>Percent Nat. Abundance</u>	<u>(γ,n) Threshold (MeV)</u>
<u>General Nuclei</u>		
H-2	0.02	2.2
Li-6	7.5	5.6
Li-7	92.5	7.3
Be-9	100.	1.7
C-12	98.89	18.7
C-13	1.11	4.9
N-14	99.63	10.6
N-15	0.37	10.8
O-16	99.76	15.7
O-17	0.04	4.1
O-18	0.20	8.0
<u>Nuclear Nuclei</u>		
Pu-239	--	5.6 [5.6]*
Pu-240	--	6.5 [6.1]
Pu-241	--	5.3 [5.4]
U-232	--	7.3 [6.7]
U-233	--	5.7 [6.0]
U-235	0.72	5.3 [5.8]
U-236	--	6.5 [5.9]
U-238	99.27	6.1 [5.8]
Th-232	100.	6.4 [6.0]
<u>Structural Nuclei</u>		
Cu-63	69.2	10.8
Cu-65	30.8	9.9
Fe-54	91.8	11.2
Fe-56	2.1	7.6
Fe-58	0.3	10.0
W-182	26.3	8.0
W-183	14.3	6.2
W-184	30.7	7.5
W-186	28.6	7.3
Al-27	100.	13.1
Ca-40	96.94	15.7
Ca-43	0.14	7.9
Ca-44	2.09	11.1
Si-28	92.2	17.2
Si-29	4.7	8.5
Si-30	3.1	10.6

[]* - Photofission threshold energy (MeV)

2. SYSTEM COMPONENTS

The transportable GNT demonstration system consists of two main sub-systems, the accelerator subsystem and the detection sub-system. Figure 2.1 presents a block diagram for the GNT demonstration system. The components of the accelerator sub-system generate the selected energetic X-rays and provide the electron beam diagnostics. The detection subsystem components permit the measurement of the induced photoneutrons and/or photofission neutrons. Since every major sub-system component weighs less than 113.5 kg (250 pounds) and the entire system can be transported in a small van, the GNT demonstration system is suitable for on-site inspection applications.

2.1 Accelerator System

The accelerator sub-system consists of two major units: the radio frequency (RF)-drive system and the selectable-energy linear accelerator (VARITRON). The RF-drive system supplies the RF power to the VARITRON. A typical plan view of the major components of the field-deployable GNT accelerator system is shown in Figure 2.2. (Note the X-ray Head indicated in this figure is the VARITRON mentioned above.) The GNT demonstration system uses a HESCO power supply system (referred to in this figure as the Mini-Linatron). Complete details of the accelerator system are found in References 4 and 5. To support the operation of the accelerator, HESCO has trained and certified INEL operators.

2.1.1 RF-drive System

The GNT demonstration system uses the same transportable power modules from the Mini-Linatron System which HESCO uses for normal, in-field radiography applications. The HESCO Mini-Linatron system⁴ is a multi-component, S-band, side-coupled cavity design, linear accelerator system designed to operate with a number of accelerators with nominal beam energies ranging from 1 to 6 MeV. The basic system, shown in Figure 2.3, includes the control console (directly in front of the person), the radio frequency (RF) Head component (upon which the person is sitting), and the modulator power supply (wheeled assembly to the left). The RF Head component provides direct RF power to the VARITRON accelerator section. The interconnecting cables, flexible RF wave guide (between the electron accelerator and RF head component), and the small, portable water chiller unit are not shown. Figure 2.3 also shows a transportable 6 MeV accelerator unit (shown directly behind the modulator power supply) which is not part of the GNT system.

Figure 2.1. GNT technology system block diagram.

+ 10 Atmosphere; * Current-Sensitive; † Double Differentiation Circuit

Figure 2.2 Block diagram of field-deployed GNT system.

Figure 2.3. HESCO Mini-Linatron system components.

The accelerator power is provided by microwaves generated by a 2.1 MW magnetron tube located in the RF Head. The tube is energized by a 45 kV, 4 μ s electrical pulse supplied by the pulse forming network (PFN) in the modulator unit and the step-up pulse transformer in the RF Head. Control of the discharge of the PFN is by a high power Thyratron tube in the modulator. The rate of discharge (i.e., the pulse rate) is controlled from the RF-drive control console. Power for the PFN is supplied by a 10kV DC supply in the modulator whose output is doubled by a charging choke/diode circuit. The input system power requirement is approximately 10 kW supplied from a 3-phase 208/240 Vac main grid or portable generator.

The water cooler unit is connected to the RF head and the VARITRON system. The magnetron in the RF Head is the primary component requiring cooling. In the VARITRON system, both the accelerator wave guide and the electron-to-X-ray convertor require cooling. Normal tap water is used as the coolant; the reservoir is normally filled on-site.

2.1.2 VARITRON (X-ray Head) System

The VARITRON, shown in Figure 2.4 consists of the electron accelerator (X-ray head) and the beam analysis assembly. The VARITRON system is supported by the VARITRON control console (See Section 2.1.2.3). The VARITRON system accelerates electrons to a selected energy, permits measurement of the beam energy and current of the accelerated electrons, and produces the desired X-rays. Figures 2.5a and 2.5b show a top-view and side-view schematic, respectively, of the VARITRON accelerator unit and the forward-positioned beam analysis assembly. The guide enclosure (left portion) in Figures 2.5a and 2.5b represent the electron accelerator unit, while the beam analysis facility is shown on the right. The entire X-ray Head system is positioned on top of a variable-height table with an maximum vertical extension of about one meter. The control console enables the operator to remotely select various operational parameters.

2.1.2.1 Electron Accelerator. The electron accelerator, shown in Figure 2.6 with its enclosure removed, consists of: one Varian Model 3000A linear accelerator waveguide with an output vacuum valve, an electron gun filament, injection control system, control cabling, signal output, water cooling connections, and enclosure. The accelerator waveguide is a series of tuned RF cavities, that when excited by microwave energy, will capture and accelerate injected electrons. Power from the RF-drive system is supplied to the accelerator with a flexible (up to 9 m) RF connection from the RF-Head to a RF input coupling connector at the back end of the enclosure housing (see Figure 2.2). This RF input connector attaches to an internally fixed RF input waveguide which connects directly to the accelerator structure. The enclosure back-end panel also contains coupling connections for all electrical and coolant attachments.

Figure 2.4. Overview of VARITRON unit (i.e., X-ray Head).

Figure 2.5a. VARITRON schematic: top view.

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Figure 2.5b. VARITRON schematic: side view.

Figure 2.6. Internal view of VARITRON unit (with guide enclosure removed).

A vacuum ion pump (Vac-Ion) provides the necessary vacuum to minimize beam dispersion due to scattering. A vacuum valve allows isolation of the electron accelerator and the beam analysis assembly. The electron filament (see Figure 2.5b) is located opposite to the vacuum valve end of the accelerator structure. This unit is the source of all injected electrons. The injection control system includes the isolation transformer, the high voltage (HV) relays, and divider network.

2.1.2.2 Beam Analysis Assembly. The beam analysis assembly, located at the output end of the accelerator section, is shown in Figure 2.7. This assembly generates the desired X-rays and allows beam energy and current measurements during X-ray production. The assembly consists of a bending magnet, an electron-to-X-ray convertor, a removable X-ray beam collimator, an analysis vacuum chamber, a secondary Vac-Ion pump, a vacuum valve, and a removable foreline trap and vacuum roughing pump. The entire assembly is completely removable from the accelerator unit. The assembly components are fixed on a separate, removable 0.635 cm thick aluminum base plate supported by two aluminum I-beams extending the full length of the base of the accelerator system. Vacuum connection to the accelerator section is with a bellows-type vacuum tube; electrical connections are on the enclosure front and back panels. The electrical diagnostic signals from the beam analysis assembly include deflected beam relative intensity, electron beam current in the convertor, and vacuum conditions.

The bending magnet, used in the beam energy analysis, is a small, custom-fabricated, air-cooled unit which provides a 20-degree deflection of 10 MeV electrons. The magnet has two 2.54 cm copper coils producing a maximum field strength of 1.2 kG, a 7.62 x 10.16 cm (along the beamline) pole face, and a 2.79 cm pole-to-pole gap. Including the steel core, the overall dimensions are 13.97 by 410.16 cm. The magnet weighs 18.16 kg and is completely removable from the supporting base plate. The magnet current is controlled by the magnet power supply in the VARITRON control console.

As shown in Figure 2.5a, the vacuum chamber of the beam analysis assembly is rectangular with two arm extensions: a 2.54 cm diameter tube aligned with the primary beam direction and a rectangular (3.81 x 1.91 cm) tube positioned at 20 degrees with respect to the main beamline. The 20-degree deflection port allows beam transport compatible with the bending magnet design.

The beamline-centered vacuum tube leads directly to the electron-to-X-ray convertor. The convertor, sized for a 2-10 MeV X-ray production, is a 0.551 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 0.127 cm thick.

Figure 2.7. VARITRON beam analysis assembly.

The convertor is positioned such that the tungsten composite faces the incident electrons. The convertor has a water coolant channel to prevent convertor damage and vacuum degradation from thermal outgassing. Surrounding the convertor is a cylindrical tungsten collimator 9.88 cm long and 13.21 cm in diameter. The collimator design reduces the 90-degree photon dose at one meter to no more than 1 percent of the forward dose at one meter. A longitudinal bore hole enables collimator positioning over the vacuum tube such that the convertor is located approximately 7.87 cm from the front face of the collimator. The collimator contains the primary X-ray emission within a $\pm 15^\circ$ forward cone angle. As shown in Figure 1.3, this angle results in maximum intensity reductions of 38% and 62% at 4 and 8 MeV electron energies, respectively.

The 20° vacuum tube extends from the magnet position for about 23 cm. Centered at approximately 1.91 cm from the end of this extension is a 0.318 cm thick faraday cup probe. When the bending magnet is energized, the electron beam is deflected from its nominal straight beam line trajectory. The extent of the deflection is a function of the beam energy and the magnet field strength.

The magnet power supply is controlled at the VARITRON control console usually located with the system power supply modules during operation. By varying the magnet power and measuring the corresponding beam intersecting the faraday cup probe, an electron beam energy profile can be determined.

Preliminary experiments indicated that scattering of the defocused electron beam off the vacuum wall may contribute erroneously to the beam charge collections. An upgraded vacuum chamber extension, shown in Figure 2.8, replaced part of the rectangular vacuum tube with a circular section, added two rectangular angle-defining slits, and slightly modified the faraday cup. Subsequent results showed enhanced measurement data.

Numerical predictions show that for a 9 MeV electron beam, the multi-material, VARITRON convertor design will stop about 99.6% of the incident electrons. Since the electron stopping power for a fixed convertor design increases with decreasing electron beam energy, this design provides a good means of measuring the electron beam convertor current. A ceramic coupler is used to insulate the convertor end from the remainder of the vacuum chamber; hence, the convertor behaves as a faraday cup. Charge collected at the convertor from the incident beam electrons is applied across a nominal 1 kOhm in-line resistor for charge dissipation. During operation, the pulse-to-pulse convertor voltage is measured across a load resistor (at the VARITRON control console) and is directly related to the electron beam current.

Figure 2.8. Upgraded VARITRON beam analysis assembly.

2.1.2.3 Control Console The VARITRON control console, shown in Figure 2.9, is a desk mounted enclosure that controls the beam analysis magnet current, the Vac-Ion pump, and the accelerator filament voltage. The Vac-Ion pump controller is on the left side of the console, a magnet power supply is along the top of the console, and the electron gun filament and injection voltage control unit is on the right side of console. There are also electrical monitoring connections immediately below the filament control monitor.

The Vac-Ion controller provides the power to the high capacity pump located on the beam analysis assembly and indicates the vacuum pressure. This pump is used during vacuum pumpdown and also as a back-up for the main Vac-Ion pump in the accelerator section.

The magnet power supply provides and regulates the current to the coils in the beam analysis magnet. Two liquid crystal displays on the magnet power supply indicate the magnet voltage and supplied current. This current supply is used to analyze the deflected electron beam spectra.

The electron gun filament voltage of the electron accelerator controls the amount of source electrons. The filament voltage is varied by means of a panel-mounted variable transformer (Variac). Input to the variac is from a voltage isolation transformer in the accelerator enclosure, as shown in Figure 2.5a, that isolates the gun output from any AC-line variations. The filament voltage varies from 0 to 110 Vac; and the variac output is mechanically limited (in the control console) to avoid filament damage.

2.1.3 Operational Capabilities

Table 2.1 shows the GNT demonstration system's key operational specifications using the HESCO Mini-Linatron power supply.

TABLE 2.1. SELECTED GNT SYSTEM OPERATIONAL SPECIFICATIONS

Electron kinetic energy	2 - 10 MeV
Electron pulse width	0.5 - 4.0 μ s
Pulse rate	60 - 500 Hz
Peak beam current	300 mA
Max. X-ray dose at 1-m	1000 R/min
Beam width on convertor	3-4 mm (dia.)
Electron beam injection voltage	38.1 kV
Magnetron current	31 - 72 A

Figure 2.9. VARITRON control console.

2.2 Detection System

The complete GNT detection system, shown in Figure 2.10, consists of a portable, four-channel neutron detection assembly (the box on the right) and a portable data acquisition system. The block diagram for the detection system is shown in Figure 2.1. Using existing interconnecting cables, the detector box and the acquisition system can be separated by as much as 46 meters. There are four signal cables and two power cables. The four signal cables are standard RG62 coaxial cables; one for each neutron detector. The power cables provide power to the pre-amplifier/amplifier modules and high voltage to the neutron detector tubes.

Inside the detector assembly are four, 10-atmosphere, helium-3 gas tube proportional counters used as neutron detectors. As indicated in Figure 2.1 each detector channel has its own independent pre-amplifier, amplifier, double differentiation circuit, pulse height discriminators and signal conditioning amplifier. Data from all of the final signal amplifiers are combined in a multichannel scaling (MCS) module and transferred to a portable computer for data analysis.

2.2.1 Data Acquisition System

The data acquisition system consists of a portable, NIM-standard electronics rack and a portable COMPAQ-III computer utilizing a multichannel analyzer acquisition board (Nuclear Data AccuSpec/B) and a compatible software program (Nuclear Data AccuSpec Multichannel Analyzer). The portable NIM-rack, shown in Figure 2.10, is a 30 x 30 x 20 cm enclosure containing the following electronic components (left to right):

- 1) an INEL-built timer control module (use is optional),
- 2) an INEL-built signal distribution module to boost discriminator logic signals to about 5 V,
- 3) a multichannel scaler module (ND 578) with a ribbon cable to the multichannel analyzer board in the computer, and
- 4) a high-voltage power supply module (ORTEC 556) for the high voltage bias of the detectors.

The timer module controls the data acquisition process based on input from the accelerator triggering signal. The module is operator programmed to impose a fixed delay (usually 10-15 μ s) after the trigger signal. This delay prevents the system from acquiring data until after the neutron detectors recover from the primary X-ray flash occurring immediately after each trigger signal.

Figure 2.10 GNT detection system. (The acquisition computer is located directly above the electronic module and the neutron detector assembly is shown to the right).

2.2.2 Detector Assembly

The tripod mounted detector assembly is shown in Figure 2.11; and a schematic of the assembly is presented in Figure 2.12. A detailed description of the assembly has been given in References 2 and 3; a brief description follows.

The detector assembly consists of a 35.60 cm long and 25.40 cm square box containing four 10-atmosphere helium-3 neutron detectors. These detectors, having an approximately 2.54 cm diameter active region, are embedded in a virgin polyethylene block, approximately 15 cm square. These detectors are aligned such that the cylindrical axis is parallel to the long dimension of the assembly. For normal interrogation applications, the long dimension of the assembly is pointed at the target. Two inches of borated polyethylene surrounding the virgin polyethylene block help to shield the detectors from reflected slow "room return" neutrons. The die-away time, defined as the time required for the neutron population within the assembly to decrease by one-exponential fold ($1/e$) of its initial value, is approximately 68.5 μ s.

Calibrations using ^{252}Cf and $^{239}\text{PuBe}$ sources have shown an overall detection assembly efficiency (based on all four He-3 detectors) of approximately 2×10^{-4} counts/source neutron at a 1 meter source-to-detector face distance.

Directly behind the virgin block, and within the borated polyethylene, is a cavity which contains the pre-amp/amplifier, differentiation and discriminator units, and signal conditioning amplifiers (one for each detector). To assure removal of thermal neutrons and to alleviate electromagnetic interference, the entire assembly is encased in a composite sheet of 0.05 cm cadmium and 0.1 cm copper, respectively.

A second stage amplifier with an additional differentiation circuit has been added to each of the detector channels. This modification provided two important advantages:

- 1) ability to detect individual neutron pulses when the tubes have not completely recovered from the flash event, and
- 2) significantly reduced detector shielding requirements by operating within the flash response.

Figure 2.11. Deployed, tripod-mounted GNT detector.

Figure 2.12. GNT detector assembly schematic.

2.2.3 Detection Methodology

For operations at a given electron beam energy, the detection system measures neutron temporal response in each detector channel for a finite time interval between accelerator pulses. Measurements are initiated by the accelerator trigger pulses. Figure 2.13 is a graphical representation of the derivation of a typical detector channel response.

From the start of each accelerator trigger signal, data collection begins. The data collection time depends on the MCS dwell time and data acquisition software parameter settings. For each detector an initial saturation response occurs, depending on the X-ray intensity level used, followed by neutron counts. As indicated in Figure 2.13, a representative channel amplifier output shows neutron pulses superimposed on the X-ray flash response. A second stage amplifier differentiates this signal and isolates these pulses for pulse-height discrimination. The discriminated signal, for a given nominal electron beam energy, results in a temporal output signal for each accelerator pulse. The temporal signals for each channel are accumulated for all the accelerator pulses used for a specific test. Neutron data accumulated in each detector channel are categorized into two arbitrary regions: typically 10 - 700 μ s (prompt) and 700 μ s - up to time between accelerator pulses (delayed). Signal-to-noise ratios for prompt response are much larger than for the delayed response.

A GNT neutron target signature (neutron response versus electron energy) is based on accumulated temporal responses at multiple (usually up to six) nominal electron beam energy operations. A *complete* target signature requires the following measurements for each nominal electron beam energy:

- 1) Using the accelerator trigger pulse but no X-ray generation, obtain neutron detector response without a target present. This step provides test facility background.
- 2) Using the accelerator trigger pulse but no X-ray generation, obtain neutron detector response with target present. This step is primarily applicable to targets containing spontaneously fissioning or other nuclear materials.
- 3) Using the accelerator trigger pulse with X-ray generation, obtain neutron detector response without a target present. This step characterizes any non-target induced photoneutrons.
- 4) Using the accelerator trigger pulse with X-ray generation, obtain neutron detector response with target present. This step determines the total detector response.

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Figure 2.13. Graphical representation of a detection channel response.

Four separate measurements are not required for every test. Measurement #1 is independent of the electron beam energy, and hence, is only required for the initial GNT system set-up in a testing facility or after a detector/accelerator position change. All test results to date have shown that source emissions from testing facilities are insignificant compared to the target neutron emissions. Measurement #2, which is also independent of the electron beam energy, is needed only once per target position and is only needed for targets containing nuclear materials. Hence, for a specific test, the only required energy-dependent, multiple data collections are Measurements #3 and #4. An accelerator operating at 120 Hz (values up to 1000 Hz are possible), produces almost 15,000 pulses in two minutes. Thus, a statistically valid target response can be obtained from short irradiation periods. These energy-dependent measurements are post-processed to obtain a given target signature.

3. SYSTEM OPERATIONS

The GNT system operates in two primary modes: selective beam energy operations and beam analysis.

3.1 Selective Beam Energy Operations

Commercially-available electron accelerators used for radiography are typically fixed energy devices; however the GNT VARITRON system allows operator control of the beam energy between 2 and 10 MeV in a single field-deployable unit. Beam energy variation is not a continuous function but must be selected within operational stability regions dictated by the specific power supply used. The GNT demonstration system has used the 2.1 MW magnetron power supply of the HESCO Mini-Linatron system.

Three key system parameters determine the beam energy: the electron gun filament voltage, the electron gun injection voltage, and the RF drive power. Increasing the voltage to the gun filament (at the VARITRON control console) provides more electrons at the cathode and, depending on the injection voltage, controls the electron bunching for acceleration. Increasing the amount of electrons "loads" the acceleration waveguide cavity and decreases the efficiency of the accelerator, resulting in lower beam energies. The injection voltage, supplied by the RF-drive power system, is applied between the cathode of the electron gun and the accelerator waveguide at the same time RF power is applied. This injection voltage pulses gun filament electrons into the accelerator waveguide. The accelerator, consisting of a series of tuned microwave cavities resonating at a selected microwave energy, captures and accelerates the injected electrons. Varying the RF power of the applied microwave energy varies the capture and acceleration efficiency of the accelerator in an approximately linear manner.

Figure 3.1 shows the measured VARITRON performance curves (peak bending magnet current [corresponds to nominal beam energy] versus injection current for various magnetron current settings) using the HESCO Mini-Linatron power supply system. Other magnetron power supplies are expected to have similar performance curves. The magnetron currents shown in this figure indicate regions of stable magnetron operation. When varying beam energies, the accelerator operator must also vary both the injection current and RF power to remain within a region of stability (stay on one of the "load" curves). The energy selection process is now a manual operation, but the process could be automated.

Figure 3.1 VARITRON performance curves (peak bending magnet current vs injection current) for various magnetron currents.

3.2 Beam Analysis Operations

For a given stable acceleration mode, the beam current is determined by measuring the voltage across a known-valued resistor attached to the electron-to-X-ray convertor as described in Section 2.1.2.2. The voltage is measured by an oscilloscope connected to the "target current" port of the VARITRON control console, and the beam current is calculated using Ohm's Law. The total charge is obtained by integrating the beam current over the total pulse duration for a given test.

Energy measurements are performed with a small, custom-made, 1.2 kG dipole magnet and a 20° analysis port containing a faraday probe at the end of the port (See Section 2.1.2.2). The magnet, which has been described in Section 2.1.2.2, was sized to allow a 20° bend for 10 MeV electrons. Experimental field mapping, using a calibrated Hall probe along the horizontal mid-plane of the gap, has shown near-uniform ($\pm 5\%$) magnetic fields within the gap, and a rapid field decrease (two-to-three orders of magnitude) within 5 cm of the edge of the magnet (i.e. the fringe field area). Table 3.1 shows the measured peak magnet field along the beamline mid-plane versus the applied magnet current.

TABLE 3.1. MEASURED PEAK MAGNET STRENGTH VERSUS MAGNET CURRENT

Peak Magnet Current <u>I_B (A)</u>	Magnetic Field <u>(Gauss)</u>
2	150
3	240
4	370
6	570
8	780
10	1000
12	1100
14	1420
16	1650
18	1830
20	2030

The following linear correlation has been fit to the data:

$$I_B(A) = [B(\text{gauss}) + 60.83]/105.4.$$

An operational characteristic of the VARITRON magnet power supply is that the relationship is not valid for magnet field strengths below 0.58 A.

Using this peak magnet current and field relationship, the magnetic field measurements (including magnetic fringe fields), and the supporting magnetic field and beam energy calculations (presented in Appendix C), Figure 3.2 presents the relationship between the kinetic energy (E) of the electrons reaching the faraday cup and the peak magnet current (I_p) applied to the magnet. The best fit to numerous acquired performance data defines the electron beam energy as follows:

$$E(\text{MeV}) = [I_p(\text{A}) - 1.061]/1.0305.$$

Figure 3.3 presents measured beam energy profiles with corresponding integrated responses for various operational conditions (i.e., injection current and magnetron current) for the VARITRON, as permitted by the performance curves of Figure 3.1. Detailed examinations of these profiles show that the peaks correspond to a beam energy content of greater than 70% for all electron energies. Assessments have defined a nominal electron beam energy as being approximately 0.3 MeV greater than this peak operational energy, to encompass at least 90% of the total beam energy content and to provide a good measure of the photoneutron production capability of the resulting electron beam. Hence, the nominal VARITRON beam energy can be easily determined from Figure 3.2 and the applied magnet current; or

$$E^{\text{nom}}(\text{MeV}) = E(\text{MeV}) + 0.3.$$

Figure 3.2. Peak bending magnet current versus electron beam kinetic energy.

Figure 3.3. Measured energy-dependent electron distribution profiles and corresponding integrated responses for several operational conditions.

4. CHARACTERIZATION NEUTRON SIGNATURES

A series of tests were performed to obtain and characterize neutron signatures for selected object materials. The operational performance characterization has already been described in Section 3. Neutron signatures were obtained from a 815 g beryllium bar, a one liter container of heavy water (220 g of deuterium), and a depleted uranium assembly consisting of two 15 kg rectangular forms (7.5 x 6.3 x 17.5 cm) separated by about 5 cm. All objects were placed on the beam centerline one meter in front of the X-ray source. The detector was aligned at one meter from the object at an orientation of 90-degrees from the beam centerline.

The methodology described in Section 2.2.3 was used. Most of the signature data were obtained from 5000 accelerator pulses per nominal beam energy operation, with up to six selected nominal beam energies. Each beam energy operation provides both prompt and delayed signature data. For a machine operating at a frequency of 100 Hz, this requires less than one minute per operation; or optimally, up to 6 minutes per signature. If desired, the frequency can be easily increased to 500 Hz, resulting in 20 seconds per beam operation.

Figure 4.1 presents prompt signature (prompt neutrons per coulomb on the X-ray convertor) comparison for the three targets. The data includes two sigma (95%) uncertainties; most of the uncertainty results from a ± 10 % measurement uncertainty of the beam current. Beryllium and heavy water (deuterium) produce neutrons at all nominal beam energies shown. The higher beryllium yields are mainly due to its larger target mass. The depleted uranium target produced no neutrons at beam energies below the uranium photoneutron and photofission thresholds (~ 6 MeV). The corresponding delayed neutron signatures (delayed neutrons per prompt neutrons) are shown in Figure 4.2. Beryllium or deuterium produced no delayed neutrons. Significant delayed neutrons were produced by the depleted uranium target. The anomalous delayed neutron response at the nominal electron energy of 5.8 MeV suggests some type of data collection problem, as indicated by the large data uncertainty.

Signatures were also obtained for a combination of all targets. The distance between the source and the targets was maintained at one meter. The depleted uranium target was positioned directly behind the beryllium and heavy water targets; the latter being beside one another. Figures 4.3 and 4.4 present the prompt and delayed signatures, respectively, with and without the uranium in the combined target configuration. Since the effect of uranium was being investigated, measurements were not made at nominal energies below 5.0 MeV. A comparison of the prompt signatures indicate the addition of a neutron emitting material, but does not provide information regarding the type of material.

Figure 4.1. Prompt neutron signatures for beryllium, heavy water, and depleted uranium.

Figure 4.2. Delayed neutron signatures for beryllium, heavy water, and depleted uranium.

Figure 4.3. Prompt neutron signature for combined beryllium and heavy water target with and without depleted uranium.

Figure 4.4. Delayed neutron signatures for combined beryllium and heavy water target with and without depleted uranium.

Figure 4.4, which shows the corresponding delayed neutron signature, shows that the additional material is a delayed neutron emitter; hence, nuclear material.

A full demonstration test has been documented (Reference 6).

5. MINIMUM DETECTABLE LIMITS (MDL) ASSESSMENT

A series of tests were performed to determine the minimum detectable limits (MDL) of the GNT demonstration system for selected nuclear and non-nuclear materials in various testing configurations. The MDL results indicate the usefulness of the GNT system in export controls and other counter-proliferation activities.

5.1 Test Description

During March 2-9, 1993 the MDL tests were performed in the Idaho State University (ISU) Beam Particle Laboratory Test Cell. The 4 meter high test cell is located approximately 3 meters below ground level. A selected testing configuration within the facility is shown in Figure 5.1. The transportable power supply, described in Section 2.2.1, was provided by HESCO.

The detector was positioned at a right angle to the electron beam centerline in all tests. The long dimension of the detector assembly was always parallel with the floor and pointed toward the target. The beam centerline was fixed at 0.87 m from the test cell floor. From the X-ray source, the nearest distance to a wall was 1.2 meters. With the VARITRON unit in a fixed-position, MDL tests were performed for various target and detector configurations. The nominal accelerator source (converter)-to-target (centerline) distance and target-to-detector (front face) distance were one meter. During each test, the X-ray dose was monitored by a portable, commercial (Radcal, Inc.) ionization chamber located 0.5 cm off the beamline and approximately 0.8-m (along the beam line) from the accelerator source. This off-axis positioning of the ionization chamber enabled, fixed-position, dose monitoring comparisons for all targets. Table 5.1 describes the target materials used in this assessment.

Target geometries were selected to minimize photon attenuation effects (obtain "thin" target responses) of the interrogating photon interactions. This enabled direct correlations between target mass and neutron emission response. For all tests, the target materials were placed as close to on-beam centerline as physically possible, while still assuring the "thin" target response.

The MDL assessment included tests at several different nominal beam energies, each consisting of 30,000 accelerator pulses. A large number of accelerator pulses were used to provide good statistical results. All temporal neutron responses between 15 and 615 μ s after an accelerator pulse were categorized as "prompt" and those between 616 and 7695 μ s as "delayed."

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Figure 5.1. Nominal testing configuration in ISU test cell.

TABLE 5.1. MDL TARGET MATERIAL DESCRIPTION

<u>Material</u>	<u>Form</u>	<u>Description</u>
Beryllium each,	Metal	(half-hex, Six units; 135.8 g 10.2 cm long)
Deuterium	Heavy Water	3 to 513 grams of D ₂ O (>99% enriched)
Natural Uranium	UO ₂ Pellets (0.95 cm diameter	49 to 148 g of Uranium and 1.4 cm high)
Plutonium	Metal (94% Pu-239)	39 foils; 1 g each of plutonium (1.54 cm diameter and 0.17 cm thick)

The power supply was always operated at 60 Hz, resulting in a total test time of 8.3 minutes for each nominal beam energy measurement. Only the plutonium targets produced measurable spontaneous neutrons. Data from this MDL assessment are presented in Appendix C.

5.2 MDL Calculational Methodology

The determination of an MDL value for a given target and testing configuration was accomplished by multi-step process described in Section 2.2.3. After verification that no neutron emission sources were present in the testing facility, the natural room return signal response with and without the target in place (Measurements #1 and #2) were obtained. Then the specific nominal beam energy operations for a given target were selected. For each selected nominal beam energy operation (with X-rays ON), two tests were required: one showing the "room-only" neutron stimulation (without target) response and the other showing total neutron stimulation (with target) response (Measurements #3 and #4.)

The measured prompt and delayed neutron counts were normalized to the total charge value and the measured dose. For these MDL tests the charge (C) per pulse was determined by graphically integrating the oscilloscope trace of the accelerator pulse width area (current versus time) for each nominal electron beam energy operation. The total charge per test was determined by multiplying the charge per pulse by the total number of accelerator pulses recorded for that test. Equations 1 and 2 show the formulas used to normalize the total background (X-ray ON but no target material; Measurement #3) and the total neutron counts (X-ray ON and target material present; Measurement #4).

$$Bkg_{Ni} = \frac{Bkg_i}{Charge_i * Rad_i} \quad (1)$$

where:

- Bkg_{Ni} = normalized background count for Bkg_i
- Bkg_i = raw background for test i
- $Charge_i$ = total charge for the i^{th} test (C)
- Rad_i = measured radiation dose rate for the i^{th} test (R/min)

$$Counts_{Ni} = \frac{Counts_i}{Charge_i * Rad_i} \quad (2)$$

where: $Counts_{Ni}$ = normalized counts for the i^{th} test
 $Counts_i$ = raw counts for the i^{th} test

Equations 3 and 4, respectively, were used to obtain the mean and standard deviation of the background counts for each nominal electron energy operation.

$$\overline{Bkg}_N = \frac{\sum_{i=1}^n Bkg_{Ni}}{n} \quad (3)$$

where: $\overline{Bkg}_N$ = average normalized background for specific energy
 n = the total number of measurements of background at that energy

$$\sigma_{Bkg_N} = \left(\frac{\sum_{i=1}^n (Bkg_{Ni} - \overline{Bkg}_N)^2}{n - 1} \right)^{1/2} \quad (4)$$

where: σ_{Bkg_N} = the standard deviation of the normalized background at that energy

Equation 5 defines the minimum detectable (normalized) count, $Counts_{Min}$, that is detectable above a two standard deviation (i.e., 95% confidence) average total background. Figure 5.2 shows a graphical representation of this MDL definition.

$$Counts_{min} = 2 * \sigma_{Bkg_N} + \overline{Bkg}_N \quad (5)$$

Figure 5.2. Graphical MDL representation.

As previously indicated, the photon attenuation in the selected target materials is negligible, and hence, the neutron responses are assumed to be linear with respect to the mass of the target material at a specific accelerator energy. This linear relationship is shown in Equation 6. For all MDL tests, the y-intercept (A) was defined as the mean background ($\overline{Bkg}_N$).

$$Counts = A + B * Mass(grams) \quad (6)$$

Finally, using the minimum count response from Equation 5 and the slope (B) determined from Equation 6, the minimum mass of target material which can be detected with the GNT demonstration system is determined as:

$$MDL = \frac{(Counts_{min} - \overline{Bkg}_N)}{B} \quad (7)$$

The numerator of Equation 7 is recognized to be twice the standard deviation of the total background response.

5.3 Results

The MDL methodology described in Section 5.2 was applied to all four target materials with various nominal accelerator energies (2.5 to 7.5 MeV) and testing configurations. Figure 5.3 shows the various target (T_i) and detector ($D_{i,j}$) locations assessed. For any location change of one component (target or detector), the other remained at the nominal one meter position. The 15-degree cone represents the collimator defined angle. The detector positions were selected so as to minimize the direct exposure to the primary X-rays.

5.3.1 Prompt Neutron Response

The typical MDL for prompt neutrons produced by a given material in a fixed target and detector geometry follows a quadratic function versus nominal electron beam energies. Below the photoneutron threshold energy of a target material, the response is not measurable due to insufficient counts. Above 8 MeV, the MDL will increase with increasing beam energy due to the increased background from the neutrons emitted by structural materials.

T = Target positions (T_1 and T_2 at 1 and 2 m from x-ray source)
D = Detector positions
15° angle represents radiation cone defined by tungsten collimator

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Figure 5.3. Various testing configurations.

Table 5.2 presents the measured prompt neutron MDL. An MDL was identified for all target materials tested except for plutonium, which was limited by a maximum available mass of 39 grams.

For the nominal testing configuration ($D_{1,2}$ and T_1 in Figure 5.3), both beryllium and deuterium had prompt MDL of less than 1 gram at a nominal electron

TABLE 5.2. TARGET ELEMENT PROMPT NEUTRON MDL
(Nominal Configuration unless otherwise noted)

<u>Beryllium</u>		<u>Deuterium</u>		<u>Uranium (Nat.)</u>		<u>Plutonium</u>	
Nominal Energy (MeV)	MDL (g)	Nominal Energy (MeV)	MDL (g)	Nominal Energy (MeV)	MDL (g)	Nominal Energy (MeV)	MDL (g)
2.5	1.2	2.5	0.7	6.0	40	6.0	>39
4.5	0.54	4.5	0.1	6.5	44	7.2	>39
6.0	2.2	6.0	0.2	6.5 ²	85	7.2 ¹	26
		7.2	0.4 ¹	7.2 ³	32		
7.5	23.7	7.5	3.5	7.5	103	7.5	>39

- 1) Target-to-detector distance was 2 meters.
- 2) Accelerator-to-target distance was 2 meters.
- 3) Target-to-detector distance was 0.5 meters.

beam energy of approximately 4.5 MeV. Consistent with its photofission/photoneutron threshold of about 6 MeV, the natural uranium target MDL was observed as a broad minimum of about 40-44 g between 6.0 and 6.5 MeV.

5.3.1.1 Accelerator-to-Target Variation. The prompt neutron MDL increases with increasing target-to-X-ray source distance. For a nominal 6.5 MeV operation using the natural uranium target, the prompt response MDL at two meters (T_2 in Figure 5.3) is about twice that at one meter (See Table 6.2).

Using the 2 meters accelerator-to-target and 1.41 m target-to-detector distances, a factor of eight was anticipated based on a basic $1/r^2$ source strength dependence where "r" is distance. Two factors could account for this "lower than expected" MDL with increasing accelerator-to-target position:

- 1) Increasing the target-to-accelerator distance in the MDL test configuration (See Figure 5.1) caused the target to be in closer proximity to the test cell wall. This produced a more intense distributed source of secondary scattered neutrons which would be counted as prompt.
- 2) Increasing accelerator-to-target distance exposed the side of the nominally-positioned detector, and hence, increased the solid angle and net counting response.

Hence, while additional MDL data would be desirable, current results indicate that the accelerator-to-target distance should be minimized for optimal MDL sensitivity.

5.3.1.2 Target-to-Detector Variation. MDL variations from changes in target-to-detector distances were determined for deuterium and plutonium. At 7.5 MeV, the prompt MDL for deuterium is 3.5 g for a nominal one meter target-to-detector distance, and at 2 meters is decreased to 0.4 g at 7.2 MeV. The plutonium prompt MDL also decreased with increasing target-to-detector distance; 32 g at 0.5 m and 26 g at 2 m. This response occurs because the high energy component of the electron beam stimulates neutron production in structural materials, especially the tungsten collimator, increasing the background. As the target-to-detector distance increases, the collimator-to-detector distance increases more, resulting in fewer neutrons from the collimator reaching the detector. Obviously, the prompt MDL must eventually begin to increase with increasing detector-to-target distance. The optimum target-to-detector distance to obtain the lowest MDL has not been determined, but it appears to be greater than the nominal one meter. While not experimentally shown at lower nominal beam energies, similar prompt MDL trends are expected.

5.3.2 Delayed Neutron Response

Delayed neutron MDLs are only applicable to nuclear materials. Delayed neutron response cannot be measured below the nuclear material's photofission threshold energy. The MDL increases with increasing nominal electron beam energy mostly because of the increasing background arising from increased neutron production in structural materials. Table 5.3 presents the MDL obtained from the delayed neutron response of plutonium and natural uranium.

TABLE 5.3. TARGET ELEMENT DELAYED NEUTRON MDL
(Nominal Configuration unless otherwise noted.)

<u>Uranium (Nat.)</u>		<u>Plutonium</u>	
<u>Nominal</u> <u>Energy</u> <u>(MeV)</u>	<u>MDL</u> <u>(g)</u>	<u>Nominal</u> <u>Energy</u> <u>(MeV)</u>	<u>MDL</u> <u>(g)</u>
		0.0	9
6.0	35	6.0	8
6.5	58	7.2	16
6.5 ¹	200	7.2 ²	10
		7.2 ³	>39
		7.5	14

- 1) Accelerator-to-target distance was 2 meters.
- 2) Target-to-detector distance was 0.5 meters.
- 3) Target-to-detector distance was 2 meters.

For the nominal configuration, uranium showed a low 35 g delayed MDL with a 6.0 MeV beam operation and the MDL increased with increasing beam energies as was observed in the prompt MDL response. The delayed MDL response for plutonium suggests that the best detection limit is obtained by measuring its spontaneous emissions directly.

Doubling the accelerator-to-target distance results in a factor of four increase in uranium MDL, as is expected from a simple $1/r^2$ dependence of source strength with distance. Unlike the prompt MDL results, the increase in the uranium delayed MDL is much more pronounced.

The plutonium delayed MDL at 7.2 MeV operation increased with increasing target-to-detector distance (MDL = 10 g at 0.5-m, MDL = 16 g at 1.0-m, and MDL > 39 g at 2-m).

6. SUMMARY

An active photon interrogation system, the Gamma Neutron Technology (GNT) technology, has been developed at the Idaho National Engineering Laboratory to support arms control verification missions. The demonstration system consists of a selective-energy (2-10 MeV), electron-accelerator, a portable tripod-mounted detector assembly, and a portable data acquisition system. The electron accelerator is transportable in a small van and has both beam energy and current measurement capability.

Tests showing operational design performance and beam energy profile measurements have been performed using a commercially available power supply. Prompt and delayed neutron signatures for various non-nuclear and nuclear targets were acquired in less than six minutes with an operational X-ray dose at 1 meter of less than 250 R/min.

A minimum detectible limit assessment has indicated that critical non-nuclear materials can be detected in less than gram quantities for one meter accelerator-to-target distance and one meter target-to-detector distance configuration operating with an approximately 4.5 MeV electron beam energy. A similar one-meter configuration for uranium showed a 40-44 g MDL with an approximately 6.5 MeV electron beam. Prompt neutron results indicate that minimum detectible limits may be enhanced by optimizing this configuration for a given site deployment. Minimum detectible limits for targets with high spontaneous fission rates are not enhanced by active interrogation.

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APPENDIX A

VARITRON Key Design Specifications

Basic electron accelerator design specifications required to meet GNT application requirements.

- 1) The unit must be fully operational and directly compatible with clearly identified and available rent/lease system(s). The rented/leased system should (at a minimum):
 - a) allow full specified operation of the X-ray unit
 - b) be based on S-band RF operation
 - c) be fully transportable (each separate component estimated at < 300 pounds)
 - d) be functional with standard 110 V and 220 V grid power (supplied on-site)
 - e) allow pulse-mode operation
 - f) provide nominal operating conditions: 100 Hz, 10 mA peak current, 3-4 μ s pulse-width
 - g) sustain unattended nominal conditions for at least 20 minutes
 - h) allow for multiple 20 minute operations with operator interaction
 - i) provide performance repeatability
 - j) have safety interlocks to protect system and operating personnel
 - k) allow for operator control at least 30 feet from the X-ray unit.
- 2) The unit must have the capability for tuned operation at any nominal electron energies between 2 and 10 MeV. S-band operation should provide this range capability in a single unit.
- 3) The unit must measure the electron beam energy spread on-site.
- 4) The unit must measure (with $\leq 10\%$ uncertainty) electron beam current onto convertor during operation.
- 5) The minimum average DC electron beam current of 0.5 μ A at all nominal energies.
- 6) The unit must include high-energy X-ray production convertor(s).
- 7) The unit must provide an electron beam spot size of ≤ 0.5 cm in diameter.
- 8) The unit must have the X-ray output beam parallel to the ground.
- 9) The unit must provide biological X-ray shielding (i.e., tungsten collimator) around the convertor equivalent to reducing the perpendicular X-ray dose to less than or equal to one (1) percent of the total forward dose.

APPENDIX B

Electron Bending Magnet Predictions and Field Measurements

The VARITRON electron beam bending magnet was designed to produce a 20-degree deflection of a 10 MeV beam at 1.2 kG. Upon installation of the electron beam bending magnet into the VARITRON, a series of spatial magnetic field measurements (corresponding to the locations shown in Figure B.1) were performed using a Hall probe for a beam axis field of approximately 1 kG. Table B.1 shows the actual field measurements at these locations for an applied magnet current (I_B) of 10.3 A.

To predict the deflection of a given electron beam (kinetic energy) onto the faraday cup probe under the influence of the magnetic field, a numerical model was developed. The model, based on the following equation and a peak-normalized, spatial magnetic field (Table B.1), uses an iterative technique to progressively calculate the deflected electron position as a function of spatial magnetic field. By peak normalizing the spatial field distribution, the distribution becomes proportional to the applied magnet current.

The bending radius (R) of an electron in a pure magnetic field is given by:

$$R = \frac{mv}{qB} = \frac{1}{qB} \frac{\sqrt{K^2 + 2*m_0*c^2*K}}{c}$$

where m_0 = electron rest mass,
 m = relativistic mass of electron,
 q = electron charge,
 v = electron velocity,
 B = magnetic field,
 c = speed of light,
 K = electron kinetic energy, i.e. beam energy.

The following iterative scheme was used to determine the peak magnetic field for a given electron beam energy so that electrons arrive at the faraday cup position. The following procedure is used in the program:

Figure B.1. Top-view of magnetic field measurements along the electron beam centerline (z,y coordinates are in inches).

Note: 1) Row D is the aligned with electron beam centerline (left to right).
 2) Faraday cup (FC) located at z = 13.25" and y = 4.25".
 3) "+" indicates the start of 20-degree line from beam line to faraday cup.

TABLE B.1. MAGNETIC FIELD MEASUREMENTS FOR $B=1$ kG AND $I_B=10.3$ A

Location	z (in)	y (in)	B (G)
A6	5	3	11.0
A7	6	3	9.1
A8	7	3	4.0
A9	8	3	2.2
A10	9	3	1.4
A11	10	3	1.0
A12	11	3	0.7
B1	0	2	728.0
B2	1	2	860.0
B3	2	2	889.0
B4	3	2	864.0
B5	4	2	638.0
B6	5	2	104.0
C1	0	1	810.0
C2	1	1	994.0
C3	2	1	994.0
C4	3	1	995.0
C5	4	1	760.0
C6	5	1	126.0
C7	6	1	11.0
C8	7	1	8.0
C9	8	1	5.5
C10	9	1	1.7
C11	10	1	1.3
C12	11	1	1.2
D1	0	0	845.0
D2	1	0	995.0
D3	2	0	995.0
D4	3	0	994.0
D5	4	0	768.0
D6	5	0	126.0
D7	6	0	11.0
D8	7	0	8.0
D9	8	0	5.4
D10	9	0	1.7
D11	10	0	1.3
D12	11	0	1.2
E1	0	-1	726.0
E2	1	-1	848.0
E3	2	-1	831.0
E4	3	-1	865.0
E5	4	-1	640.0
E6	5	-1	90.0
F6	5	-2	10.5
F7	6	-2	9.0
F8	7	-2	3.2
F9	8	-2	2.0
F10	9	-2	1.4
F11	10	-2	1.2
F12	11	-2	0.8

- 1) For a given electron beam energy and an initially estimated peak magnetic field, determine the initial radius of the circular path at the beam bending entrance (initially $Z = 0$ inch, $Y = 0.0$ inch position). This is performed by spatially interpolating the measured magnetic field profile.
- 2) Determine the center of the corresponding beam radius,
- 3) Impose a small incremental move in the beam direction and calculate the corresponding deflected position on the identified circular path.
- 4) Move the electron to the deflected position and update the magnetic field strength at this position by interpolation.
- 5) Continue this process until $z \geq 13.25$ inch (the z-location of the faraday cup) and obtain the corresponding y-location.
- 6) If electron did not arrive at the faraday cup position ($z = 13.25$ " and $y = 4.25$ "), increment the initially estimated peak magnetic field strength and repeat steps 1 through 5 until the electrons arrive at the cup position.

Additional computer calculations were also performed assuming no fringe field effect and a uniform magnetic field in the gap. The results are summarized in Table B.2 and presented in Figure B.2

TABLE B.2. PEAK MAGNETIC FIELD VERSUS ELECTRON BEAM ENERGY

<u>Electron Beam Energy (MeV)</u>	<u>Magnetic Field (Gauss)</u>	
	<u>Non-Uniform & Fringe</u>	<u>Uniform & No Fringe</u>
9	1028.7	1078.0
8	920.0	964.4
7	811.7	850.6
6	703.0	736.8
5	594.5	622.9
4	485.5	508.8
3	376.2	394.3
2	266.3	279.1

The calculational results for the uniform field support the design specification of the bending magnet (i.e., 10 MeV at 1.2 kG).

Figure B.2. Calculated peak magnetic field versus electron beam kinetic energy to arrive at the faraday cup.

Comparing the peak magnetic field differences between the non-uniform (w/ fringe field) and uniform cases clearly indicates that the fringe field has a greater effect at larger electron kinetic energies; however, this effect is still relatively small (less 5% change) for electron energy less than 10 MeV.

APPENDIX C

MDL Acquired and Supporting Data

This appendix includes the raw and processed data obtained in the minimum detectable limits (MDL) tests and utilizes Figure 5.3.

Table C.1 presents the results supporting the total integrated charge assessment for the MDL tests. The table includes the run identifier (TEST-ID), the corresponding nominal electron beam energy (ENERGY), various per pulse information, and the total accumulated charge (TOTAL CHARGE).

Table C.2 represents the total background response (X-ray On, Without any target materials) for various testing configurations. Included in this table for each corresponding test are identifiers (TEST ID), the accelerator-to-target distance (DIST-1), the target-to-detector distance (DIST-2), the nominal electron beam energy (ENERGY), the total prompt counts (PROMPTS), the total delayed counts (DELAYS), the integrated test dose (DOSE), the total integrated electron beam charge (CHARGE) onto the convertor (from Table D.1), the normalized prompt counts (CTS NORM PROMPTS) and delayed counts (CTS NORM DELAYS), and the mean (MEAN) prompt and delayed counts for each nominal energy.

Tables C.3, C.4, C.5, and C.6 present test data, along with target mass (MASS) and net counts (CTS NET), for beryllium, deuterium as heavy water, natural uranium, and plutonium (mostly Pu-239), respectively.

TABLE C.1. MDL TESTING RESULTS: TOTAL INTEGRATED BEAM CHARGE

ENERGY (MeV)	COULOMB/ PULSE UNIT	PULSE AREA	UNIT AREA	PULSE UNITS	C/Pulse PULSE	CHARGE (C)
2.5	5E-09	1.315	0.6665	1.972993	9.86E-09	0.000296
2.5	5E-09	1.815	0.675	2.688889	1.34E-08	0.000403
2.5	5E-09	1.275	0.677	1.883309	9.42E-09	0.000282
4.5	1E-08	4.72	0.665	7.097744	7.1E-08	0.002129
6	1E-08	5.3	0.6725	7.881041	7.88E-08	0.002364
6	1E-08	5.15	0.6585	7.820805	7.82E-08	0.002346
7.5	1E-08	6.2	0.682	9.090909	9.09E-08	0.002727
7.5	1E-08	6.37	0.6345	10.0394	1E-07	0.003012
7.5	1E-08	6.315	0.667	9.467766	9.47E-08	0.00284
7.2	1E-08	6.035	0.687	8.784571	8.78E-08	0.002635
6.5	1E-08	6.515	0.684	9.524854	9.52E-08	0.002857
6.5	1E-08	6.5	0.6815	9.537784	9.54E-08	0.002861
4.3	1E-08	3.015	0.663	4.547511	4.55E-08	0.001364
6.5	1E-08	6.715	0.6775	9.911439	9.91E-08	0.002973

TABLE C.2. MDL TESTING RESULTS: BACKGROUND DATA

[illegible]

TABLE C.3. MDL TESTING RESULTS: BERYLLIUM DATA

TEST ID	DIST-1 (cm)	DIST-2 (cm)	ENERGY (MeV)	MASS (gm)	PROMPTS (cts)	DOSE (Rads)	CHARGE (C)	CTS NORM (CTS/C/R)	BKG NORM	CTS NET
41BE272.N	100	100	2.5	271.6	354	4.03	0.000289	303948.8	4196.64	299752.1
41BE136.N	100	100	2.5	135.8	191	4.58	0.000284	146841.7	4196.64	142645.1
42BE272.N	100	100	4.5	271.6	13322	151.3	0.00213	41338.14	230.602	41107.53
42BE136.N	100	100	4.5	135.8	7080	155.6	0.00213	21362.11	230.602	21131.5
43BE272.N	100	100	6	271.6	33493	354	0.00237	39921.09	1609.345	38311.75
43BE136.N	100	100	6	135.8	18728	372	0.00237	21242.23	1609.345	19632.89
44BE272.N	100	100	7.5	271.6	80765	823	0.0031	31656.41	9057.052	22599.36
44BE136.N	100	100	7.5	135.8	53519	831	0.0031	20775.2	9057.052	11718.15

TABLE C.4. MDL TESTING RESULTS: HEAVY WATER DATA

TEST ID	DIST-1 (cm)	DIST-2 (cm)	ENERGY (MeV)	MASS (gm)	PROMPTS	DOSE (Rads)	CHARGE (C)	CTS NORM (CNTS/C/R)	BKG.NORM	CTS NET
410246.NN	100	100	2.5	46	37	4.3	0.000285	30191.76	4196.64	25995.12
4102100.N	100	100	2.5	100	91	5	0.000285	63859.65	4196.64	59663.01
4102512.N	100	100	2.5	512	249	4.7	0.000285	185890.3	4196.64	181693.6
420213.NN	100	100	4.5	13.4	1472	148.9	0.00213	4641.234	230.6	4410.634
420246.NN	100	100	4.5	46	4573	151.3	0.00213	14190.01	230.6	13959.41
4202100.N	100	100	4.5	100	9059	150.8	0.00213	28203.26	230.6	27972.66
4202512.N	100	100	4.5	512	36633	154.8	0.00213	111102	230.6	110871.4
430213.NN	100	100	6	13.4	5386	346	0.00235	6624.031	1609.345	5014.686
4302100.N	100	100	6	100	25705	333	0.00235	32847.74	1609.345	31238.4
54023Z.NB	100	200	7.2	3.1	9004	848	0.00263	4037.234	3910.65	126.5837
54023A.NB	100	200	7.2	3.1	9151	842	0.00263	4132.384	3910.65	221.7344
44023.NN	100	100	7.5	3.1	26363	864	0.00273	11176.82	9057.052	2119.773
54023.NN	100	100	7.5	3.1	24726	827	0.00273	10951.81	9057.052	1894.753
440233.NN	100	100	7.5	33	40507	835	0.00273	17769.74	9057.052	8712.683

TABLE C.5. MDL TESTING RESULTS: URANIUM PELLET DATA

TEST ID	DIST-1	DIST-2	ENERGY	MASS	PROMPTS	DELAYS	CHARGE	DOSE	CTS NORM PROMPTS	CTS NORM DELAYS	MEAN BKG PROMPTS	MEAN BKG DELAYS	CTS NET PROMPTS	CTS NET DELAYS
	(cm)	(cm)	(keV)	(gm)	(cts)	(cts)	(C)	(Rads)	(CTS/C/R)	(CTS/C/R)				
43UP49JH	100	100	6	49	1728	54	0.00236	361	2028.2642	63.383257	1609.345	47.95	418.91924	15.433257
43UP99JH	100	100	6	99	1884	56	0.00236	354	2255.0991	67.030547	1609.345	47.95	645.75411	19.080547
43UP148JH	100	100	6	148	2416	75	0.00236	360	2843.6911	88.276836	1609.345	47.95	1234.3461	40.326836
53UP49JH	100	100	6.5	49	4075	91	0.00284	649	2210.877	49.371731	1822	29.51	388.87697	19.861731
53UP49AJH	100	100	6.5	49	4122	81	0.00284	640	2267.8257	44.564261	1822	29.51	445.8257	15.054261
53UP148JH	100	100	6.5	148	5675	140	0.00284	634	3151.7972	77.53588	1822	29.51	1329.7972	48.243588
53UP148AJ	100	100	6.5	148	5310	115	0.00284	628	2977.2585	64.479232	1822	29.51	1155.2585	34.869232
83UP49JH	200	100	6.5	48	3343	49	0.00286	591	1977.8022	28.989623	1915.3	28.92	62.502232	0.0696229
83UP49AJH	200	100	6.5	48	3494	39	0.00286	579	2109.5798	23.551578	1915.3	28.92	194.67983	-5.368422
83UP99JH	200	100	6.5	99	3833	56	0.00286	603	2222.5701	32.471674	1915.3	28.92	307.27013	3.5516743
83UP99AJH	200	100	6.5	99	4070	58	0.00286	609	2336.7437	33.300033	1915.3	28.92	421.44372	4.3800333
83UP148JH	200	100	6.5	148	4463	60	0.00286	611	2553.9927	34.33555	1915.3	28.92	638.69265	5.4155499
83UP148AJ	200	100	6.5	148	4084	57	0.00286	595	2399.953	33.495916	1915.3	28.92	484.65299	4.5759158
54UP49JH	100	100	7.2	49	15912	129	0.00263	824	7542.4637	59.526007	7347.143	46.87	-4.679269	12.556007
54UP49AJH	100	100	7.2	49	16543	116	0.00263	834	7542.1032	52.885448	7347.143	46.87	194.9602	6.0154483
54UP99JH	100	100	7.2	99	18414	137	0.00263	838	8355.0369	62.161402	7347.143	46.87	1007.8939	15.291402
54UP99AJH	100	100	7.2	99	19328	179	0.00263	839	8759.2961	81.121378	7347.143	46.87	1412.1531	34.251378
54UP148JH	100	100	7.2	148	20147	251	0.00263	840	9119.5908	113.61579	7347.143	46.87	1772.4478	66.745789
54UP148AJ	100	100	7.2	148	21046	196	0.00263	850	9414.4487	87.676135	7347.143	46.87	2067.3057	40.806135
44UP49JH	100	100	7.5	49	24850	134	0.00273	834	10914.345	85.854016	9057.052	38.93	1857.2934	19.924016
44UP99JH	100	100	7.5	99	26469	182	0.00273	834	11625.425	79.936051	9057.052	38.93	2568.3729	41.006051
44UP148JH	100	100	7.5	148	28201	202	0.00273	848	12181.647	87.255512	9057.052	38.93	3124.595	48.325512

TABLE C.6 MDL TESTING RESULTS: PLUTONIUM FOIL DATA

TEST ID	DIST-1	DIST-2	ENERGY	MASS	PROMPTS	DELAYS	DOSE	CHARGE	CTS NORM PROMPTS	CTS NORM DELAYS	MEAN BKG PROMPTS	MEAN BKG DELAYS	CTS NET PROMPTS	CTS NET DELAYS
	(cm)	(cm)	(keV)	(gm)	(cts)	(cts)	(R)	(C)	(CTS/C/R)	(CTS/C/R)				
40PU39JH	100	100	0	39	7	62	0	0	7	62	62	36	-55	26
40PU28JH	100	100	0	28	8	62	0	0	8	62	62	36	-54	26
50PU39JH	100	100	0	39	3	62	0	0	3	62	62	36	-59	26
50PU39ZJH	100	100	0	39	6	70	0	0	6	70	70	36	-64	34
50PU39ZJH	100	50	0	39	15	155	0	0	15	155	155	36	-140	119
43PU39JH	100	100	6	39	1620	79	356	0.00237	1920.0683	93.632959	1609.345	47.95	310.72327	45.682959
43PU28JH	100	100	6	28	1624	62	359	0.00237	1908.7244	72.870021	1609.345	47.95	299.37942	24.920021
54PU39ZJH	100	100	7.2	39	16752	160	837	0.00264	7581.1882	72.408675	7347.143	46.87	234.04523	25.538675
54PU39AJH	100	100	7.2	39	18016	149	846	0.00264	8066.4804	66.713232	7347.143	46.87	719.33741	19.843232
54PU31ZJH	100	100	7.2	31	19047	147	846	0.00264	8528.1002	65.817752	7347.143	46.87	1180.9572	18.947752
54PU31AJH	100	100	7.2	31	18842	154	844	0.00264	8456.3048	69.115324	7347.143	46.87	1109.1618	22.245324
54PU19ZJH	100	100	7.2	19	18676	146	869	0.00264	8140.6702	63.639851	7347.143	46.87	795.52722	16.769851
54PU19AJH	100	100	7.2	19	18182	133	862	0.00264	7989.6998	58.444069	7347.143	46.87	642.55678	11.574069
54PU39ZJH	100	50	7.2	39	34184	281	837	0.00264	15470.113	127.16773	13566.1	50.16	1904.0133	77.007735
54PU39AJH	100	50	7.2	39	33938	300	841	0.00263	15343.856	135.63429	13566.1	50.16	1777.7555	85.474294
54PU19ZJH	100	50	7.2	19	28985	191	844	0.00263	13057.953	86.046889	13566.1	50.16	-508.1467	35.886889
54PU19AJH	100	50	7.2	19	32044	221	860	0.00263	14167.477	97.709789	13566.1	50.16	601.37723	47.549789
54PU39ZJH	100	200	7.2	39	9040	112	849	0.00263	4048.6011	50.15966	3910.65	52.56	137.95113	-2.40034
54PU39AJH	100	200	7.2	39	9143	137	839	0.00263	4143.535	62.087312	3910.65	52.56	232.88499	9.527312
44PU39JH	100	100	7.5	39	25463	144	842	0.00273	11077.323	62.645193	9057.052	38.93	2020.2713	23.715193
44PU28JH	100	100	7.5	28	26325	135	860	0.00273	11212.625	57.500639	9057.052	38.93	2155.5726	18.570639
44PU14JH	100	100	7.5	14	24859	156	858	0.00284	10201.829	64.020487	9057.052	38.93	1144.7767	25.090487

DOE-HQ

C. M. Makris
M. F. O'Connell

DOE-ID

J. H. Nadler
J. D. Barrett, III
M. S. Pellechi
D. Majumdar

INEL

M. D. Anderson
S. J. Fernandez
J. L. Jones
Y. D. Harker
W. Y. Yoon
J. M. Hoggan
G. J. McManus
K. D. Watts
D. W. Nigg
H. E. Mitchell
J. W. Mandler
D. L. Hagrman

ISU

J. F. Harmon
A. G. Stephens

MIT

Xiao-Lin Zhon, 24-215A

LANL

Yi-Fen Yen, MS H846
M. W. Johnson, J-562

HESCO

W. A. Johnson

Varian Associates

B. Meyer