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Electron Linear Accelerator
as a Neutron Camera*

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Richard E. Morgado

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ABSTRACT

We present the results of a literature search into the present state-of-the-art techniques in producing, moderating, collimating, and imaging thermal neutrons, with an emphasis on radiographic diagnosis. The portable linear accelerator source we describe compares favorably with commercially available laboratory facilities for neutron production, while surpassing existing sources in portability.

I. INTRODUCTION

A portable, pulsed-neutron beam for neutron radiography, derived from a low-energy electron accelerator of modest size and cost, is an attractive prospect for the nondestructive testing community. The portable electron linear accelerator (LINAC) developed for x-radiography in the field is capable of delivering a moderately intense neutron beam by photoneutron production from low-Z targets. Besides providing portability and on/off capability, the LINAC also circumvents licensing problems common to reactor sources. Additional characteristics desirable in a neutron camera include a useful thermal neutron flux ($\sim 1 \times 10^6$ n/cm²-s); a low gamma-ray background ($\sim 10^5$ n/cm²-s-mR); reasonably short exposure times; large useful area coverage (~ 25 cm by 25 cm); and low angular divergence. Because not all of these characteristics can be met with the LINAC described here, compromises must be found. One possible solution is to design a target and a moderating and collimating assembly with good beam thermalization and emittance in a module of modest size. A versatile design that allows tradeoffs in intensity, resolution, and beam area would suit a variety of field applications.

The diagnostic information contained in a thermal neutron radiograph complements x-radiographic information. Thermal-neutron-absorption cross sections vary approximately in an inverse manner to x-ray attenuation coefficients as a function of atomic number; therefore, image information not readily obtained from one modality may be derived from the other.

In addition, thermal neutrons can also distinguish between isotopes of certain high-Z elements.

Radiographic imaging of neutrons is achieved either with film and converter foils positioned directly in the beam or indirectly by transferring the image from an activated foil to film. Recent developments include position-sensitive neutron detectors with a resolution and detection efficiency that may also be suitable.

II. LINAC DESIGN SPECIFICATIONS

The objective was to design and produce a modular, portable device with an x-radiographic capability equal to a laboratory facility (see Fig. 1). The bremsstrahlung source is a pulsed, variable-energy, standing-wave, S-band LINAC, whose instantaneous dose rate allows flash radiography in the single-pulse mode. The available electron energies produce thick-target bremsstrahlung spectra, which can be used in a variety of assaying techniques. These include (1) direct photofission in a selectable energy range over which cross-section differences between fissionable materials are maxima; and (2) prompt neutron activation and neutron-induced fission resulting from photo-produced neutrons from low-Z targets. Table I gives the basic operating parameters.

Fig. 1. Photograph of the accelerator waveguide and associated modules.

TABLE I
LINAC PARAMETERS

Attribute	Value
Electron beam energy	6, 8, and 10 MeV
Peak beam current	100 mA
Average beam current	30 μ A
Maximum duty factor	3×10^{-4}
X-ray output (R/min in air at 1 m)	600 at 8 MeV
Macro pulse length	4 μ s
Pulse repetition rate	10 to 120 Hz
Average beam power	300 W
Microwave power	Magnetron, 2998 MHz, 2.4 MW peak
Focal spot size	2.0 mm
Dose/pulse (maximum)	0.1 R at 1 m in air
Target material	0.5 radiation lengths of tungsten
Estimated peak neutrons/s (from ^9Be)	3.0×10^{10}
Peak neutrons/s (from deuterium)	5.3×10^{10}
Total weight	1000 lb, 7 modules

The primary electron beam is inaccessible, and the useful photon beam emerges from the wave-guide assembly as a thick-target bremsstrahlung spectrum. Initially, the beam is uncollimated and unflattened, so that its cross-sectional area and intensity distribution are determined by the electron beam energy and the distance from the target to the point of interest. Beam-flattening and collimation may be added to improve x-radiography, but with an accompanying reduction in intensity. We assume that these radiographic appendages can be dismounted to let the unmodified, full-intensity, bremsstrahlung beam emerge. This beam is used as a starting point to assess the LINAC's potential as a neutron camera.

III. BREMSSTRAHLUNG SPECTRA

Thick-target bremsstrahlung spectra are carefully measured¹ and calculated for our energies-of-interest.^{2,3} Bremsstrahlung conversion efficiencies (that is, electron energy in, divided into photon energy out) in the energies-of-interest achieve maxima for target thicknesses between 0.4 and 0.5 times the mean range of the incident electrons² (see Fig. 2). For 10-MeV electrons on tungsten, this maximum efficiency is 10%. The 10-MeV thick-target bremsstrahlung spectrum is shown in Fig. 3.

Fig. 2. Bremsstrahlung efficiency for monoenergetic electron beams incident perpendicularly on tungsten targets.

Photoneutrons are also produced in the tungsten target, but the high threshold energy (7.4 MeV) and low atomic cross section render this component negligible for this discussion. We will disregard both these neutrons and the neutrons produced directly by electrons and assume that the maximum thick-target bremsstrahlung efficiency in tungsten is achieved.

A 10-MeV thick-target bremsstrahlung beam has an opening cone half-angle of 10° . We assume that all the photons will strike the adjacent, large photoneutron target.

IV. NEUTRON PHOTOPRODUCTION TARGET

Efficient photoproduction of neutrons at low energies requires the bremsstrahlung beam to impinge on a material with a low photoproduction threshold, a large photonuclear cross section, and/or a small atomic cross section. The average photon energy of a 10-MeV thick-target bremsstrahlung beam is approximately 2.5 MeV, which limits target materials

Fig. 3. Measured bremsstrahlung energy spectra.

to either ${}^9\text{Be}$ or ${}^2\text{H}$ (deuterium) with 1.67- and 2.26-MeV thresholds, respectively. Although deuterium has the larger cross section by a factor of 2, ${}^9\text{Be}$ is the more desirable material, because it melts at 1285°C and has excellent thermal conductivity, negligible activation, low cost, and machinability.

Despite a small photonuclear cross section, neutron yields comparable to high-energy (>30 MeV) beams on heavy metals are predicted for low-energy beams on low- Z targets.⁴ When target length is not a problem, as in the present situation, it can be increased to one atomic mean-free path because the atomic cross sections are similarly small. Unlike x-radiography, which requires a small source size for good resolution, the diffusive nature of the thermalization process negates any attempt to achieve a point source. Instead, the effective spot size is determined by the collimator length (L) and aperture (D) that form the collimating assembly. For ${}^9\text{Be}$, the (γ, n) cross section is approximately 1 mb (Fig. 4), whereas the atomic cross section is 0.35 b. The neutron yield depends more on the reduced attenuation of x rays than it does on the (γ, n) cross section. Consequently, neutron yields comparable to high-energy electrons on high- Z targets are possible. For the purpose of this exercise, we assume a ${}^9\text{Be}$ of ample dimension (an advantage, because ${}^9\text{Be}$ is also a good moderator) bombarded by a thick-target bremsstrahlung spectrum that, in turn, was produced by 30 μA of 10-MeV electrons on tungsten.

Fig. 4. Low-energy photonuclear cross sections for deuterium and beryllium.

V. NEUTRON YIELD

We can determine the neutron yield per electron when the bremsstrahlung efficiency, target thickness, and (γ, n) cross section are folded together. The best estimates in the literature at 10 MeV are 10^9 n/ μ A/s (Figs. 5 and 6). Therefore, the 30- μ A average current on the proposed LINAC would produce 3×10^{10} neutrons into 4π for ${}^9\text{Be}$. We can approximate spectral shape and average neutron energy from data measured at 27-MeV electron energy,⁵ unfolded, and normalized to a 10-MeV spectrum (Fig. 7). The calculated average neutron energy is 1 MeV.

Fig. 5. Graph of neutron yield/electron energy.

Fig. 6. Neutron production efficiency for various target materials. The number of neutrons produced per 1000 MeV of electron energy is shown as a function of the electron beam energy for various target materials. A target thick enough to attenuate 5-MeV gamma rays by a factor of 11e is assumed. The dashed line is the efficiency for 100-MeV electrons on tungsten. Note that no significant gain in efficiency is obtained for an electron energy greater than 10 MeV (Ref. 4)

Fig. 7. The ${}^9\text{Be}(\gamma, n)$ yield for thick-target bremsstrahlung from $E=10$ MeV, assuming 100% ground-state transitions.

For purposes of neutron radiography, the neutrons must be thermalized (~ 0.025 eV) by multiple collisions with a hydrogenous moderating assembly. Thermal neutrons have a high probability of interaction, making them easier to detect and contrast against surrounding material. The thermal neutron content of the moderated beam can be varied for different applications and penetrations. The design and construction of an efficient and compact moderating assembly is the most serious challenge to the efficacy of the mobile LINAC as a neutron camera.

VI. MODERATOR AND COLLIMATING ASSEMBLY

The literature contains several designs for moderating and collimating assemblies designed around accelerator⁶⁻⁸ and radioisotopic⁹ sources. An optimized system requires detailed transport and diffusion calculations with various materials, geometries, and collimator designs. The object is to produce the largest thermal flux with a low gamma-ray contamination in a minimum-sized moderator. The need for low gamma-ray contamination may be difficult to achieve in the high gamma-ray field of an electron accelerator. Several collimator assemblies may be required for different situations that require either high spatial resolution or reduced exposure times.

The moderating assembly consists of dense polyethylene surrounded by a fast-neutron reflector and a thermal neutron absorber. Polyethylene minimizes the size while providing stability and ease of fabrication. The hydrogen in polyethylene causes a neutron to lose, on the average, 1/e of its kinetic energy per collision, while presenting a small capture cross section to fast neutrons. The fast-neutron reflector is a thin, lead sheet that serves as a (n,2n) multiplier. The thermal neutron absorber is a thin sheet of cadmium for removing the uncollimated flux.

The collimating assembly defines the thermalized neutron flux emit-tance. Detailed transport calculations determine the optimized point at which the collimator is inserted into the moderating assembly, because the flux is extremely sensitive to this perturbation. Care must be taken to minimize the primary-, scattered-, and capture-gamma-ray back-ground contamination. The collimator entrance should be inserted into the moderator volume at the location of the peak thermal neutron flux.

The collimator is characterized by its length (L) from the source to the film plane and the source-opening diameter (D). A geometric unsharpness, U_g , grows with reduced L/D and as the distance from the object to the film increases. Typical L/D values range from 10 to 100. The collimator, like the moderator assembly, should be composed of lead and cadmium.

The thermalization factor K, defined as

$$K = \frac{\text{Total Fast Neutron Yield}}{\text{Peak Thermal Flux}}$$

depends upon both the design and materials of the moderator and the average energy of the fast-neutron flux. A crude extrapolation of K for our moderator assembly of ~33 can be based on values in the literature^{8,9} for a ²⁵²Cf source with an average neutron energy of 2.3 MeV and a Van de Graaff source at 5 MeV. This yields a thermal flux of 9×10^8 n/cm²-s for the mobile LINAC as a conservative estimate. The flux is consistent with the requirements for practical direct and indirect radiography.

The effect of collimation on the output thermal flux at the radiographic image plane is expressed by¹⁰

$$\Phi = \Phi_0 \frac{D^2}{16L^2} ,$$

where

Φ - thermal flux at the image plane,

Φ_0 - peak thermal flux in the moderator,

D - collimator entrance aperture, and

L - collimator length.

Table II lists the predicted LINAC outputs of thermal neutrons for a range of collimation ratios.

The need for portability requires that the moderating assembly be no larger than any one component of the LINAC assembly. The present design limits this value to 200 lb or an 18-in. cube of polyethylene (which could adversely affect the thermalization factor). Figure 8 shows the schematic of a moderator assembly.¹¹

TABLE II
NEUTRON FLUX FOR SEVERAL COLLIMATION RATIOS

<u>L/D</u>	<u>$\Phi(n/cm^2-s)$</u>
1	5.7×10^7
10	5.7×10^5
20	1.4×10^5
40	3.6×10^4
100	5.7×10^3

Fig. 8. Target, moderator, and collimator schematic.

VII. PRACTICAL NEUTRON RADIOGRAPHY

A. Fluence

For radiographic quality (1.8 film density), the minimum thermal neutron fluence at the converter is 1.6×10^7 n/cm². For an L/D of 10, we anticipate 5.7×10^5 n/cm²-s; therefore, a direct converter film exposure requires less than 1 min. For transfer radiography with an indium foil, 4×10^5 n/cm²-s gives exposure and transfer times of several hours. Faster x-ray film can be used for indirect exposures, which reduces the exposure and transfer time to less than 1 h.

B. Cadmium Ratio

The cadmium ratio, which is the ratio of the count rate of a bare fission chamber to the count rate of a cadmium-covered fusion chamber, measures the thermal content of the moderated beam. The bare count rate measures both the thermal and epithermal components, whereas the cadmium-covered rate measures the epithermal content. The standard value of the cadmium ratio for good quality radiography is 18 or larger. Careful design of the moderator and collimator, using Los Alamos neutron transport codes, suggests how to vary the thermal neutron yield for different applications.

C. Gamma-Ray Background

In the thermalized neutron beam, the gamma-ray component is an undesirable background that must be reduced for direct high-quality neutron radiography. This also requires careful design of the moderating and collimating assembly, making additional gamma-ray shielding (bismuth) necessary. An acceptable minimum neutron-to-gamma-ray background is 10^5 n/cm²-mR, which is the equivalent amount of each type of radiation necessary to produce a comparable film exposure. High-Z filtration reduces the gamma-ray background while minimally reducing the thermal neutron flux. If the gamma-ray field is part of the object being radiographed, gamma-ray insensitive detection techniques are required.

D. Neutron Spectrum

The moderated spectrum with the highest thermal component is generally the most useful. For thick objects, however, a deeper penetration of the epithermal component may be preferred. This suggests that an adjustable moderator design would allow the selection of the neutron spectrum to be more useful over a range of thicknesses.

E. Beam Geometry

Ideally, a diverging beam from a point source will enable coverage of large areas; however, thick objects produce images that are not sharp. Resolution will vary inversely as the L/D ratio, and the correct selection of beam-geometry parameters will depend on the situation. In some cases, resolution may not be as important as contrast between different high-Z components and between hydrogenous materials. Once a useful camera has been designed, techniques will have to be developed to establish the empirical limits of useful application, as is done with x-radiography.

VIII. IMAGING SYSTEMS

Photographic and nonphotographic imaging systems are applicable to neutrons. Most systems have been designed around reactor sources because reactors have been the only viable source of neutrons up to the present. Several imaging methods are briefly described here.

A. Direct Method

Film-foil converter imaging can be achieved by direct prompt emission or by delayed transfer of activation products. The direct method is preferred when the gamma-ray background is below the film fogging level. Then gadolinium foil (1.5 to 25 μ) is the converter of choice because it has the largest thermal-neutron-absorption cross section and the largest low-energy (70 keV) beta-conversion radiation. This allows the shortest exposure times with good resolution from the short-range beta particles.

B. Transfer Method

The transfer method is necessary in high gamma-ray backgrounds or when the object is highly radioactive. This method requires a converter material with a sufficiently long half-life for the induced radioactive products of neutron absorption. Indium is preferred for its cost and convenient half-life (54 min), although samarium, dysprosium, and gold are also used. Reasonable exposure times require neutron fluences higher than the direct method. Table III lists the properties of the converters relevant to neutron radiography.

TABLE III

PROPERTIES OF TYPICAL THERMAL NEUTRON RADIOGRAPHY DETECTION CONVERTERS

<u>Material</u>	<u>Useful Reactions</u>	<u>Cross Section for Thermal Neutrons (b)</u>	<u>Half-Life</u>
Lithium	${}^6\text{Li}(n, \alpha){}^3\text{He}$	910	Prompt
Boron	${}^{10}\text{B}(n, \alpha){}^7\text{Li}$	3 830	Prompt
Rhodium	${}^{103}\text{Rh}(n, \gamma){}^{104\text{m}}\text{Rh}$	11	4.5 min
	${}^{103}\text{Rh}(n, \gamma){}^{104}\text{Rh}$	139	42 s
Silver	${}^{107}\text{Ag}(n, \gamma){}^{108}\text{Ag}$	35	2.3 min
	${}^{109}\text{Ag}(n, \gamma){}^{110}\text{Ag}$	91	24 s
Cadmium	${}^{113}\text{Cd}(n, \gamma){}^{114}\text{Cd}$	20 000	Prompt
Indium	${}^{115}\text{In}(n, \gamma){}^{116\text{m}}\text{In}$	157	54 min
	${}^{115}\text{In}(n, \gamma){}^{116}\text{In}$	42	14 s
Samarium	${}^{149}\text{Sm}(n, \gamma){}^{150}\text{Sm}$	41 000	Prompt
	${}^{152}\text{Sm}(n, \gamma){}^{153}\text{Sm}$	210	47 h
Gadolinium	${}^{155}\text{Gd}(n, \gamma){}^{156}\text{Gd}$	61 000	Prompt
	${}^{157}\text{Gd}(n, \gamma){}^{158}\text{Gd}$	254 000	Prompt
Dysprosium	${}^{164}\text{Dy}(n, \gamma){}^{165\text{m}}\text{Dy}$	2 200	1.25 min
	${}^{164}\text{Dy}(n, \gamma){}^{165}\text{Dy}$	800	140 min
Gold	${}^{197}\text{Au}(n, \gamma){}^{198}\text{Au}$	98.8	2.7 days

Converter-film combinations for the two techniques have been developed to a high degree by personnel working in nondestructive testing, where reactors or radioactive sources are used as neutron cameras. The techniques have been applied to the inspection of jet engines; composite materials; electronic components; lubrication of critical components; metal-jacketed explosive devices (in which light material must be imaged within heavy materials); and corrosion inspection (in which hydrogen-containing substances are imaged).

C. Position-Sensitive Neutron Detectors

More recently, multiwire proportional chambers (MWPCs) with high-pressure (5 atm) ^3He have been developed to image neutrons for biology.^{12, 13} High detection efficiencies (~90%) and good resolution (~1 mm) have been achieved. Nonpressurized, converter foil-wire chamber combinations have also been investigated.^{14, 15} Pressurized systems have limited the active area and are difficult to construct, whereas nonpressurized devices have poor resolution and low detection efficiency. They could also provide near real-time imaging as the two-dimensional detected neutron coordinates are displayed on a computer terminal while the data are recorded.

D. Neutron Scintillators and Image Intensifiers

Markedly reduced exposure times are achieved when (n, α) material is mixed with a phosphor, such as zinc sulfide. Approximately 1 s with the mobile LINAC produces an exposure on fast x-ray film. A neutron scintillator can also be optically coupled to an image-intensifier tube and an inexpensive vidicon. However, normal television frame rates (30 frames/s) for motion detection require thermal intensities of 10^6 to 10^7 n/cm²-s.

IX. APPLICATIONS

The neutron radiography described in the literature has involved high spatial resolutions comparable to x rays. This demands a well-collimated beam with small angular divergence that, in turn, requires a high initial neutron flux. As a result, attention has focused primarily on reactor sources for the required intensities of thermalized neutrons. However, radioactive (γ, n) , (α, n) , and spontaneous fission sources have short half-lives, high gamma-ray backgrounds, and low intensities (10^4 n/cm²-s-Ci). Positive ion accelerators have been considered, but cost, bulk, complexity, and high-peak neutron energy have discouraged investigations. Recent developments of radio-frequency quadrupole (RFQ) accelerators may overcome these difficulties. Other neutron sources⁶⁻⁸ at electron energies ≤ 5.5 MeV are the electron accelerators, such as the linear and Van de Graaff¹⁶ accelerators. Their potential has long been recognized¹⁰ despite their relatively low intensities (8×10^4 n/cm²-s) and high gamma-ray backgrounds. Neutron yield, however, increases dramatically with electron energy between 5 and 10 MeV (Fig. 2).

The mobile LINAC overcomes objections for bulkiness and complexity as a natural result of the original design specifications (Fig. 9). The thermal neutron flux, crudely estimated here for the mobile machine, is comparable to laboratory facilities, with the exception of a reactor. The mobile accelerator exceeds the capacity of the only portable device (a 16000-lb ^{252}Cf source multiplier) in flux, portability, safety, and flexibility.

The advantages of neutron radiography are derived from the thermal neutron characteristics of being able to distinguish between

- low-Z elements (H, Li, B, Cd) in assemblies with high-Z elements (hydrides in metal);
- neighboring elements in the periodic table;
- isotopes of high-Z materials; and
- objects in high gamma-ray fields.

Fig. 9. Portable 10-MeV LINAC.

However, the above situations cannot be addressed by x-radiography. Figure 10 demonstrates the differences of the mass-absorption coefficients across the periodic table between thermal neutrons and x rays. Even more dramatic are the differences that occur between uranium and plutonium and their respective isotopes (Table IV).

Fig. 10. Mass absorption coefficients for neutrons and x rays (Ref. 11).

TABLE IV

THERMAL NEUTRON CROSS SECTIONS FOR PLUTONIUM AND URANIUM ISOTOPES

Isotope	Thermal Cross Section (b)
Uranium (natural abundance)	≈ 16
²³³ U	581
²³⁴ U	105
²³⁶ U	7
²³⁷ U	---
²³⁸ U	11.1
²³⁹ U	14
²³⁹ Pu	1026
²⁴⁰ Pu	295
²⁴¹ Pu	1400
²⁴² Pu	30

A simple calculation illustrates the basis for distinguishing between neighboring elements on the periodic table and between isotopes of the same element. Consider an amorphous object composed of ^{238}U and a fissionable material, either ^{235}U or ^{239}Pu . We can determine the relative transmitted intensity of thermal neutrons per unit thickness in grams per square centimeter as the following:

$$\frac{I}{I_0} = \exp\left(-\frac{N\sigma_t}{\rho} x\right), \quad (2)$$

where

I/I_0 = fractional-transmitted-intensity per g/cm^2 ,

N = atoms/ cm^3 = $N_0\rho/A$,

ρ = density (g/cm^3),

N_0 = Avogadro's number,

A = atomic weight,

σ_t = total thermal neutron cross section (absorption + scatter),
and

x = g/cm^2 .

Substituting the appropriate values from Table IV in Eq. (2) gives

<u>Isotope</u>	<u>I/I_0</u>
^{238}U	0.97
^{235}U	0.17
^{239}Pu	0.08

A similar calculation with gamma-ray mass-absorption coefficients results in identical opacities for all components. If the assembly is imbedded in a relatively thick compound containing low-Z material with a large thermal-neutron-absorption cross section, additional information is required from a gamma-ray radiograph. The information in either radiograph greatly enhances the information provided by the other.

Neutron radiography in a high gamma-ray field requires either the transfer method or a gamma-ray-insensitive imaging system. The gamma-ray field can be reduced to a useful level through shielding with a corresponding reduction in neutron flux. The transfer method is feasible

at our estimated intensity, but it requires more time to process than direct methods. Position-sensitive gaseous detectors have a high gamma-ray insensitivity and may be useful in this situation.

Radiographing materials that are highly opaque to thermal neutrons (such as low-Z or thick, high-Z materials) may be improved by using the epithermal component in a moderated beam: the increased penetration is substantial, and the attenuation differences are not overly reduced.

X. CONCLUSIONS

The combination of materials and thickness used in preceding examples has been selected for illustrative purposes. Real situations will involve thicker samples in arrangements that sometimes may not be appropriate to neutron investigation; a similar statement can be made about x rays. However, the examples demonstrate dramatically the contrasting capability of thermal neutrons.

Intense, well-collimated beams with high thermal content and low gamma-ray background, although ideal, may not necessarily provide useful information in field applications. When dimensional accuracy is not essential, but time and the determination of material composition and relative size are, beam geometry can be sacrificed for beam intensity.

The limitations of the mobile LINAC for neutron radiography include

- marginal intensity for high-resolution, high-contrast radiography;
- possibly high background gamma-ray contamination;
- limited depth of penetration;
- a small cross-sectional area of beam; and
- an additional moderator and collimator module to reduce portability.

The above limitations have all been addressed and tentative solutions have been suggested. Failure to overcome one or two limitations would not necessarily undermine the overall effectiveness of the LINAC. However, the capability already exists in the machine, and we would be remiss not to investigate the possibilities.

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