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EVALUATION OF PHOTONEUTRON PRODUCTION AT HIGH ENERGY LINACS

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Evaluation of Photoneutron Production at High Energy LINACS

Executive Summary

This report describes an estimate of neutron production at a 9 MeV LINAC, and the potential for photoactivation of materials present at the LINAC facility. It was found that only isotopes of U, W, Ta, and Pb had daughters whose activities might be measurable. The LINAC was found to be capable of producing in the neighborhood of 10^{10} neutrons/second from these heavy metals, and that subsequent neutron activation might be more of a concern. Monte Carlo simulation of neutron transport and capture in the concrete and steel found in the LINAC vault indicates that ^{55}Fe may be produced in measurable quantities.

Introduction

Photoneutron production is the well known phenomenon in which one or more neutrons are emitted by a nucleus subsequent to the absorption of a high energy x or gamma ray. Neutron production at a LINAC (or any x ray source) occurs when the bremsstrahlung beam from the converter within the accelerator head is incident on materials in which the threshold for the (γ, n) reaction is lower than energy of the electron beam. Although photoneutron cross sections are not large, the tremendous number of photons available from a high-energy bremsstrahlung source makes the process quite productive. With proper selection of neutron target material and beam current, a 9 MeV electron beam may be expected to produce 10^{10} neutrons/second with energies ranging from thermal to a few MeV.

Artificial radioactivity is induced in the neutron target material because of the loss of one or more neutrons from otherwise stable species. For example, natural Pb consists of the isotopes ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb . Clearly only the first two isotopes are of significance because ^{203}Pb , and ^{205}Pb are unstable, and photoneutron production would create radioactivity where there was none before. In contrast to this, however, in the cases of elements with no stable isotopes (such as U), photoneutron production would simply add to the natural activity of the material. Detectability then becomes a problem of finding the additional activity in the presence of a large natural background.

In this study, photoneutron production at a 9 MeV electron LINAC was estimated. From a list of photoneutron thresholds of all known isotopes, those with energy less than 9 MeV were selected. From those, only isotopes considered likely or known to be found at the LINAC were investigated. The bremsstrahlung spectrum per electron was estimated and then scaled by the known beam current of the accelerator. Photoneutron cross sections were obtained from the scientific literature and they and the bremsstrahlung spectrum were used to calculate the photoneutron production.

In the remainder of this report, the bremsstrahlung spectrum, photoneutron cross sections, and computer code used to fold them together are described. The resulting photoproduction rates,

integrated over all possible neutron energies, are given for the candidate isotopes. Tables of cross section parameters and thresholds are found in the appendix.

Bremsstrahlung Spectrum

The bremsstrahlung spectrum was estimated with results generated by researchers at the Tomsk Polytechnic University, Tomsk Russia¹. Using a Monte Carlo code, they calculated the thick target bremsstrahlung yield by following electrons, with incident energies from 4.0 to 10.0 MeV, as they were stopped in a tungsten block. The code also followed created photons as they traversed the block and accumulated the number of photons exiting the block in a cone with opening angle of 20°. Absorption in the exit window of the accelerator head was taken into account. Table 1 shows the data, per incident electron, for a 9 MeV beam. The table begins at 1.5 MeV because the lowest photoneutron threshold is 1.67 MeV in Be.

Table 1. Photons per incident electron per MeV

Photon Energy Bin (MeV)	dN/dE (10 ⁻⁴ /MeV)
1.50 - 2.00	154.0
2.00 - 2.50	123.0
2.50 - 3.00	92.4
3.00 - 3.50	70.5
3.50 - 4.00	57.3
4.00 - 4.50	44.9
4.50 - 5.00	37.4
5.00 - 5.50	21.4
5.50 - 6.00	24.8
6.00 - 6.50	21.0
6.50 - 7.00	16.2
7.00 - 7.50	12.8
7.50 - 8.00	10.1
8.00 - 8.50	5.64
8.50 - 8.75	2.96
8.75 - 9.00	1.01

Photoneutron Thresholds

Photoneutron thresholds were obtained from the publicly accessible database at the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. A table of the data, sorted by threshold energy, can be found in the appendix. Only those isotopes whose threshold is below 9 MeV are listed.

Isotope Selection

There are 157 isotopes for which the (γ, n) threshold lies between 2 and 9 MeV. Of these, many, like ^{57}Fe , result in a stable daughter. Others result in a daughter that either instantaneously (as is the case with $^9\text{Be}(\gamma, n)^8\text{Be}$, $^8\text{Be} \rightarrow 2\alpha$) or with short half-life (few days, such as $^{204}\text{Pb}(\gamma, n)^{203}\text{Pb}$, $^{203}\text{Pb} \rightarrow ^{203}\text{Tl}$) decays into stable granddaughters. These materials do not lead to measurable radioactivity and were not considered further.

A search of a list of isotopes with thresholds below 9 MeV was conducted to discover those that would lead to radioactive daughters with half-lives longer than a few days. Those daughters with shorter half-lives are not important because their rapid decay renders them harmless in short order. Isotopes (such as rare earth elements) were also discarded if there was no reason to believe they were present at the LINAC in any significant quantity. Similarly, isotopes not commonly found in structural materials were ignored. These considerations and interviews with LINAC personnel culled the list to Pb, Ta, W, and U. Of these, only ^{206}Pb , ^{180}Ta , ^{186}W , ^{182}W , ^{238}U , ^{235}U , and ^{234}U lead to important daughters.

Table 2. Isotopes of importance

Parent	Threshold	Daughter	Half-Life
^{238}U	6.152	^{237}U	6.75 days
^{235}U	5.298	^{234}U	245,000 yrs
^{234}U	6.844	^{233}U	159,000 yrs
^{206}Pb	8.088	^{205}Pb	15.1×10^6 yrs
^{186}W	7.194	^{185}W	75 days
^{182}W	8.064	^{181}W	121 days
^{180}Ta	6.645	^{179}Ta	1.8 yrs

Photoneutron Cross Sections

Photoneutron cross sections were obtained from the Atlas of Photoneutron Cross Sections². This work is a compilation of over 200 measurements performed on dozens of isotopes. The data are presented as graphs of cross section as a function of photon energy superimposed on Lorentzian fits. (The Lorentzian shape of the cross section is predicted by the liquid drop model of the nucleus.) The parameters of Lorentzian curves are tabulated separately in the Atlas.

In the cases of ^{182}W and ^{180}Ta cross section data are unavailable. For these the parameterization for the natural material was used. This approach is justified on the basis of the mechanism of photonuclear reactions.

In heavy nuclei, photoneutron production proceeds through a two step process. First the photon is absorbed, and a short-lived (picoseconds to femtoseconds) excited state of the parent nucleus is formed. This state has an excitation energy well above photoneutron threshold. While this state lives, energy is shared among the nucleons until one or more nucleons are able to escape. Because of the number of nucleons in a heavy nucleus, such as W or Ta, each nucleon sees an average potential due to the strong nuclear force from every other nucleon. Since this average potential cannot be strongly affected by the presence or absence of a few particles, the probability of nucleon emission is similarly not a strong function of the number of nucleons. Consequently, the cross section does not vary tremendously from isotope to isotope. Therefore a measurement of the ^{nat}W cross section will be very close to the actual cross section for the individual isotopes. A glance at the table in the Atlas bears this argument out.

Photoproduction

The equation that governs the buildup of a radioactive species contains a term that accounts for the production of the species and a term that accounts for its decay. In the infinite dilution, model, the production term neglects the loss of source material. That is, it is assumed either that there is an infinite supply of source material or that the depletion of the source is negligible. The latter, is tantamount to assuming that the product of irradiating flux, production cross section, and irradiation time is small (compared to unity). If the infinite dilution model is inappropriate, then the buildup equation must be solved with a time-dependent production term. This can be much more difficult. In this section, the production term will be evaluated, and the implications of the data in Tables 1 and 2 will be considered.

Consider a block of material, as shown in Figure 1, with a depth and time dependent density of target atoms given by $\rho(z,t)$, presenting area A to a photon flux Φ_0 . In addition, assume that the material is characterized by a linear attenuation coefficient, μ , that is not affected by photoproduction.

Figure 1. Geometry of photoactivation

The flux reaching a slice of thickness dz located at depth z is then independent of time and given by

$$\Phi(z, t) = \Phi(z) = \Phi_0 e^{-\mu z} \quad (1)$$

If dN represents the number of target nuclei in the slice, the photoproduction, dP , in the slice is given by

$$dP = -\frac{\partial}{\partial t}(\rho(z, t)A dz) = \Phi_0 e^{-\mu z} \sigma_\gamma \rho(z, t)A dz \quad (2)$$

and is just the time rate of change of the number of target atoms in the slice, dN . σ_γ is the photoneutron cross section of the material. Solving Equation 2 yields the density of target atoms as a function of depth and time.

$$\rho(z, t) = \rho(z, 0) e^{-\Phi_0 \sigma_\gamma t e^{-\mu z}} \quad (3)$$

Since $\rho(z, 0)$ is just the density of the block prior to irradiation, it is just a constant, ρ .

The total production in the block is obtained by integrating Equation 3 over the volume of the block. That is,

$$P = \Phi_0 \sigma_\gamma \rho A \int_0^Z e^{-\mu z} e^{-\Phi_0 \sigma_\gamma t e^{-\mu z}} dz \quad (4)$$

Equation 4 is easily solved by changing variables to $u = -\Phi_0\sigma_\gamma te^{-\mu z}$. Total photoproduction is then given by

$$P = \frac{\rho A}{\mu t} [e^{-\Phi_0\sigma_\gamma te^{-\mu z}} - e^{-\Phi_0\sigma_\gamma t}] \quad (5)$$

where Z is the thickness of the block and t is the irradiation time. It remains now to determine the values of the exponents in Equation 5, especially $\Phi_0\sigma_\gamma t$.

If Φ_0 and/or σ_γ are functions of photon energy (as they are in this problem) then $\Phi_0\sigma_\gamma$ should be replaced by

$$\Phi_0\sigma_\gamma \rightarrow \int \frac{d\Phi_0(E_\gamma)}{dE_\gamma} \sigma_\gamma(E_\gamma) dE_\gamma \quad (6)$$

where the integration is carried out from threshold to the maximum photon energy of interest. The data of Table 1, therefore, were combined with the parameterizations in the Atlas according to equation 6 with a numerical integration program, YIELD (listing can be found in the Appendix). The results are given in Table 3, below.

Table 3. Integrated $\Phi_0\sigma_\gamma$

Parent	$\Phi_0\sigma_\gamma$ (10^{-4} barns/e $^-$)
^{238}U	1.64
^{235}U	1.84
^{234}U	0.87
^{206}Pb	0.128
$^{\text{nat}}\text{W}$	0.31
^{180}Ta	0.45

No allowance has been made here for isotopic abundance. Note that ^{238}U and ^{235}U have the highest flux-cross section products. This is because of the low photoneutron thresholds of these isotopes coupled with the weighting of the bremsstrahlung spectrum to low energy. Most of the neutrons from these isotopes will have low energy.

The cases of W and Ta need some explanation. Since cross section data was not available for all the isotopes of interest, some approximations were necessary. In the case of W, the parameters from the Atlas for the natural mixture was used and the threshold was calculated as the naturally

weighted average of the various W isotopes. In the case of Ta, the parameters for ^{181}Ta were used with the threshold for ^{180}Ta . No significant effects are expected because of these approximations.

The desired exponent in Equation 5 can now be calculated from the flux-cross section integral. Given that the average LINAC current is 0.1 mA, and the area of the photon beam is 976 cm^2 at 1 meter from the exit window of the accelerator, it is only necessary to multiply the values in Table 3 by $(0.0001 \text{ coul/sec} \times 6.25 \times 10^{18} \text{ e}^-/\text{coul} / 976 \times 10^{24} \text{ barns})$ to have $\Phi_0\sigma_\gamma$ in units of inverse seconds.

Table 4. Integrated $\Phi_0\sigma_\gamma$

Parent	$\Phi_0\sigma_\gamma (10^{-17} \text{ s}^{-1})$
^{238}U	10.5
^{235}U	11.8
^{234}U	5.57
^{206}Pb	0.819
$^{\text{nat}}\text{W}$	1.98
^{180}Ta	2.88

From this table it is seen that even for irradiation times of 10 years (approximately 3.15×10^8 seconds), the exponents in Equation 5 are vanishingly small. In the limit as $\Phi_0\sigma_\gamma t \rightarrow 0$, equation 5 becomes

$$P = (\Phi_0 A) \frac{\sigma_\gamma}{\sigma_T} (1 - e^{-\mu Z}) \quad (7)$$

where σ_T is the total photoabsorption cross section (including non-nuclear processes). Note that this result does not depend on time, and is just the infinite dilution model corrected for absorption in the block. Production may be considered to occur at the constant rate given by Equation 7.

The terms in this last result have simple interpretations. $\Phi_0 A$ is the number of photons per second incident on a block of area A. σ_γ/σ_T is the probability of a photonuclear reaction given that some photon interaction occurs. $1 - e^{-\mu Z}$ is just the probability of a photon interaction somewhere in an absorbing block of thickness Z.

Buildup Equation and Expected Yields

The buildup of a radioactive species is governed by the difference between a production term and the radioactive decay, as shown in Equation 8.

$$\frac{dn}{dt} = fP - \lambda n \quad (8)$$

where f is the isotopic abundance of the parent, P is the production rate due to irradiation of the parent, and λ is the decay constant of the product.

Since the program YIELD calculates $\Phi_0 A \sigma_\gamma$ (because Φ_0 is expressed in photons/e⁻) integrated from threshold to 9 MeV, it remains only to account for the total photon interaction cross section and the absorption in the block. The latter may be considered complete because materials, such as heavy metals, used for collimation are 2 to 4 mean free paths thick.

Examination of tables of photon cross sections³ indicates that the absorption cross section is not a strong function of energy over the energy range of interest (5 to 9 MeV). In this interval, pair production is rising while Compton scattering and photoelectric absorption are falling, making the sum approximately constant. The rise of the photonuclear cross section, being only at most 1% of the total, does not significantly affect the total cross section.

Assuming complete absorption, and using an average total cross section, the following production rates are calculated from the data in Table 4.

Table 5. Production Rates

Parent	f	Production Rate (s ⁻¹)
²³⁸ U (DU)	0.998	5.7×10^9
²³⁵ U (DU)	0.002	1.28×10^7
²³⁴ U (DU)	10^{-5}	2.99×10^4
²⁰⁶ Pb	0.241	1.21×10^8
^{nat} W	1.0	1.45×10^9
¹⁸⁰ Ta	0.00012	2.58×10^5

The production rate in Table 5 includes the isotopic abundance factor, f . The isotopic abundances of the U isotopes are for depleted uranium (DU).

The solution of Equation 8 for the radioactivity of the product after a time t is easily found to be

$$\lambda n = fP(1 - e^{-\lambda t}) = fP(1 - 2^{-t/t_{1/2}}) \quad (9)$$

Table 6 summarizes the solution in Equation 9 for the various products after 10 years of continuous irradiation.

Table 6. Induced Radioactivity

Product	$t_{1/2}$	Activity (Bq)
^{237}U (DU)	6.75 d	5.7×10^9
^{234}U (DU)	245,000 y	362
^{233}U (DU)	159,000 y	1.30
^{205}Pb	15.1×10^6 y	55.5
^{185}W	75 d	4.15×10^8
^{181}W	121 d	3.81×10^8
^{179}Ta	1.8 y	3.03×10^4

These activities can be expressed as activity per unit mass of material. The block of material used in this computation is 17.63 cm in radius (corresponding to a radiation cone with an opening angle of 20 degrees), 5 cm thick. The volume of this block is 4882 cc.

Table 7. Induced Radioactivity per Unit Mass

Product	Induced (pC/gm)	Natural (pC/gm)
^{237}U (DU)	1.64×10^6	4.12×10^5 (DU)
^{234}U (DU)	0.104	4190 (^{234}U)
^{233}U (DU)	3.73×10^{-4}	4.12×10^5 (DU)
^{205}Pb	0.272	
^{185}W	1.24×10^5	
^{181}W	1.09×10^5	
^{179}Ta	10.1	

This table shows the activity levels expressed as pC/gm of block immediately after irradiation. Although there is considerable ^{237}U activity, it is only a factor of 4 larger than the naturally occurring activity. After 90 days, the level falls to 158 pC/gm, and after 180 days, 0.0154 pC/gm. Even after 90 days, the ^{237}U level would be lost in the natural activity of DU. The induced activities of ^{233}U and excess ^{234}U are obviously undetectable among the naturally occurring uranium activity. As an aside, LINAC personnel⁴ had observed the temporary increase in activity level due to ^{237}U immediately after irradiations.

^{205}Pb is not naturally occurring, but would probably not be detected at the level quoted above with a simple beta/gamma survey meter. This isotope decays by electron capture and produces an x ray that is very close in energy to the x ray induced naturally in lead bricks by cosmic rays and the small amount of ^{210}Pb that is usually found in the bricks. The level of ^{179}Ta would probably be noticeable to a survey meter, but the induced activity is clearly small on a per gram basis.

The tungsten isotopes, however, present an obvious problem. They have long half-lives and would require years of storage to decay to undetectable levels. However, in actual collimators, tungsten occurs as inserts that intercept no more than 8% of the beam area⁵. Consequently, tungsten activities should be reduced by a factor of 12.

The question of LINAC duty factor has not yet been considered. LINAC personnel⁶ have indicated that although the machines are capable of round-the-clock operation, the usual practice has been to use them for approximately 1.5 hours each day. This would reduce the production term and the activity levels by a factor of 0.0625. In addition, the LINAC was placed, on average, approximately 4 meters from the collimator, rather than 1 meter. This contributes an additional factor of 0.0625, thus reducing the activities by an overall factor of 0.0039. Table 8 shows the restated figures (including the factor of 12 for tungsten).

Table 8. Induced Radioactivity

Product	$t_{1/2}$	Activity (Bq)	Induced (pC/gm)	Natural (pC/gm)
^{237}U (DU)	6.75 d	2.23×10^7	6.38×10^3	4.12×10^5 (DU)
^{234}U (DU)	245,000 y	1.41	4.06×10^{-4}	4190 (^{234}U)
^{233}U (DU)	159,000 y	0.005	1.46×10^{-6}	4.12×10^5 (DU)
^{205}Pb	15.1×10^6 y	0.217	1.06×10^{-3}	
^{185}W	75 d	1.35×10^5	40.4	
^{181}W	121 d	1.24×10^5	35.5	
^{179}Ta	1.8 y	118	0.039	

Note that the activities for U, Pb, and Ta are calculated for solid blocks of the material 35 cm in diameter and 5 cm thick. The activities for W are calculated for solid blocks 10 cm in diameter, 5 cm thick.

Neutron Capture

The production rates in Table 5 indicate that a 9 MeV LINAC is potentially as prolific a generator of neutrons as is a D-T tube. Assuming that to be true, it is worthwhile to consider the ramifications of neutron capture in the concrete walls of the room and in the collimator support fixturing. A Monte Carlo simulation of neutron transport was performed to determine the probability of neutron capture in various materials in the LINAC vault.

The vault was modeled as a 20 m long by 10 meter wide by 10 meter high room (inside dimensions) with 3 m thick concrete walls, floor, and ceiling. The neutron source was taken to be a 0.5 m square by 5 cm thick solid depleted uranium block. Neutrons were originated uniformly within the volume of the block.

It was observed at the vault that the uranium collimator was situated in a steel and aluminum fixture. For the purposes of this simulation, the exact dimensions are not critical and the fixture was approximated to be a steel base plate, four steel support pipes (at the corners of the base plate), an aluminum table, and an aluminum cap plate, all centered on the floor. The base plate was 120 cm square by 15 cm thick. Each support pipe was 182.5 cm long, 10 cm inside diameter, with 1 cm wall. The uranium block rested on a 2.54 cm thick aluminum slab, 140 cm above the center of the floor. The cap plate was 2.54 cm thick, with its top surface being 2 m above the center of the floor. The geometry of the fixture is shown in Figure 2.

Concrete was found to account for 94% of the captures. This, of course, occurs because of the massive amount of the material in the simulation. Of all the isotopes present in concrete, only the 5 shown in Table 9 are of concern because they lead to moderately long-lived daughters.

Table 9. Isotopes of interest in concrete.

Parent	Daughter	Half-life
³⁹ K	³⁶ Cl	3×10^5 y
⁴⁰ Ca	⁴¹ Ca	10^5 y
⁴⁴ Ca	⁴⁵ Ca	162.7 d
⁵⁴ Fe	⁵⁵ Fe	2.7 y
⁵⁸ Fe	⁵⁹ Fe	44.5 d

Figure 2. Geometry of Fixture

Equation 9, above applies equally well to buildup by neutron capture as well as to buildup by photoproduction. The only change is the meaning of the factor f . In the case of neutron capture, this factor accounts for the probability of absorption by the specific isotope. That is, f is the product of the isotopic abundance of the specific isotope, its thermal neutron capture cross (assuming that most captures are due to thermalized neutrons), and the probability of absorption by the natural species, divided by the thermal capture cross section of the natural material.

$$f = \frac{A \cdot \sigma_{\gamma} \cdot W}{\sigma} \quad (10)$$

where σ_{γ} is the capture cross section of the isotope, σ is the capture cross section of the natural material, W is the probability of capture in the natural, and A is the isotopic abundance of the

isotope. The factor W was calculated with the Monte Carlo code MCNP, and the remaining factors were taken from Nuclides and Isotopes, 14th Edition⁷.

For a source strength of 10^{10} neutrons/second, and irradiation time of 10 years, the expected activities, in all the concrete (1.17×10^4 metric tons), found from equations 9 and 10 is shown in Table 10.

Table 10. Buildup in concrete.

Daughter	Activity (Bq)	Activity (pC/gm)
³⁶ Cl	51.7	1.19×10^{-7}
⁴¹ Ca	4.66×10^4	1.08×10^{-4}
⁴⁵ Ca	2.96×10^7	0.0683
⁵⁵ Fe	4.78×10^7	0.110
⁵⁹ Fe	1.28×10^6	2.95×10^{-3}

These levels are negligible.

A similar analysis can be done for the fixture and baseplate. In these cases only iron isotopes are important, since the half-life of ²⁸Al is only 2.24 minutes. The mass of the support columns and base plate are 1.98×10^5 and 1.70×10^6 grams, respectively. The buildup in these structures is shown in Tables 11 and 12.

Table 11. Buildup in steel columns.

Daughter	Activity (Bq)	Activity (pC/gm)
⁵⁵ Fe	7.78×10^5	106.1
⁵⁹ Fe	1.92×10^4	2.62

Table 12. Buildup in steel base plate.

Daughter	Activity (Bq)	Activity (pC/gm)
⁵⁵ Fe	2.70×10^6	42.9
⁵⁹ Fe	6.68×10^4	1.06

Per gram activities here are significantly larger than in the concrete because of the proximity of the structures to the source and their smaller mass than the concrete. However, it should be remembered that the under "average" operating conditions the LINAC was placed approximately 4 meters away from the collimator and operated only 1.5 hours per day. Thus, all figures in Tables 10 through 12 reasonably may be divided by a factor of 256. This puts the highest induced activity of ^{55}Fe at approximately 0.41 pC/gm.

Conclusions and Recommendations

In conclusion, uranium removed from a 9 MeV LINAC should be checked for ^{237}U activity. It is a beta/gamma emitter with easily recognized gamma rays. It would also make its presence known because its activity would decay with a 6.75 day half-life. In addition tungsten and tantalum should also be checked, although tantalum is probably of only minor concern. Lead need only be checked if it comes from a 9 MeV machine since its threshold is just above 8 MeV.

From the point of view of photoactivation, tungsten presents the gravest problem. The isotopes have moderately long half-lives and photoproduction is fairly efficient in this material. However, all may not yet be lost. The results in Table 7, since they are calculated for 10 years' continuous irradiation of a solid block, undoubtedly overstate the induced activity. Table 8 shows that although the tungsten activity would be measurable, even taking geometry, and duty factor into account, the activity per gram of material would remain small.

Of a greater concern may be the neutron production itself from the LINAC. These devices can represent sources as strong as 10^{10} neutrons/second and undoubtedly cause radioactivity in their surroundings by neutron capture. A Monte Carlo analysis of neutron capture in steel and aluminum structures near the LINAC indicates that the material of interest is iron because of the production of ^{55}Fe . The greatest production (on a per gram basis) occurs in the steel members in the fixture holding the collimator. Depending on LINAC operating conditions, up to 100 pC/gm of ^{55}Fe might be produced. However, when duty factor and geometry are taken into account, a more likely figure is closer to 0.4 pC/gm. Therefore, it is recommended that steel in a high energy (>7 MeV) LINAC be surveyed for ^{55}Fe . Since the most activation would occur close to the collimator, steel from collimator supports is a reasonable place to start. If activation were not found there, it is almost certain that activation would not be measurable in materials situated at a larger distance from the collimator.

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Appendix

Photoneutron Thresholds Sorted by Threshold Energy

The following table lists isotopes and photoneutron thresholds sorted by threshold energy for all naturally occurring isotopes with threshold energy below 9 MeV. The data were obtained from the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. The number of significant digits quoted for the threshold energy is identical to what is quoted by NNDC.

Isotope	Threshold
9Be	1.665300
2H	2.224570
17O	4.143330
13C	4.946311
235U	5.297840
239Pu	5.646500
6Li	5.660000
145Nd	5.755500
149Sm	5.871600
189Os	5.920600
179Hf	6.099030
195Pt	6.105060
143Nd	6.123590
238U	6.152000
183W	6.190700
201Hg	6.230200
163Dy	6.270930
176Lu	6.287980
187Os	6.292600
147Sm	6.342000
157Gd	6.360050
173Yb	6.367600
177Hf	6.378800
226Ra	6.396000
155Gd	6.435100
167Er	6.436100
232Th	6.438100
161Dy	6.454360
119Sn	6.485200
113Cd	6.540200
125Te	6.575900
131Xe	6.605200
171Yb	6.614800
180Ta	6.645000
199Hg	6.664000
207Pb	6.737790
21Ne	6.761110
73Ge	6.782900
101Ru	6.802100
97Mo	6.821100

234U	6.843700
176Yb	6.864200
137Ba	6.905760
129Xe	6.907600
123Te	6.939400
117Sn	6.944500
135Ba	6.971970
111Cd	6.975840
67Zn	7.052200
105Pd	7.094100
142Ce	7.168900
186W	7.194300
91Zr	7.194600
7Li	7.249960
170Er	7.258800
25Mg	7.330670
148Nd	7.332900
187Re	7.359500
208Pb	7.367820
95Mo	7.369060
150Nd	7.380000
180Hf	7.388200
184W	7.411700
77Se	7.418810
160Gd	7.451400
209Bi	7.459800
99Ru	7.464000
83Kr	7.464000
174Yb	7.464600
138La	7.470000
204Hg	7.495000
115Sn	7.545700
205Tl	7.546400
198Pt	7.557000
192Os	7.558000
146Nd	7.565250
181Ta	7.577000
178Hf	7.626300
57Fe	7.646030
164Dy	7.658080
175Lu	7.666700
185Re	7.669000
202Hg	7.754310
168Er	7.771100
193Ir	7.771850
190Os	7.791600
40K	7.799500
144Nd	7.817020
61Ni	7.820040
203Tl	7.849000
96Zr	7.854000

196Pt	7.921880
43Ca	7.933000
151Eu	7.934000
158Gd	7.937330
53Cr	7.939170
154Sm	7.967600
150Sm	7.985700
165Ho	7.988800
188Os	7.989300
172Yb	8.019700
200Hg	8.028300
169Tm	8.033400
18O	8.044400
136Xe	8.060000
182W	8.064000
191Ir	8.070000
197Au	8.071000
206Pb	8.088100
159Tb	8.133900
148Sm	8.141500
49Ti	8.142360
176Hf	8.165400
162Dy	8.196950
94Zr	8.220000
152Sm	8.257600
186Os	8.262000
100Mo	8.289000
194Pt	8.370400
204Pb	8.395000
180W	8.412000
130Te	8.419000
87Sr	8.428120
10B	8.436300
170Yb	8.470000
29Si	8.473560
166Er	8.474400
198Hg	8.484000
124Sn	8.489000
156Gd	8.536370
134Xe	8.548000
153Eu	8.550280
160Dy	8.576100
152Gd	8.589000
138Ba	8.611720
92Zr	8.634800
174Hf	8.640000
33S	8.641580
98Mo	8.642500
184Os	8.650000
192Pt	8.676000
116Cd	8.700200

128Te	8.775000
139La	8.778000
122Sn	8.814400
110Pd	8.818000
93Nb	8.831000
196Hg	8.840000
164Er	8.846000
47Ti	8.877700
154Gd	8.895300
104Ru	8.904000
190Pt	8.911000
132Xe	8.936000
99Tc	8.967000
123Sb	8.969300
133Cs	8.986800

Photoneutron Cross Section Parameters

The following Lorentz parameters are taken from Reference 2.

Isotope	E_1 (MeV)	σ_1 (mb)	Γ_1 (MeV)	E_2 (MeV)	σ_2 (mb)	Γ_2 (MeV)
^{238}U	10.77	311	2.37	13.80	459	5.13
^{235}U	10.90	328	2.30	13.96	459	4.75
^{234}U	11.13	371	2.26	13.94	401	4.46
^{206}Pb	13.59	514	3.85			
$^{\text{nat}}\text{W}$	12.56	268	2.66	15.17	328	4.69
^{181}Ta	12.30	259	2.43	15.23	341	4.48

Cross sections were parameterized as

$$\sigma(E_\gamma) = \sum_{i=1}^2 \frac{\sigma_i}{1 + \left[\frac{E_\gamma^2 - E_i^2}{E_\gamma \Gamma_i} \right]^2}$$

Pb only has a single set of parameters because it is a spherical nucleus. The other isotopes, having ellipsoidally shaped nuclei, exhibit a splitting of the photoneutron cross section corresponding to vibrations along the principal axes of the nuclear ellipsoid.

The parameters for ^{181}Ta were used in calculations for ^{180}Ta because no data for ^{180}Ta is available. However, it is evident from the table that the Lorentz parameters vary only slowly with the number of nucleons. Consequently, the results should not be strongly affected by this substitution. The actual threshold for ^{180}Ta was used in all calculations.

Computer Program YIELD

The computer program YIELD was written to perform the numerical integration of the data in Tables 1 and 2 from threshold to 9 MeV. The data of Table 1 was used as provided; the cross section data was integrated over the bins of Table 1 and multiplied by bremsstrahlung data. YIELD accumulated the sum of such products. The code was written in the C language.

```
#include <math.h>
#include <stdio.h>
#include <stdlib.h>

struct lorentz {
    double e ;
    double sigma ;
    double gamma ;
} ;

typedef struct lorentz LORENTZ ;

double lorntz(double eg, LORENTZ *l) {
    return (l->sigma/(1.0 + pow((pow(eg, 2.0) - pow(l->e, 2.0))/
        (eg * l->gamma), 2.0))) ;
}

double avglor(double e1, double e2, LORENTZ *l) { /* average value of */
    return ((lorntz(e1, l) + lorntz(e2, l) + /* lorentzian by */
        4.0 * lorntz(0.5*(e1+e2), l))/6.0) ; /* simpson's rule */
}

main() {
    int i, i0 ;
    int npts ;
    LORENTZ lorentz ;
    double phisig, t ;
    FILE *ptr ;
    char fname[81] ;
    double *eg, *brems ;
    double *deg ;
```

```

printf("\nBrems file name: "); /* get brems data */
scanf("%s", fname);
ptr = fopen(fname, "r");
fscanf(ptr, "%d", &npts);
eg = (double *)malloc(npts * sizeof(*eg));
deg = (double *)malloc(npts * sizeof(*deg));
brems = (double *)malloc(npts * sizeof(*brems));
for(i = 0 ; i < npts ; i++) fscanf(ptr, "%le %le", eg + i, brems + i);
fclose(ptr);

npts--; /* one less bin than points */
for(i = 0 ; i < npts ; i++) deg[i] = eg[i+1] - eg[i]; /* bin widths */

printf("\nE1, sigma1, gamma1: "); /* get lorentz parameters */
while(scanf("%le %le %le", &(lorentz.e),
            &(lorentz.sigma),
            &(lorentz.gamma)) != EOF) {
    printf("\nThreshold: ");
    scanf("%le", &t);
    for(i0 = 0 ; eg[i0] < t ; i0++) /* find first interval above threshold */
        phisig = brems[i0-1] * (eg[i0] - t) *
            avglor(t, eg[i0], &lorentz); /* adjust for short interval */
    for(i = i0 ; i < npts ; i++) phisig += (brems[i] * deg[i] *
            avglor(eg[i], eg[i+1], &lorentz));
    printf("\nE2, sigma2, gamma2: ");
    if (scanf("%le %le %le", &(lorentz.e),
            &(lorentz.sigma),
            &(lorentz.gamma)) != EOF) {
        phisig += (brems[i0-1] * (eg[i0] - t) *
            avglor(t, eg[i0], &lorentz)); /* adjust for short interval */
        for(i = i0 ; i < npts ; i++) phisig += (brems[i] * deg[i] *
            avglor(eg[i], eg[i+1], &lorentz));
    }
    printf("\nIntegral of phi*sigma = %g\nE1, sigma1, gamma1: ", phisig);
}
free(eg);
free(deg);
free(brems);
}

```

The following is the bremsstrahlung data file used by YIELD.

```

38
.5000E-01 .273E-03
.5800E-01 .109E-01
.5900E-01 .159E-02
.6700E-01 .125E-01
.6800E-01 .327E-02
.6950E-01 .154E-02
.8000E-01 .546E-02
.1000E+00 .124E-01
.1250E+00 .222E-01
.1500E+00 .409E-01
.1750E+00 .504E-01
.2000E+00 .548E-01
.2500E+00 .572E-01
.3000E+00 .549E-01
.3500E+00 .529E-01
.4000E+00 .444E-01
.5000E+00 .382E-01
.6000E+00 .310E-01
.8000E+00 .231E-01
.1000E+01 .178E-01
.1250E+01 .167E-01
.1500E+01 .154E-01
.2000E+01 .123E-01
.2500E+01 .924E-02
.3000E+01 .705E-02
.3500E+01 .573E-02
.4000E+01 .449E-02
.4500E+01 .374E-02
.5000E+01 .314E-02
.5500E+01 .248E-02
.6000E+01 .210E-02
.6500E+01 .162E-02
.7000E+01 .128E-02
.7500E+01 .101E-02
.8000E+01 .564E-03
.8500E+01 .296E-03
.8750E+01 .101E-03
.9000E+01 0.0

```

MCNP Input File for Activation Calculation

```

9 MeV LINAC U photoneutron source in 20 m by 10 m by 10 m room
1 1 -2.505 1 -2 5 -8 9 -12 $ concrete walls
2 1 -2.505 3 -4 5 -8 9 -12
3 1 -2.505 2 -3 5 -6 9 -12
4 1 -2.505 2 -3 7 -8 9 -12
5 1 -2.505 2 -3 6 -7 9 -10

```

```

6      1  -2.505      2  -3      6  -7  11 -12
C
7      3  -19.3      13 -14  15 -16  17 -18      $ U block
C
8      2  -7.860      2 -19  31 -32  33 -34      $ Steel base plate
9      5  -2.70      21 -22  31 -32  33 -34      $ Al top plate
10     5  -2.70      20 -13  35 -36  37 -38      $ Al table
12     2  -7.860      19 -21  23 -24      $ leg 1
13     4  -0.00129  19 -21 -23
14     2  -7.860      19 -21  25 -26      $ leg 2
15     4  -0.00129  19 -21 -25
16     2  -7.860      19 -21  27 -28      $ leg 3
17     4  -0.00129  19 -21 -27
18     2  -7.860      19 -21  29 -30      $ leg 4
19     4  -0.00129  19 -21 -29
C
11     4  -0.00129  2  -3      6  -7  10 -11  24  26  28  30 #7 #8 #9
                                     #10 $ air
20     4  -0.00129  22  -3 -24
21     4  -0.00129  22  -3 -26
22     4  -0.00129  22  -3 -28
23     4  -0.00129  22  -3 -30
C
24     0              -1 : 4 : -5 : 8 : -9 : 12      $ end of the world

1      pz  -800.00      $ room/concrete
2      pz  -500.00
3      pz   500.00
4      pz   800.00
5      px -1300.00
6      px -1000.00
7      px  1000.00
8      px  1300.00
9      py  -800.00
10     py  -500.00
11     py   500.00
12     py   800.00
C
13     pz  -360.00      $ U block
14     pz  -310.00
15     px   -2.54
16     px    2.54
17     py  -25.00
18     py   25.00
C
19     pz  -485.00
20     pz  -362.54
21     pz  -302.54
22     pz  -300.00
C
23     c/z  54.00  54.00  5.0  $ leg 1

```

```

24  c/z  54.00  54.00  6.0
C
25  c/z -54.00  54.00  5.0  $ leg 2
26  c/z -54.00  54.00  6.0
C
27  c/z -54.00 -54.00  5.0  $ leg 3
28  c/z -54.00 -54.00  6.0
C
29  c/z  54.00 -54.00  5.0  $ leg 4
30  c/z  54.00 -54.00  6.0
C
31  px   -60.00
32  px    60.00
33  py   -60.00
34  py    60.00
C
35  px   -45.00
36  px    45.00
37  py   -45.00
38  py    45.00

m1    1001 -0.004532  $ concrete
      8016 -0.512597
      11023 -0.011553
      12000 -0.003666
      13027 -0.035548
      14000 -0.360364
      19000 -0.014219
      20000 -0.043546
      26000 -0.013775
m2    26000 -0.985      $ cold-rolled steel
      6012 -0.015
m3    92238  99.799990  $ DU
      92235   0.2
      92234  0.000010
m4    7014 -0.78      $ air
      8016 -0.21
      18000 -0.01
m5    13027  1.0      $ Al
sdef x d1 y d2 z d3 erg d4      $ photoneutron source in U block
si1      -2.54      2.54
sp1       0.00      1.00
si2     -25.00     25.00
sp2       0.00      1.00
si3    -360.00   -310.00
sp3       0.00      1.00
si4   0.0 0.348 0.848 1.348 1.848 2.348 2.598 2.848
sp4   0.0 2.347075e-02 2.601437e-02 2.360182e-02 2.157045e-02
1.411117e-02
      4.405434e-03 1.651954e-03
imp:n  1 22r 0

```

NPS 250000
PHYS:N 20.0 20.0
PRINT

Distribution:

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