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Efficiency of Xenon Ionization Chambers
from 10 to 80 keV

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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by
Peter B. Lyons

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EFFICIENCY OF XENON IONIZATION CHAMBERS FROM 10 - 80 keV

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ABSTRACT

The efficiency of a xenon ionization chamber for x rays in the 10 to 80 keV energy range is discussed. A chamber with gas pathlength of 33.7cm with a fill pressure of 48 psia is considered. Theoretical calculations are presented of the major energy loss mechanisms for such a chamber. Chamber efficiencies exceeding 92% are obtained below 35 keV. In the 35 to 80 keV range, efficiencies are between 60 and 80%.

1. Introduction

Previous studies have dealt with possible deviations from unit efficiency for the "small" xenon ionization chambers. These "small" chambers have gas path lengths of 8 - 10 cm and are maintained at pressures slightly above ambient. Such chambers maintain high absorption efficiency (> 99%) below 10 keV, and are subject to small ($\leq 2\%$) energy loss mechanisms. The work on these chambers was summarized in a recent report¹.

A second class of xenon chamber, the "large" chamber, is discussed in this report. Cross sectional dimensions of the chamber under consideration are given in Figure 1. Gas pathlength is 33.7 cm and xenon fill pressure is 48 psia.

This report will adopt symbols identical to those of Ref. 1. Calculations of certain loss mechanisms will be presented for energies up to 80 keV. The approximations used for the small chambers are not appropriate for the much larger losses studied herein.

11. Energy Fluence Rate Determination

Equation 9 of Ref. 1 is numerically correct for the small xenon chambers, but the increased losses of the large chambers invalidate this equation. The previous form was

$$\Psi = I \bar{W} / A \epsilon T (I - f) \quad (1)$$

whereas the general form, correct for all chambers is

$$\Psi = I \bar{W} / AT (\epsilon - f) \quad (2)$$

For ϵ near 1 and $f \ll 1$, as is true for the small chambers below 15 keV, Eq. 1 $\approx$ Eq. 2. Eq. 2 must be used for the large chambers.

The loss correction f calculated in this report is given by

$$f = f_e + f_s + f_L + f_k \doteq f_e + f_s + f'_L + f_k \quad (3)$$

where f_k is the correction for loss of xenon K X rays. Since escape of L X rays to the plates is of negligible significance, $f_L \doteq f'_L$.

Below 6 keV, $f_s \doteq f'_s$ was used. Both f'_L and f'_s are pressure independent.

III. Calculation of f_k .

The general equation used for this loss mechanism was

$$f_k(E) = \frac{\omega_k}{E} \frac{\tau_k}{\tau} \frac{\tau}{\sigma_T} \frac{1}{4\pi} \int_{z=0}^L e^{-\mu z} \sum_{i=1}^4 P_i E_{k,i} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} e^{-\mu(E_{k,i}) \ell(\theta, \phi, z)} \sin\theta \, d\theta \, d\phi \, \mu \, dz$$

All cross section information in this report was taken from reference 2 and evaluated at energy E unless so stated. The values $\omega_k = 0.875$ and $\mu_k/\mu_T = 0.833$ were used; τ/σ_T ranged from 0.978 to 0.926 for energies from the K-edge up to 80 keV. The various K X-ray transitions were averaged into four energies with probabilities P_i . The quantity $\ell(\theta, \phi, z)$ represents the gas pathlength at a given (θ, ϕ) orientation for a given depth z in the gas.

Equation 4 may be rewritten as

$$f_k(E) = \frac{\omega_k}{E} \frac{\tau_k}{\tau} \frac{\tau}{\sigma_T} \mu \int_{z=0}^L e^{-\mu z} P(z) \, dz \quad (5)$$

$$\text{where } P(z) = \frac{1}{4\pi} \sum_{i=1}^4 P_{f_{k,i}} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} e^{-\mu(E_{k,i})l(\theta,\phi,z)} \sin \theta d\theta d\phi. \quad (6)$$

$$\text{Also note that } P(z) = P(L-z) \quad (7)$$

A code was written, debugged, and executed on the GE Mk II time share system. An $80 \times 40 \times 10$ ($z \times \theta \times \phi$) grid was used for the integration. Portions of the ϕ integral of $P(z)$ are exactly integrable, and the resulting grid size was $(0.42 \text{ cm} \times 4.5^\circ \times 4.5^\circ)$. Grid size tests indicated that accuracies of better than 2 - 3% in the integral evaluation should result. Use of eq. (6), and a single evaluation of $P(z)$ resulted in minimal computer time. At the K-edge f_k is at a maximum of 38.9%, falling to 12.4% at 80 keV. As will be emphasized later, with this large a fraction of the energy flux striking the chamber walls and plates (stainless steel), a significant problem may exist with reradiation from the walls of some fraction of this energy.

IV. Calculation of f_s .

The general equation used for coherent and incoherent scattered losses was

$$f_s \Big|_q = \frac{E_f}{E} N \int_{z=0}^L \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} e^{-\mu z} \frac{d\sigma_q}{d\Omega} e^{-\mu(E_f)l(\theta,\phi,z)} \sin \theta d\theta d\phi dz \quad (8)$$

where q refers to the coherent or incoherent cases and

$$f_s = f_s \Big|_{\text{coh}} + f_s \Big|_{\text{inc}}. \quad (9)$$

The coherent differential cross section was taken as

$$\frac{d\sigma}{d\Omega}_{\text{coh}} = \left(\frac{e^2}{mc^2} \right)^2 \frac{1 + \cos^2 \theta}{2} f^2(\sin(\theta/2)/\lambda) \quad (10)$$

The scattering factor f was approximated by an analytic expression³ for $\sin[(\theta/2)/\lambda] < 1.5$ and was taken from reference 4 for higher values. For coherent scattering $E_f = E$ was used.

The incoherent scattering differential cross section was taken as ⁵

$$\frac{d\sigma}{d\Omega}_{inc} = \left(\frac{e^2}{mc^2}\right)^2 \frac{1 + \cos^2\theta}{2} S(\sin(\theta/2)/\lambda) \xi(\theta) \quad (11)$$

where

$$\xi(\theta) = \left[\frac{1 + \frac{(E/mc^2)^2 (1-\cos\theta)^2}{(1+\cos^2\theta) \left[1 + \frac{E}{mc^2} (1-\cos\theta)\right]}} \right] \left[1 + \frac{E}{mc^2} (1-\cos\theta) \right]^{-2} \quad (12)$$

The incoherent scattering factor S was taken from reference 6 and the Compton equation was used to evaluate E_f . All scattering cross sections were renormalized such that the total cross sections agreed with ref. 2.

Equations 8-12 were integrated on the LASL/CCF CDC 6600 computers. An 80 x 80 x 20 integration grid was used yielding a grid size of 2.3° for the θ and ϕ integrations. The distance required to attenuate the incident beam by a factor of 10^4 (as long as this distance was less than L) was divided into 80 equal increments to obtain the z-grid size. The maximum z-grid size was 0.4 cm. Tests indicated that better than 1% integration accuracy should be attained with this grid.

V. Upper limits to flux re-radiation.

A. Transmitted Primary Beam

Primary flux striking the lucite end plate can be scattered back into the gas volume. Fluorescent radiation from the low-Z lucite is negligible. Crude upper limits to the scattered flux may be simply obtained by treating the scattering as isotropic. Equation 3 of ref. 1 then yields the result that the fraction of the incident energy flux which is re-radiated is

$$[0.5 (1 - \ln 2) (\sigma_{coh} + \sigma_{inc})/\sigma_T] (1-\epsilon) \quad (13)$$

Below 60 keV, the maximum addition to (c-f) is 0.003 from this reradiation source.

B. Plates and Chamber Walls

Both scattered and fluorescent contributions to the reradiation may be of importance for this re-radiation source. Iron was used for all surfaces in the calculation as an approximation. (The iron K x-ray energy is 6.5 keV.) An upper limit to this correction is

$$1/2 \left(\omega_K \frac{6.5}{30} \frac{\tau_K}{\sigma_T} \right)_{30 \text{ keV}} + \frac{\sigma_{inc} + \sigma_{coh}}{\sigma_T} \left(\frac{\omega_K \frac{6.5}{30} \frac{\tau_K}{\sigma_T}}{30 \text{ keV}} \right) f_K + 1/2 \left(\omega_K \frac{6.5}{E} \frac{\tau_K}{\sigma_T} + \frac{\sigma_{coh} + \sigma_{inc}}{\sigma_T} \right) f_s \quad (14)$$

where the factor of 0.5 represents simply the maximum solid angle available for scattering into the gas volume and 30 keV is the average xenon K X-ray energy. Below and above the K-edge of xenon, this upper limit for the correction to ϵ -f is 0.003, and 0.023, respectively. Between 40 and 80 keV, the correction is 0.01 - 0.02.

C. Total Upper Limits

A reasonable upper limit to re-radiation errors is given by a sum of the two above contributions. This total is given in Table 1. Another source not included is electron emission from the plates, but this should be considerably smaller effect than re-radiation. (For an XRD detector, with Cu cathode, 0.005 electrons are emitted per 30 keV x ray at normal incidence. Even though the number increases for non-normal incidence like $1/\sin \theta$, this should remain a small effect).

It might also be noted that the range of a 60 and 80 keV electron in xenon at 48 psia pressure is roughly 0.7 and 1.1 cm, respectively. Thus electrons from the central irradiated area will not strike the plates.

Table 1

Upper Limit to Re-radiation Correction

<u>Energy (keV)</u>	<u>Addition to ϵ-f</u>
20	$.1 \times 10^{-2}$
30	.3
34.56	.6
34.56	2.3
40	1.9
50	1.5
60	1.5
70	2.1
80	3.4

VI. Conclusion

The quantities f and $(\epsilon$ -f) are shown in figures 2 and 3, respectively, for the dimensions of Fig. 1 and a fill pressure of 48 psia. The losses are pressure dependent, in contrast to the situation discussed in ref. 1 pertaining to the small chambers. The computer codes are in a convenient form for calculation with any combination of chamber dimensions or pressure and can be easily rerun for other cases if required.

Table 1 listed upper limits to corrections for re-radiation from the chamber walls and plates. This effect reduces f and increases ϵ , thereby increasing the overall chamber efficiency. In addition, the use of the total cross section for evaluating the escape probability of the scattered x rays introduces further uncertainty. In effect, this demands that no doubly-interacting x rays reach the plates (i.e., one interaction within the primary beam and a subsequent interaction elsewhere in the gas volume). This is, of course, an invalid assumption; but a completely correct treatment would require a Monte-Carlo treatment of the losses. Upper limits to error from double-interactions may be readily assigned and are included in Table 2.

Uncertainty also exists from errors in the differential scattering cross sections and the total cross sections. Allowance of 10% uncertainty in f for total cross sections and a 15% uncertainty in f for the scattering cross sections, together with the two upper limits discussed above, leads to the total uncertainties in the quantity ϵ - f shown in Table 2. The errors discussed in reference 1 for f_L and f_e are also included.

Table 2

Uncertainty in Calculated Chamber Efficiency (ϵ - f)

<u>Energy (keV)</u>	<u>Uncertainty in (ϵ-f) , (%)</u>
1.5 - 10	< 0.7
10 - 20	< 0.3
20	0.3
30	1.0
34.56	1.4
34.56	9.0
40	7.4
50	5.6
60	4.7
70	4.9
80	6.1

The theoretical calculations show that the large xenon ionization chambers are a highly efficient beam intensity detector. For energies below the K-edge of xenon, errors in calculated chamber efficiencies should not exceed 1.5%, while the overall chamber efficiency exceeds 91%. Above the K-edge, efficiencies are much lower and uncertainties are close to 10%

for some energies. For accurate dosimetry at higher energies, absolute calibration of the large chambers would be necessary. Below the K-edge, the calibration program completed for the small chambers (from 1.7 - 10.5 keV) can be used to infer equivalent accuracy in the higher energy region insofar as no new physical processes come into existence and calculated losses are very small. However, saturation curve behavior, and upper limits to the useful intensity range for the chamber must be re-determined for the large chambers.

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R = 4.13 cm
D = 2.16 cm
W = 4.45 cm
L = 33.7 cm

Figure 1

Figure 2

Figure 3

CM/rm: 260(25)