Development of a Model of an X-ray Tube Transmission Source

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Abstract– **In support of the development of an x-ray tube based source for transmission measurements of UF_6 gas, we have developed a one-dimensional, spreadsheet-based model of the source. Starting with the spectrum produced by an x-ray tube we apply the linear attenuation coefficients for various notch filters, the aluminum pipe, and UF_6 gas. This model allows calculation of the transmitted spectrum based on the type of filter, the thickness of the filter, the x-ray tube high voltage, the Al pipe thickness, and the UF_6 gas pressure. The sensitivity of the magnitude of the transmission peak produced by the notch filter to any of these variables can be explored quickly and easily to narrow the choices for experimental measurements. To validate the spreadsheet based model, comparisons have been made to various experimental data.**

I. Introduction

The classical approach for monitoring the enrichment of UF_6 in a pipe or container involves two simultaneous measurements with a gamma-ray spectrometer. One measurement is a passive measurement of the 186-keV gamma ray from the decay of ^{235}U. The other is the attenuation of a transmission source by the UF_6 gas.

We are developing an x-ray tube source to replace isotopic sources [1]. The system concept is shown in Fig. 1. A "notch" filter material such as ruthenium, silver, etc. is placed in the beam from the x-ray tube and converts the bremsstrahlung distribution generated by the x-ray tube into a peak just below the K-edge of the filter material. The selection of the HV for the X-ray tube and the thickness of the "notch" filter affects the magnitude and shape of the transmission peak. We have developed a one-dimensional, spreadsheet-based model. Our model is used to estimate the effects of parameter changes and to design experiments.

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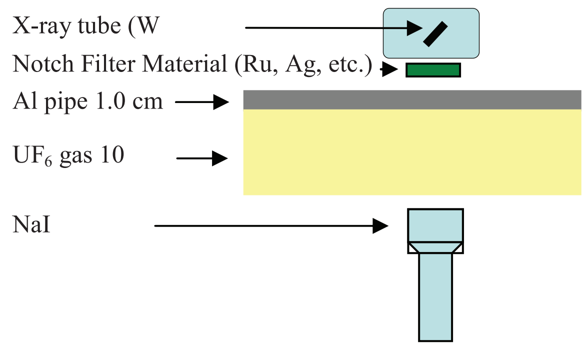

Fig. 1. Conceptual basis of x-ray tube transmission source model.

II. Basic Analytical Model

The x-ray spectrum produced by the x-ray tube is calculated for discreet energies according to

$$\Phi(E) = k(\frac{E_c}{E} - 1)^n \tag{1}$$

where k is a scaling factor, E_c is the cutoff energy in MeV, and n=0.96 for a tungsten anode x-ray tube.[2]

The linear attenuation coefficients [3] for a notch filter material are then applied to produce the spectrum with a peak just below the K absorption of the filter material, ruthenium in this example.

$$\Phi_{Ru}(E) = \Phi(E)e^{(-\mu_{Ru}\rho_{Ru}t_{Ru})} \tag{2}$$

The attenuation of the transmission peak through the Al pipe is calculated. The pipe is assumed to have a .5 cm wall thickness. The passage of the transmission peak through both sides of the pipe is combined and modeled as a 1.0 cm slab.

$$\Phi_{Al}(E) = \Phi_{Ru}(E)e^{(-\mu_{Al}\rho_{Al}t_{Al})} \tag{3}$$

Finally the attenuation of the UF_6 gas is calculated. The density of the gas is calculated for a given pressure (about 0.001 g/cm^3 at 50 torr). The "thickness" of the UF_6 is the 10 cm inner pipe diameter.

$$\Phi_{UF6}(E) = \Phi_{Al}(E)e^{(-\mu_{UF6}\rho_{UF6}t_{UF6})} \tag{4}$$

A. Variation of High Voltage

High Voltage (HV) variations in the x-ray tube are a major factor in creating instability of the transmission source. Variations affect both the intensity and the energy distribution and cutoff energy of the bremsstrahlung spectrum generated by the x-ray anode. These variations in the transmission peak in turn affect the attenuation in the "notch" filter, UF_6 gas and the pipe wall.

Intensity plots, or simulated spectra, were generated for various x-ray voltages. Fig. 2 shows data for a 0.05 cm Ag notch filter (K-edge at 25.5 keV) and x-ray tube voltages of 31, 33, and 35 keV on a semi-log scale. The total intensity of the transmission peak can be calculated by integrating over the energies below the Ag K-edge. For measurements made with a NaI detector the transmission peak extends beyond the K-edge due to the detector resolution; the region of interest (ROI) is set accordingly when determining peak areas.

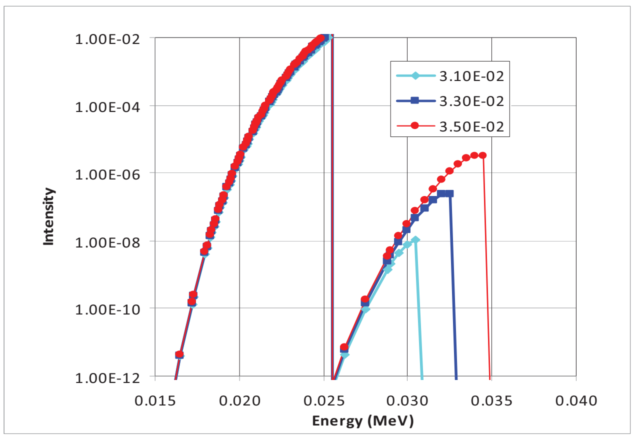

Fig 2. Intensity vs. energy for various cut-off energies for a 0.05 cm Ag filter.

Calculated transmission peak intensities were tabulated for a range of x-ray high voltages from 27 kV to 33 kV that were also experimentally measured. The sensitivity of the transmission peak intensity to changes in high voltage was calculated for each x-ray voltage according to (5).

$$S_{tr}(E_c)=\frac{\Delta I_{tr}/I_{tr}}{\Delta E_c/E_c} \qquad (5)$$

Fig. 3 shows the agreement. The trend shows decreasing sensitivity to fluctuations in voltage as x-ray tube voltage increases. The spreadsheet was expanded to produce values for additional energies beyond those experimentally measured.

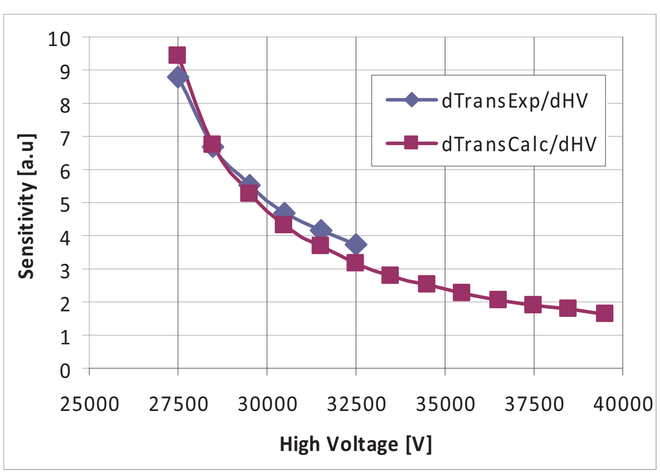

Fig 3. Sensitivity of Transmission peak to HV as calculated and measured.

This sensitivity is not the only factor in the choice of high voltage, however.

B. Variation of Pressure

The purpose of transmission measurements is to determine the quantity (or pressure) of UF_6 gas present in a pipe. If the transmission peak can be measured through the attenuation of an empty pipe, the attenuation due to the UF_6 gas can be separated out from the total attenuation and the gas pressure calculated.

By changing the density of the UF_6 gas in our model, we generated spectra and calculated peak intensities as described above. Peak intensities were compared to the transmission peak intensity for 0 torr pressure, i.e. an empty pipe, to yield relative transmission fractions. These values were compared to experimental data as shown in Fig. 4. Both model and experiment used a ruthenium "notch" filter with a thickness of 0.0329 cm. The systematic error can be primarily explained by the approximation of the cylindrical pipe as a slab in the model [4].

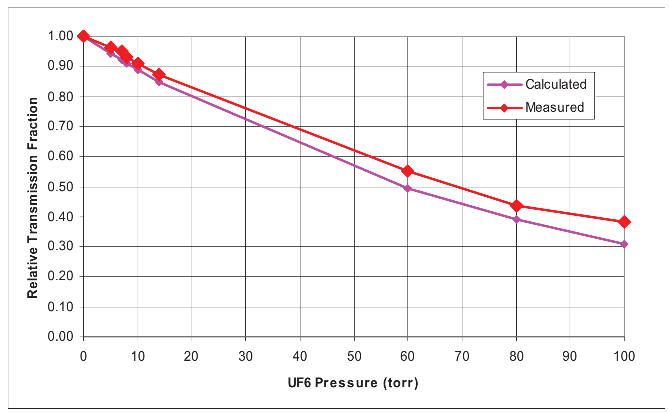

Fig 4. Experimental and calculated relative transmission fractions at various UF6 gas pressures.

C. Comparison of Target Materials

The spreadsheet model allows the comparison of various potential notch filter materials. Because ruthenium and silver were available for experimental use, we focus on their comparison. Fig. 5 and Fig. 6 show the transmission peak generated by a ruthenium and a silver notch filter, respectively, and the narrowing effect on the peak due to the attenuation from the aluminum pipe. The linear attenuation coefficient of Al is shown with a secondary scale at the right of the graph.

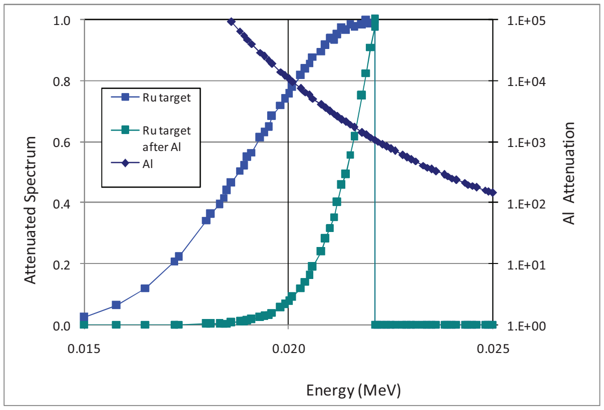

Fig 5. Transmission peak formed by ruthenium notch filter and effect of Al pipe attenuation.

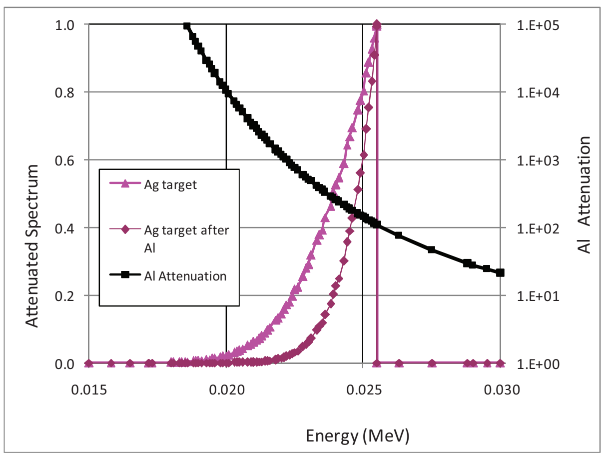

Fig 6. Transmission peak formed by silver notch filter and effect of Al pipe attenuation.

Calculation of peak areas showed that the ruthenium K-edge peak (22.1 keV) was attenuated by a factor of 1086 in the Al pipe and a factor of 1.86 in 50 torr UF_6 gas. For the silver K-edge peak (25.4 keV), attenuation in Al was by a factor of 110 and attenuation in UF_6 was by a factor of 1.55.

Although the higher energy peak from the Ag filter is absorbed 15% less in the UF_6 gas, its absorption is 1000% less in the Al pipe wall, making the measurement of UF6 gas pressure less sensitive to variations in pipe wall thickness. The results of continuing the comparison of notch filter materials with K-edges in the 22 – 30 keV range is shown in Table I. Isotopic sources in comparable energies are included for comparison.

TABLE I. COMPARISON OF X-RAY NOTCH FILTER MATERIALS AND ISOTOPIC SOURCES

	X-Ray Filter	Isotopic Source	X-Ray Filter						Isotopic Source
	Ru	Cd-109	Rh	Pd	Ag	Cd	In	Sn	Am-241
K-edge (keV)	22.10	22.16	23.20	24.40	25.50	26.70	27.90	29.20	59.50
Density (g/cm3)	12.44	N/A	12.41	12.00	10.49	8.65	7.31	7.30	N/A
Attenuation Factor in Al	1085	1028	445.6	198.3	109.5	62.14	39.27	26.20	2.13
Attenuation Factor in UF6 (50 torr)	1.86	1.86	1.74	1.63	1.55	1.47	1.42	1.36	1.05
Attenuation Factor in UF6 (5 torr)	1.06	1.06	1.06	1.05	1.04	1.04	1.04	1.03	1.005

In general, higher energy transmission peaks have a *slightly* smaller absorption in UF_6 gas; but this is offset by a *much* smaller absorption in Al pipe, thus improving the ratio [5].

III. CONCLUSIONS

A simple one-dimensional linear attenuation model can be used to support the selection of "notch" filter materials and parameter settings for an x-ray tube based transmission source. Results show good agreement with experimental results where available, and can be used to extend conclusions drawn from experimental results.

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