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R.H. Thomas and S.V. Thomas

April 1983

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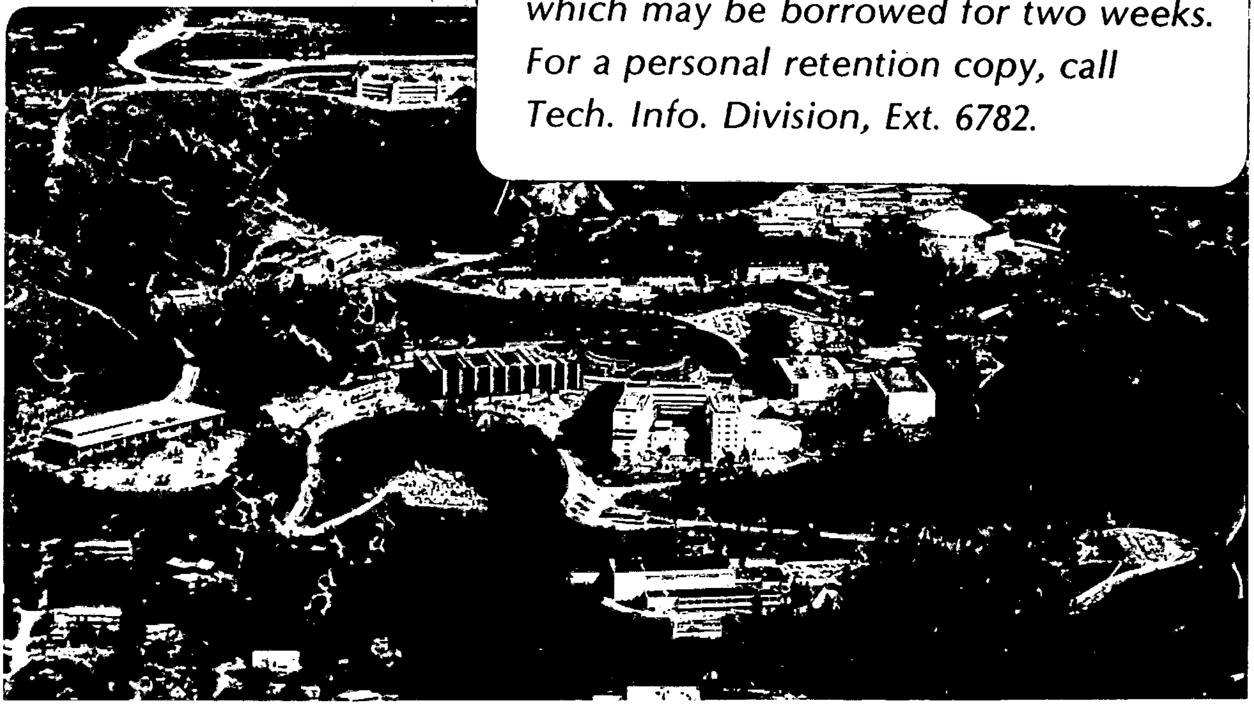

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May 25, 1983

Prof. G. Roessler
The Editor, Health Physics
Editorial Office
Dept. of Nuclear Engineering Science
University of Florida
Room 202, Nuclear Science Center
Gainsville, FLA. 32611

Dear Madam:

Variance and Regression Analyses of Moyer Model Parameter Data - a Sequel

The present authors recently joined with Lieu and Stevenson in applying variance and regression analysis [Ch74, Fi70, Sn80] to experimental determinations of the Moyer Model Parameter, $H_o(E_p)$ [Li83].* A primary purpose of the analysis of Lieu et al. was to determine an empirical formula for the variation of $H_o(E_p)$ with primary proton energy E_p. The analysis concluded that the experimental data, either untransformed in or log-log transformation, may be fitted with a straight line. In log-log transformation an equation of the form

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* The Moyer Model parameter, $H_0(E_p)$, appears in the equation:

$$H = H_0(E_p)\ r^{-2} \exp(-\beta\theta) \exp(-d/\lambda)$$

used in the calculation of the dose equivalent at the surface of accelerator shields. For further details see Moyer (Mo62), Patterson and Thomas (Pa73) and Stevenson et al. (St82).

$$H_o(E_p) = k\ E_p^m \tag{1}$$

was assumed by Lieu et al. for regression analysis. Lieu et al. pointed out three possible hypotheses for the exponent, m, of equation 1. Of these, two hypotheses (m = 0.5, 1.0) are not well based upon any sound theoretical principle while the third (m = 0.75) is suggested by data obtained from calculations of the transport of the hadron cascade initiated by energetic protons through matter (Fe 72). The best estimate of the coefficient m obtained by regression analysis was m = 0.77 ± 0.26, in good agreement with the suggested value of 0.75, but the data were not sufficiently accurate to eliminate the alternative values of m = 0.5 or 1.0. Lieu et al. called for new experiments, particularly in the energy range 100-500 Gev to more closely define our knowledge of the parameter m.

The extrapolation of the Moyer parameter to higher energies has recently become important because high-energy facilities in the energy region of 20 Tev are now being considered. These facilities are extremely large - the storage rings of a 20 Tev Proton Collider Facility have a circumference of about 60 kilometres. Unwarranted conservatism in the design of hadron shielding for such installations can be prohibitively expensive (Co83, Th83, We82).

Recently Cossairt et al. have reported measurements of absorbed dose on the surface of earth/concrete shielding above the Fermilab proton synchrotron (Co82). Using data summarized by Stevenson et al. (St82) and assuming a quality factor of five for the radiation field, these new measurements permit values of the Moyer parameter H_o to be calculated for the energy at which measurements were made (350 Gev). Values of 212 x 10^{-13} Sv.m^2 and 446x10^{-13} Sv.m^2 are obtained. While these measurements are in only fair agreement with each other, we shall show they add greatly to the precision with which we know the energy variation of $H_o(E_p)$.

Tesch has suggested that the new data of Cossairt et al. are compatible (within a factor of two) with a linear variation of $H_o(E_p)$ with proton energy (corresponding to a value of $m = 1$ in equation 1) (Te83). We will suggest that the energy variation of the experimental data (plotted in Figs. 1 and 2) is better represented by a somewhat smaller value of m.

Table 1 summarizes the experimentally determined values of $H_o(E_p)$ included in the analysis reported here.

Table 1. Summary of values of Moyer model parameters, $H_o(E_p)$, used in this analysis.

Primary Proton Energy, [E_p] (GeV)	Moyer Parameter, [$H_o(E_p)$] (Sv.m^2)		Source
7.4	1.4	10^{-12}	Sh69, St69
7.4	2.1	10^{-12}	Sh69, St69
10.0	0.96	10^{-12}	Ho66
13.7	2.5	10^{-12}	Gi68
13.7	3.1	10^{-12}	Gi68
21.0	1.6	10^{-12}	Ho79
23.0	3.5	10^{-12}	Ma79
25.5	3.3	10^{-12}	Gi68
25.5	5.0	10^{-12}	Gi68
25.5	6.6	10^{-12}	Ro69, St82
30.0	3.4	10^{-12}	Aw70
350	21.2	10^{-12}	Co82
350	44.6	10^{-12}	Co82

Figure 1 shows calculated regression lines for the new data set. The equation of the regression line for the untransformed data is:

$$H_o(E_p) = (0.92\ E_p + 13) \times 10^{-13}\ \text{Sv.m}^2 \qquad (2)$$

when E_p is in GeV.

A Student's t-test does not reject the possibility of a straight line forced through the origin ($p > 50$ percent) and the equation of such a regression line is:

$$H_o(E_p) = (0.96 \pm 0.10) \times 10^{-13}\ E_p\ \text{Sv.m}^2 . \qquad (3)$$

The slope of this line differs markedly from that previously given by Lieu et al. [$H_o(E_p) = (1.61 \pm 0.19) \times 10^{-13}\ E_p\ \text{Sv.m}^2$] but it is evident by inspection of Fig. 1 that neither equation (2) nor equation (3) give a good fit to the data points over the entire energy range. Partitioning the total variability to compare the About Regression Mean Square with the Within Group Mean Square gives $F_{6,5} = 0.03$, which has a probability of less than 0.5 percent (Da58). Alternatives to a linear fit to the untransformed data should therefore be explored.

Regression analysis of the new data set in log-log transformation data gives the estimated regression coefficients:

$$m = 0.80 \pm 0.10$$

$$k = (2.84 \pm 0.14) \times 10^{-13}$$

[c.f. values of $m = 0.77 \pm 0.26$ and $(3.1 \pm 2.1) \times 10^{-13}$ reported by Lieu et al.].

In contrast to the earlier analysis performed by Lieu et al., the hypotheses $m = 1$ and $m = 0.5$ are now rejected by a Student's t-test [$p = 3$ percent (one tail test) and $p = 1$ percent (two tail test), respectively].

We then conclude that the most reasonable fit to the existing Moyer model data in the energy range $5 \text{ GeV} \leq E_p \leq 500 \text{ GeV}$ is given by:

$$H_o(E_p) = 2.8 \times 10^{-13} E_p^{0.8}$$

with $H_o(E_p)$ in Sv.m^2 when E_p is in GeV.

Figure 2 shows the 95 percent confidence limits to the regression line and indicates the improved precision obtained when the new measurements of Cossairt et al. are added to the data pool. Additional data, particularly in the energy region 50-300 GeV, would continue the refinement in our knowledge of both the absolute value of $H_o(E_p)$ and its variation with proton energy.

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Fig. 1. A summary of the regression lines calculated for the untransformed data and the data in log–log transformation.

Fig. 2. $H_o(E_p)$ as a function of primary proton energy, E_p. Data points included in the analysis by Lieu et al. (Li83) are indicated thus --●. The new data of Cossairt et al. (Co82) are indicated thus --▲. The regression line $H_o(E_p) = 2.8 \times 10^{-13}\ Ep^{0.80}$ is shown as a solid line. The 95 percent confidence bands are indicated both for the analysis of Lieu et al. and the present work.

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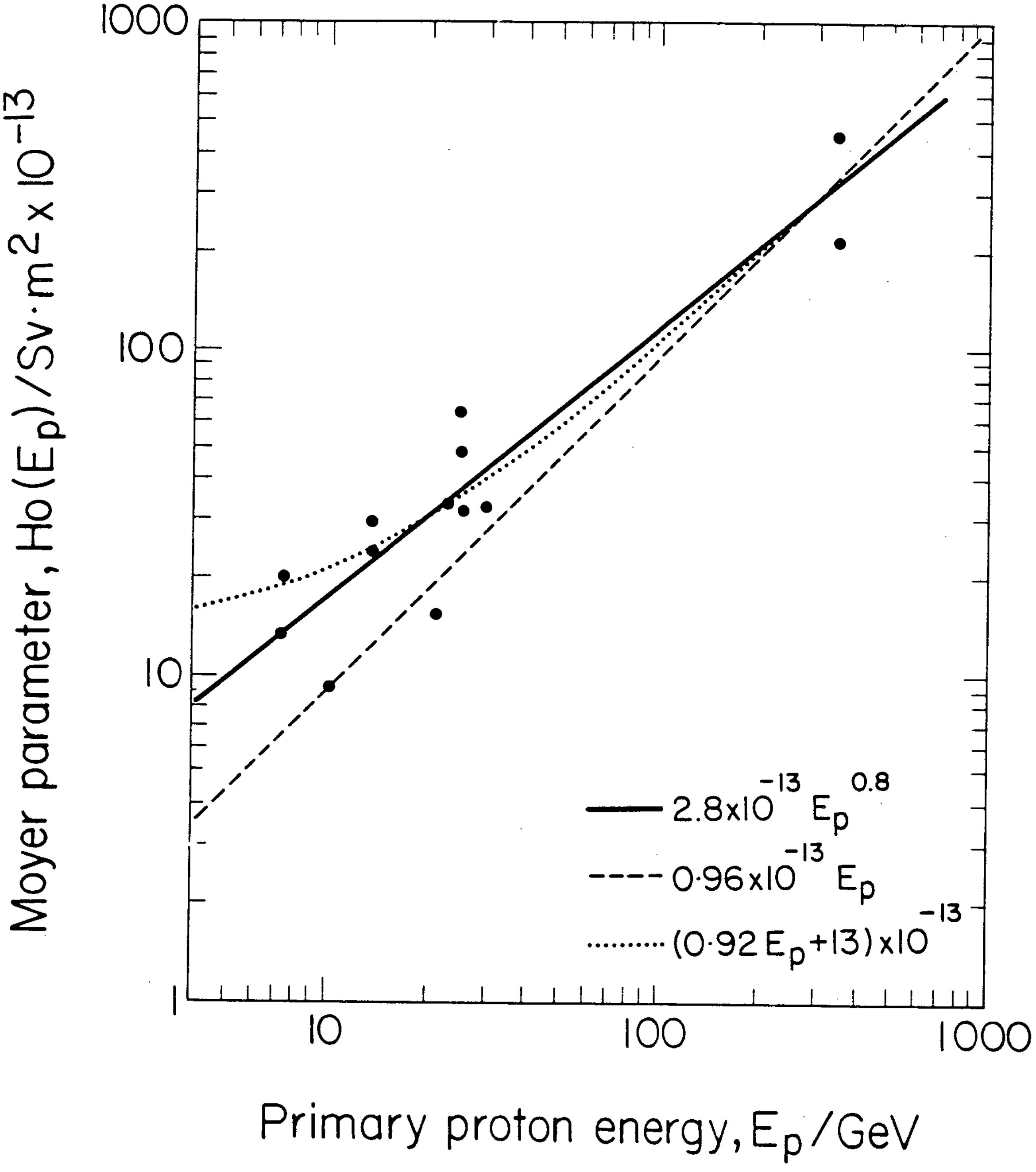

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Fig. 1

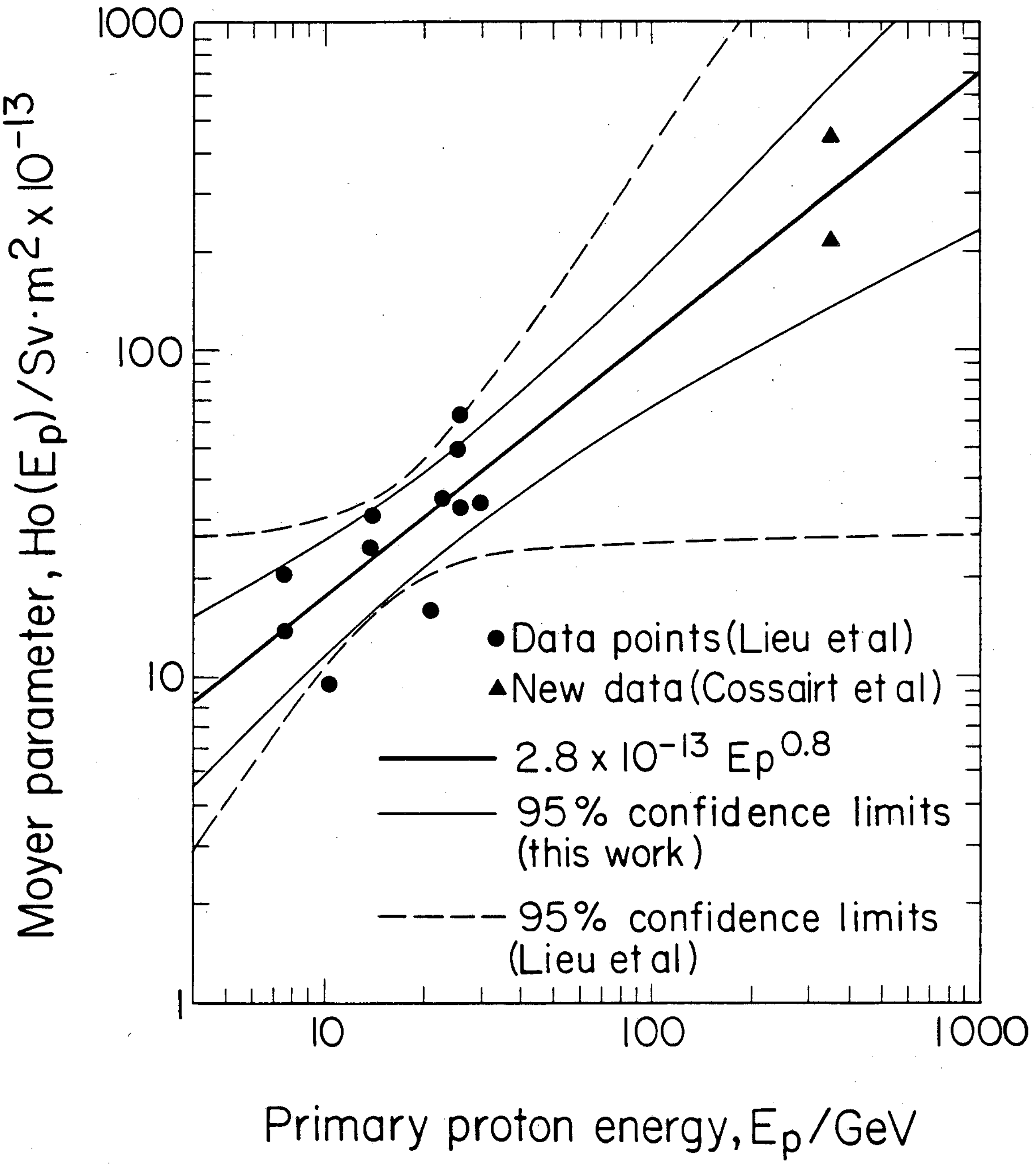

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Fig. 2

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