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RADIATION HAZARDS TO MAN

by

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FOREWORD

This report is submitted to the National Aeronautics and Space Administration, Headquarters Branch, Washington, D. C., in accordance with the requirements set forth in NASA contract NASw-1963. The work herein reported was performed by M. C. Wilkinson of the Space Sciences Group, Aerospace Division, The Boeing Company, and by Dr. Stanley B. Curtis of the Lawrence Radiation Laboratory, consultant to The Boeing Company. This work was done under the supervision of Dr. L. G. Despain.

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INTRODUCTION

In the previous work with NASA (1,2) a summary of the radiation environment both within and without the earth's magnetosphere was made from the data available through 1968. Current radiation transport techniques were then used to determine the characteristics of the typical aluminum shields used in space missions, and the particle energies and environmental uncertainties of most importance for evaluating biological effects were discussed.

In this study we report additional work done toward resolving some of the problem areas that our initial work revealed. The secondary dose contribution expected from the heavy primaries of the galactic cosmic rays is evaluated by a calculational technique developed in this study. The improvements in the solar and galactic cosmic ray environments made possible by recent experimental and theoretical work are discussed and presented. Finally, the recommendations of the National Academy of Sciences' Space Radiation Study Panel (3), are used in conjunction with a shielding analysis, to evaluate the radiation status of an astronaut during the triple solar particle event of July 10, 14, and 16, 1959.

HEAVY ION SECONDARY DOSE CALCULATIONS

In our previous work, (1), a calculation of the free space dose delivered by the galactic cosmic rays (GCR) was presented, based on the environmental data available. Year dose rates are given in Table I for the various components of the GCR spectrum that were distinguishable.

TABLE I

<u>Component</u>	<u>Yearly Dose</u>
H ($Z=1$)	4.6
He ($Z=2$)	3.5
M ($6 \leq Z \leq 9$)	1.9
LH ($10 \leq Z \leq 14$)	1.3
VH ($26 \leq Z \leq 28$)	1.3
TOTAL	12.6 rads/year

The large fraction of the total yearly dose delivered by the heavy primaries ($Z > 3$) points out the need for an accurate treatment of their transport properties in the materials of the spacecraft and the astronaut's body. The recent reports of light flashes in the eyes of the Apollo 11 through 14 missions, and the present feeling that heavy galactic primaries are the responsible agents stresses the importance of understanding the physics of the heavy primaries passage through matter so that possible biological effects can be evaluated. In Figure 1 we show the depth dose profiles for the helium and higher Z components in aluminum under two assumptions: 1) that only electromagnetic interactions attenuate the incident primaries and 2) that

the particles suffering nuclear interaction are removed from the beam (uncollided particle dose only). The wide range between these estimates indicates the need for further work to evaluate both the total dose and the quality of the radiation (LET) delivering the dose.

FORMULATION OF THE CALCULATION

Let $\phi_i(E, x)$ be the differential number flux of ions of type i at a point x in the absorber. Then it is easy to show that the relation between the incident flux and the flux at a point in the absorber is given by

$$\phi_i(E', x) = \phi_i(E, 0) \frac{S(E)}{S(E')}$$

neglecting nuclear interactions.

where $S(E)$ is the stopping power of the ions in the material.

If we include nuclear interactions, and change variables to energy per nucleon, T , we have

$$(1) \quad \phi_i(T', x) = \phi_i(T, 0) \frac{S(T)}{S(T')} \exp - \int_T^{T'} \frac{\mu_i(T) dT}{S(T)}$$

where $S(T)$ is the stopping power of the ion of type i and energy per nucleon T . If μ_i is energy independent, then we have simply $\exp -\mu_i x$ for an attenuation factor. The uncollided flux can then be determined at points of interest in the absorber.

Now ions of type i produce secondary ions of type j at points in the absorber at the following rate:

$$(2) \quad \frac{d\phi_j}{dx} (T', x) = \phi_i (T, x) \frac{N_0}{M} \sigma_i (T) P_{ij} (T, T')$$

where

$\phi_i (T, x)$ is the energy spectrum of ions of type i

$\sigma_i (T)$ is the interaction cross section for ions of type i and energy T

$P_{ij} (T, T')$ is the fragmentation parameter, giving the probability for an interaction of type i ions at energy T to produce a secondary ion of type j and energy T'

N_0 = Avogadro's number

M = the atomic weight of the absorber

$\frac{d\phi_j}{dx} (T', x)$ = the rate at which particles of type j and energy T' are being produced in the absorber at point x

Particles of type j are slowed and attenuated as they pass through the remainder of the absorber and they emerge with an energy related to their initial energy T, and remaining path length in the absorber, X-x, of

$$R_j(T) = R_j(T_f) + X-x$$

and with an intensity reduction of

$$\frac{S(T)}{S(T_f)} \exp -u_j (X-x)$$

The emerging flux of type j particles produced by type i primaries is

then

X

$$(3) \quad \phi_j (T_f, X) = \frac{N_0}{M} \int_0^X \phi_i (T, x) \sigma_i (T) P_{ij} (T) \frac{S(T)}{S(T_f)} \exp -u_j (X-x) dx$$

Now we apply these basic relations to the problem of determining the final penetrating energy spectrum of the galactic heavy primaries and induced secondaries in an absorber. First, we consider a maximum Z of 26, as only a small number of higher Z particles are present in the galactic cosmic ray flux. The penetrating flux of ^{26}Fe particles at any point in the absorber can be determined by expression (1). Once $\phi_{26}(T, x)$ is known, then the rate at which lower atomic number particles are being produced at points in the absorber can be determined by expression (2).

Consider the incident flux of ^{25}Mn . The penetrating flux of incident ^{25}Mn can be determined by expression (1). However, the total flux of ^{25}Mn at any point in the absorber is the sum of the attenuated incident flux plus the accumulated secondary flux from the ^{26}Fe , which can be determined by expression (3) for any point in the absorber. Once the total flux of ^{25}Mn has been determined at any point in the absorber, then the contribution of ^{25}Mn to lower atomic number secondary production can be determined by expression (2).

The total production rate of particles of type j is given by the following sum

$$\frac{d\phi_j}{dx}(T, x) = \sum_{i=j+1}^{26} \phi_i(T, x) \frac{N_0}{M} \sigma_i(T) P_{ij}(T)$$

where $\phi_i(T, x)$, the total flux of particles of type i , depends on both the incident flux and the accumulated secondary flux.

To determine the penetrating flux of particles, a computer program was developed to evaluate the expressions discussed numerically. This program evaluates the production rates of the secondaries at a set of thickness points in the absorber for a suitable energy grid. Then by sequential transporting the highest Z element through the absorber and determining the production rates for all lower Z elements, we obtain the final penetrating number energy spectrum.

BASIC ASSUMPTIONS USED IN THE CALCULATION

The preceding section has developed the formations used in the calculation of the secondary particles produced by the heavy galactic primaries. Now we discuss the basic assumptions used in this analysis, and some of the resulting limitations in the present calculations.

First we employ the straight ahead, or one dimensional approximation. This can be justified by use of cosmic ray interaction data as discussed in Reference 2 which shows that the heavy fragments emerging from the interaction site are strongly peaked in the forward direction. It is well known that the primary heavy particles suffer little angular deflection while passing through matter.

Second, we use the energy independent overlap cross section model used by Cleghorn, et al. (4) to fit his cosmic ray emulsion results. It was found that cross sections were essentially independent of energy in the energy range 100 MeV/nucleon to 30 GeV/nucleon. At energies below 100 MeV/nucleon, the higher Z primaries have a small range, but their cross section will probably be underestimated in this energy region.

The fragmentation function, $P_{ij}(T, T')$ represents the least well known quantity required in the calculation. Since the energy dependence of the secondary fragments has not yet been described, we make the simple assumption that $T = T'$, that is the fragments have the same velocity as the primary ion. This assumption is in agreement with an interaction model in which the heavy primary is stripped of some fraction of its mass, and proceeds on with unchanged velocity. Two sets of fragmentation parameters were then used to explore the effects of various assumptions on the final results. In the first approximation, we have used a set of fragmentation parameters which assume one ^1_1H , one ^4_2He , and an equal probability of higher Z fragments normalized to conserve Z in the incident heavy primary. This approximation, when coupled to the equal velocity approximation, leads to approximate conservation of energy, neglecting nuclear binding energies and pion formation. The second set of fragmentation parameters were developed to show the influence of an interaction model which allowed a higher proportion of small changes in incident primary charge, as in grazing collisions. Both sets of fragmentation parameters are assumed to be independent of the primary particle energy, a conclusion that is consistent with the results of Cleghorne. Figures 2 and 3 show the fragmentation parameters.

Finally, the calculations have neglected the interactions of primary and secondary ions with hydrogen. While the results of Bertini's inter-nuclear cascade calculation can be applied to this problem by a proper transformation of rest frames, this has not yet been incorporated in the calculation. The results given for tissue thus neglect the fragmentation induced by hydrogen.

RESULTS

Typical results of this calculational method have been developed with the assumptions discussed. First, using the VH group heavy particle spectrum presented in Reference 1, depth dose profiles for a unidirectional beam of particles incident normally on a slab of water and aluminum are shown in Figures 4 and 5. The total tissue dose, the $_{26}\text{Fe}$ (VH) dose, and selected lower Z secondaries are shown. For H_2O , the two sets of fragmentation parameters are represented by (1) solid lines; and (2) dotted lines. We see the expected rise and more gradual fall of the secondary dose components.

With the complete GCR spectra, as represented by VH, LH, M and Helium components, the results are as shown in Figure 6.

Finally, Meyer (5) has reviewed the galactic cosmic ray data available up to 1969, and has presented an estimate of the intensity of all the heavy primary components below $_{26}\text{Fe}$. From this compilation we have calculated the total depth dose profiles in water for incident primaries $_{2}\text{He}$ to $_{26}\text{Fe}$, and presented the results in Figure 7.

RADIATION ENVIRONMENT STUDIES

While the work in (1) and (2) reviewed the radiation environment both inside and outside the earth's magnetosphere, additional data available since that time makes it possible to update the earlier work in two areas. First, the galactic cosmic ray charge composition has been further analyzed, and estimates can now be made of the intensities of each element up to iron. Second, work by Webber (6) and (7) on solar cosmic ray propagation and prediction allows a re-evaluation of solar cycle 19 activity, and solar cycle 20 is far enough advanced that a reasonably accurate estimate of its intensity may now be possible.

GALACTIC COSMIC RAY INTENSITIES

Peter Meyer has presented (5) a review of the current experimental and theoretical understanding of the intensity and composition of the galactic cosmic rays in the near earth environment at solar minimum. In Reference 1 we found it necessary to identify galactic components of charge greater than helium in L (light), M (medium), LH (light heavy) and VH (very heavy) groups. Meyer has presented separate charge composition energy spectra for ions of up to silicon ($Z=14$) and the integral intensity of components up to iron for various energy thresholds. When these integral intensity values are used with the total ($16 \leq Z \leq 28$) component energy spectrum of Freier and Waddington, one can obtain a separate differential energy spectrum for each Z component up to iron, assuming that the spectral shape for each component is the same as the total energy spectrum.

The proton and helium energy spectra given by Meyer are essentially the same as those previously given in Reference 1. The energy spectrum above 10 GeV was taken by us as proportional to $E^{-2.5}$, while $E^{-2.6}$ is given by Meyer. This will have little effect on the total dose, as we have found that only 10% of the free space dose comes from particles of greater than 10 GeV. In Figures 8, 9, 10 and 11 we show Meyer's compilation of experimental data which describes the intensity and energy spectrum of galactic primaries of $Z=4$ to $Z=14$. Figure 12 gives the total spectrum of nuclei with $16 < Z < 28$. Table II of Reference 5 gives the abundances of $Z \geq 15$ relative to silicon.

We note also that these near earth cosmic ray fluxes can be used in conjunction with a particular choice of solar modulation function parameters to extrapolate to the interstellar environment. Meyer finds for a particular set of modulation parameters that the interstellar proton flux at 100 MeV is eight times the near earth flux. Helium and heavier nuclei fluxes are less affected by solar modulation due to their greater rigidity, and their interstellar fluxes at 100 MeV/nucleon are increased only by a factor of four. The modulation is of course energy dependent, decreasing with increasing particle energy.

SOLAR COSMIC RAY ENVIRONMENT

The irregular and unpredictable solar cosmic ray events have provided a series of challenging radiation hazard evaluation problems since the late 1950's. Once the energy spectrum of the particles was described by Freier and Webber (8) as exponential in rigidity, interest was concentrated on

the problems of short and long term prediction of the larger particle events.

Webber (9), (10) summarized the available data on the solar cosmic ray events during solar cycle 19, and suggested a correlation of the mean yearly sunspot number and the yearly fluence of solar particles of various energy ranges. In (6) this concept was further developed, and specific predictions for solar cycle 20 were made. We feel that the suggested correlation of sunspot number with the solar particle fluences observed near earth is an important hypothesis for solar particle hazard analysis, as it would allow the several hundred year records of mean sunspot number data to guide our estimates of solar particle activity, rather than being restricted to solar cycles 19 and 20 alone for data.

In addition, Webber (7) has used the particle diffusion model of Burlaga (11) to account for the changes in particle intensity at earth that may be attributed to solar longitude, rather than the absolute size of the solar particle event. The implications of this point of view for radiation hazard analysis are presented.

Prediction of Solar Particle Fluences

Several different approaches have been taken toward the long term prediction of solar particle fluences. First, we might consider the empirical approach used by Benbrook in (9). The data from solar cycle 19 were tabulated, missions of a given length were selected at all possible starting dates in

cycle 19 that would contain the mission, and the total fluence received during each mission was recorded. From these data, the probability of receiving greater than a given fluence of particles with a random selecting of mission starting times can be determined. Clearly, if one had to launch missions at random in a resurrected cycle 19 this method would be flawless.

However, cycle 19 is gone forever, and we must deal with some future cycles. To overcome this difficulty, and to attempt to estimate the probability of encountering a particle event larger than that previously observed, several groups (12), (13) have assumed the fluence of the solar particle events can be described as a random process and that by correctly identifying the distribution of the fluences and the distribution parameters, one can put the hazard evaluation problem on a proper statistical basis. The limitations of this method are also clear, one is never sure that he has selected the proper distribution and associated parameters to describe cycle 19, let alone some future cycle. As a consequence, large variations in the probability of encountering rare events are obtained. In addition, the statistical method tends to mask the cycle to cycle variations in solar cosmic ray activity, a serious limitation.

Now we review Webber's predictions for cycle 20. From the data obtained in cycle 19, Webber has postulated a correlation between the average yearly sunspot number and the integral solar cosmic ray yearly flux. This correlation is shown in Figure 13, and we note good general agreement. To use this correlation for solar cosmic ray prediction, one must

first predict the mean yearly sunspot number of the cycle of interest. While methods exist for predicting the characteristics of future cycles, based on observed periodicity in sunspot activity, the most accurate predictions are those which use the early portion of the cycles to determine its behavior. In Table II from (6) are given the yearly sunspot number predictions and the corresponding solar cosmic ray activity. Although cycle 20 is not yet completed, the prediction of a much less active cycle than cycle 19, with total particle fluences for the whole of cycle 20 comparable with the yearly fluxes from cycle 19 is being confirmed.

We feel that the correlation of yearly sunspot number with particle fluence is an important concept. First, this method has provided an accurate prediction of the observed particle fluences in cycle 20, and in particular the method points out the importance of cycle to cycle variation. Second, if we accept the correlation, it is possible to use the sunspot activity data of Wolf, shown in Figure 14, to judge the relative activity of cycle 19 with other cycles. Cycle 19 is by any criteria seen to be a very large cycle, representing a peak in solar activity that may not be seen again for a good while.

Determination of Maximum Particle Event Sizes

Of solar particle events observed in cycle 19, perhaps eight were large enough to present an acute radiation hazard to an astronaut with a moderate amount of protection. Dye and Wilkinson (14) calculated the total dose

TABLE II SOLAR PARTICLE DATA SUMMARY

DATE	LONGITUDE	J(>30 MeV)	P _o	ENHANCEMENT	J _a (>30 MeV)
2-23-56	74°W	1.0x10 ⁹	195	1.0	1.0x10 ⁹
8-31-56	16°E	2.5x10 ⁷	144	2.7	6.75x10 ⁷
1-20-57	30°W	2x10 ⁸	61	1.2	2.4x10 ⁸
7-3-57	40°W	2x10 ⁷		1.1	2.2x10 ⁷
8-9-57	-	1.5x10 ⁶			
8-29-57	-	1.2x10 ⁸	56	-	
9-21-57	6°W	1.5x10 ⁶		1.6	2.4x10 ⁶
10-20-57	45°W	5x10 ⁷	127	1.0	5x10 ⁷
11-4-57	-	9x10 ⁶			
2-9-58	14°W	10 ⁷		1.4	1.4x10 ⁷
3-23-58	78°E	2.5x10 ⁸	64	45	1.1x10 ¹⁰
4-10-58	-	5x10 ⁶			
7-7-58	8°W	2.5x10 ⁸	62	1.6	4x10 ⁸
8-16-58	50°W	4x10 ⁷	64	1.0	4x10 ⁷
8-22-58	10°W	7x10 ⁷	56	1.5	1.0x10 ⁸
8-26-58	54°W	1.1x10 ⁸	51	1.0	1.1x10 ⁸
9-22-58	-	6x10 ⁶	50		
5-10-59	47°E	9.6x10 ⁸	84	8.6	8.2x10 ⁹
6-13-59	57°E	8.5x10 ⁷		14	1.2x10 ⁹
7-10-59	70°E	1.0x10 ⁹	104	25	2.5x10 ¹⁰
7-14-59	7°E	1.3x10 ⁹	80	2	2.6x10 ⁹
7-16-59	26°W	9.1x10 ⁸	105	1.2	1.1x10 ⁹

SOLAR PARTICLE DATA SUMMARY

DATE	LONGITUDE	J(>30 MeV)	P _o	ENHANCEMENT	J _a (>30 MeV)
8-18-59	33°W	1.8x10 ⁶	-	1.1	1.97x10 ⁶
1-11-60	3°E	4x10 ⁵	-	2.0	8x10 ⁵
4-1-60	10°W	5.0x10 ⁶	116	1.5	7.5x10 ⁶
4-5-60	61°W	1.1x10 ⁶	-	1.0	1.1x10 ⁶
4-28-60	34°E	5.0x10 ⁶	104	4.4	2.2x10 ⁷
4-29-60	-	7x10 ⁶	-		
5-4-60	90°W	6x10 ⁶	127	1.1	6.6x10 ⁶
5-6-60	8°E	4x10 ⁶	-	2.0	8x10 ⁶
5-13-60	64°W	4x10 ⁶	94	1.0	4x10 ⁶
6-1-60	46°E	4x10 ⁵	-	7.5	3.0x10 ⁶
8-12-60	27°E	6x10 ⁵	-	4.0	2.4x10 ⁶
9-3-60	88°E	3.5x10 ⁷	127	100	3.5x10 ⁹
9-26-60	64°W	2.0x10 ⁶	73	1.0	2x10 ⁶
11-12-60	2°W	1.3x10 ⁹	124	1.7	2.2x10 ⁹
11-15-60	32°W	7.2x10 ⁸	114	1.1	7.9x10 ⁸
11-20-60	113°W	4.5x10 ⁷	118	1.5	6.7x10 ⁷
7-11-61	32°E	3x10 ⁶	81	4.0	1.2x10 ⁷
7-12-61	22°E	4x10 ⁷	56	3.0	1.2x10 ⁸
7-18-61	60°W	3x10 ⁸	102	1.0	3x10 ⁸
7-20-61	90°W	5x10 ⁶	120	1.1	5.5x10 ⁶
9-28-61	30°E	6x10 ⁶	121	4.0	2.4x10 ⁶
11-10-61	90°W		-	1.1	
2-4-62			-		
10-23-62	71°W	1.2x10 ⁵	83	1.0	1.2x10 ⁵

from the triple flare event of July 1959, and found that the resulting exposure to various body organs was not lethal.

The question arises, however, as to whether a larger, potentially lethal, solar particle event could occur. As not enough is yet known about the acceleration mechanisms of the solar particle events to put physical upper limits on their intrinsic size, we turn attention to the effects of the diffusion process on the observed intensity of solar particles at earth for a given solar event.

Webber (7) has used the anisotropic diffusion model of Burlaga to derive a solar longitude dependent correction factor for solar event size. Using a value of $D_{\parallel}$ to $D_{\perp}$ of 10, that is the ratio of diffusion coefficients parallel and perpendicular to the solar magnetic field lines, and assuming the effective flare source size is distributed in solar longitude as $\cos(\theta - \theta_0)$, we show the solar longitude dependent correction factor in Figure 15. This factor effectively adjusts the particle event size to that which would have been observed at earth if the event had occurred at the most favorable position for sending particles to earth, 60° W solar longitude.

In Table II we show the observed data in cycle 19 adjusted to give absolute particle event intensities. We note that the largest event, measured in terms of particles greater than 30 MeV, was the July 10, 1959 event. The biological implication of the event are discussed in the next section. An analysis of the corrected event sizes showed their size distribution was still reasonably represented by a log-normal distribution as are the observed intensities.

APPLICATION OF THE RES CONCEPT

The Space Radiation Study Panel of the National Academy of Sciences has reviewed pertinent radiological data and has recommended a method for the evaluation of radiation exposures in manned space flights (3). They have suggested that for space applications the dose equivalent, DE, measured in rems be replaced by a reference equivalent space exposure, RES, measured in units of reu. The space dose, in rads, is multiplied by a radiation quality factor QF and by other appropriate modifying factors such as dose rate, fraction of the body exposed, etc.

Written as a general expression

$$\text{RES (reu)} = D \text{ (rads)} \times QF \times (f_1 \cdot f_2 \dots f_n).$$

Once the RES is found, one can estimate the probability of a given response by appropriate tables supplied in Reference 3.

In this section we will utilize this method to evaluate the probability of early and late responses to the triple event of July, 1959.

EVALUATION OF QF_E AND QF_L FOR BODY POINTS

Now the quality factors for early and late responses are approximated by LET dependent expressions of the form

$$QF_E = 0.9 + 0.05 \bar{L}$$

$$QF_L = 0.8 + 0.16 \bar{L}$$

where $\bar{L}$ is the mean local LET at the body point of interest in keV/ μ .

To evaluate QF for the solar cosmic ray protons we have used the Boeing Secondary Proton Code, discussed in References 1 and 2 in conjunction

with the Dye model astronaut (15) to determine the primary and secondary particle energy spectra at the dose point of interest. Curves showing the rad dose, the rad dose multiplied by QF_E and QF_L are shown for two body points and as a function of the incident proton spectrums e-folding rigidity, P_0 . We have chosen the lens of the eye and a point 6 cm deep at the waist as the body points of interest. Aluminum spherical shielding of 1, 4, and 10 g/cm² thickness was used about the seated astronaut.

In Figures 16 through 21 we show the results of these calculations. Note that for the larger total shielding cases the QF_E is near one. The neutron QF , resulting from the n-p reactions in tissue, shows the largest QF . Heavy particle recoil doses, both from protons and neutrons are shown only in rad units, as the mean LET is quite high, and may not be well described by the suggested linear dependence on $\bar{L}$. Their contribution must be evaluated separately.

RES CALCULATIONS FOR THE JULY 1959 EVENTS

We now determine the predictions of Reference 3 concerning the early radiation response of an astronaut to the July 1959 events, assuming 4 g/cm² spherical shielding. First, from the observed event intensities and rigidities, we find a total dose at the body point waist 6 of 16.9 (rads x QF_E). Even allowing a dose rate modifying factor of 1, we find from Table 29 of Reference 3, a less than 10% chance of production of the early prodromal sequelae.

Now consider the possibility of observing the July 10, 1959 event at the solar longitude with the least transmission attenuation, 60° W. The

event size is increased by a factor of 25, so the exposure at the body point Waist 6 would now be 162.5 (rads x QF_E). From Table 29 again we find a ~ 50% chance of nausea, and from Table 30 a near 50% depression in the platelets, lymphocytes, and neutrophils of the blood. Again we use a dose rate modification factor of one, which is perhaps conservative. The probability of early lethality is less than 10%, if we apply the Waist 6 results and assume no dose rate modification reduction.

For late effects, consider the formation of cataracts in the ocular lens.

If we take 4 g/cm² aluminum shielding, as before, we find the total dose from the triple event to be 189 (rads x QF_L). Using a dose rate modification factor of 1, the probability of occurrence of cataracts is less than 50%.

CONCLUSIONS

From the results of the preceding studies, we draw the following conclusions about the evaluation of the heavy ion secondary doses, the galactic and solar cosmic ray environments, and the use of the RES concept for evaluating space radiation effects.

1. The principal limitation on the accuracy of the heavy primary dose calculation is in the fragmentation parameters. More detailed information on their energy and Z dependence is required to reduce the calculational uncertainties. The present set of fragmentation parameters used does indicate the general characteristics of the depth-dose profiles.
2. The influence of the heavy ion-hydrogen interactions that occur in tissue should be evaluated by incorporating the cascade data of Bertini into the code. In addition, the LET spectra should also be calculated to aid in the evaluation of biological effects.
3. The data of the galactic cosmic ray energy spectra and composition has greatly improved due to the satellite observations of the past few years, and now only the low energy portion of the heavy primary spectra (< 100 MeV/Nucleon) and the composition above $Z=14$ remain to be resolved.
4. Estimations of the Solar Cosmic Ray particle event hazard are still uncertain. The work of Webber indicates that solar cycle 19 may have been an exceptional producer of solar protons, and correlations

of sunspot activity with particle activity have worked out well in cycle 20. While no physical upper limit to solar particle event size has been developed, the event of July 10, 1959 may have been the largest intrinsic event of cycle 19, when allowance is made for propagation effects.

5. Body point doses, weighted with QF_E factors have been calculated based on the recommendations of (3). When applied to the July 1959 triple event series we find the hazard to an astronaut shielded with 4 g/cm² of aluminum gives less than a 10% chance of inducing the prodromal sequelae.

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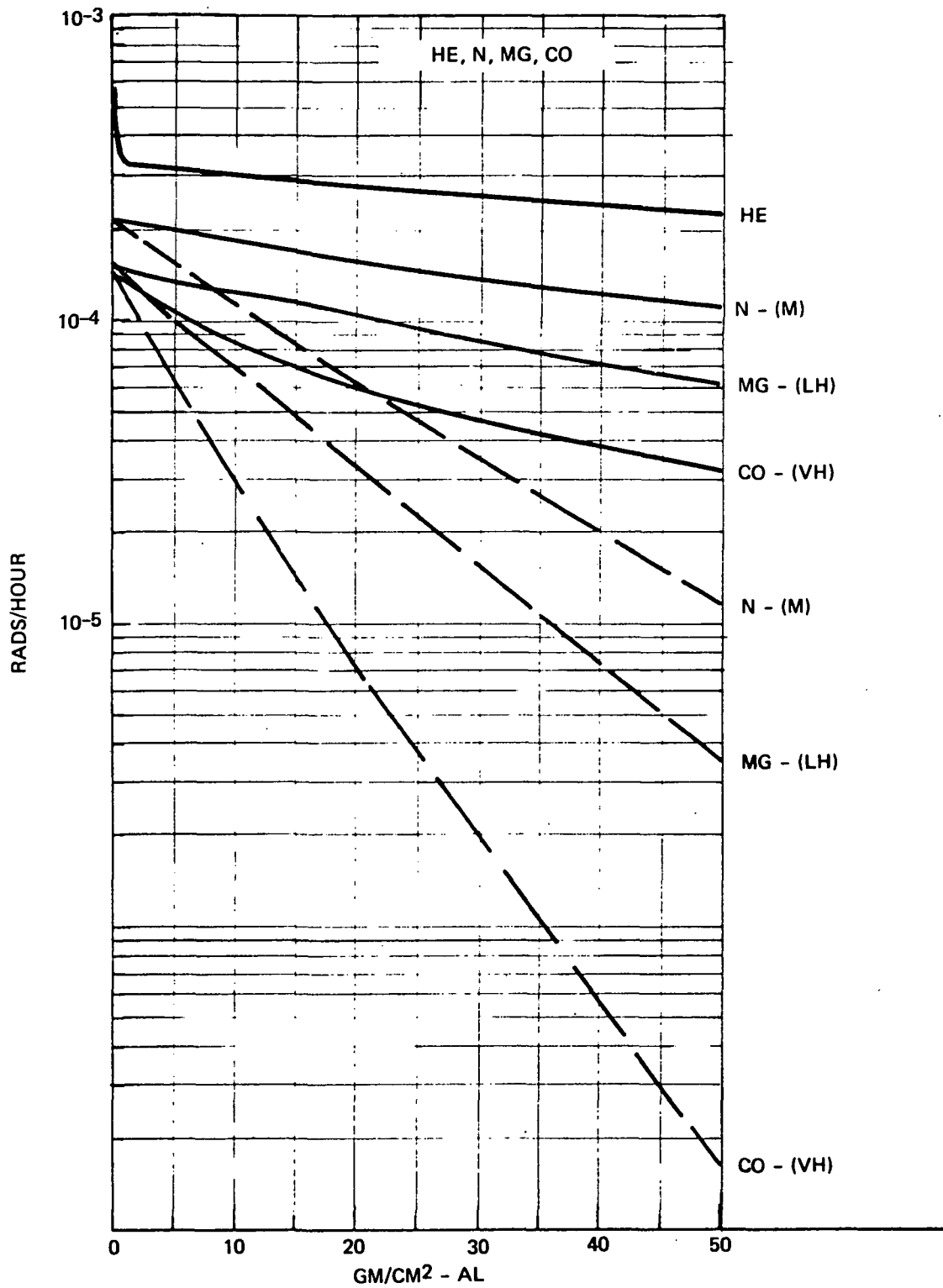


Figure 1: HEAVY PARTICLE GALACTIC DOSES

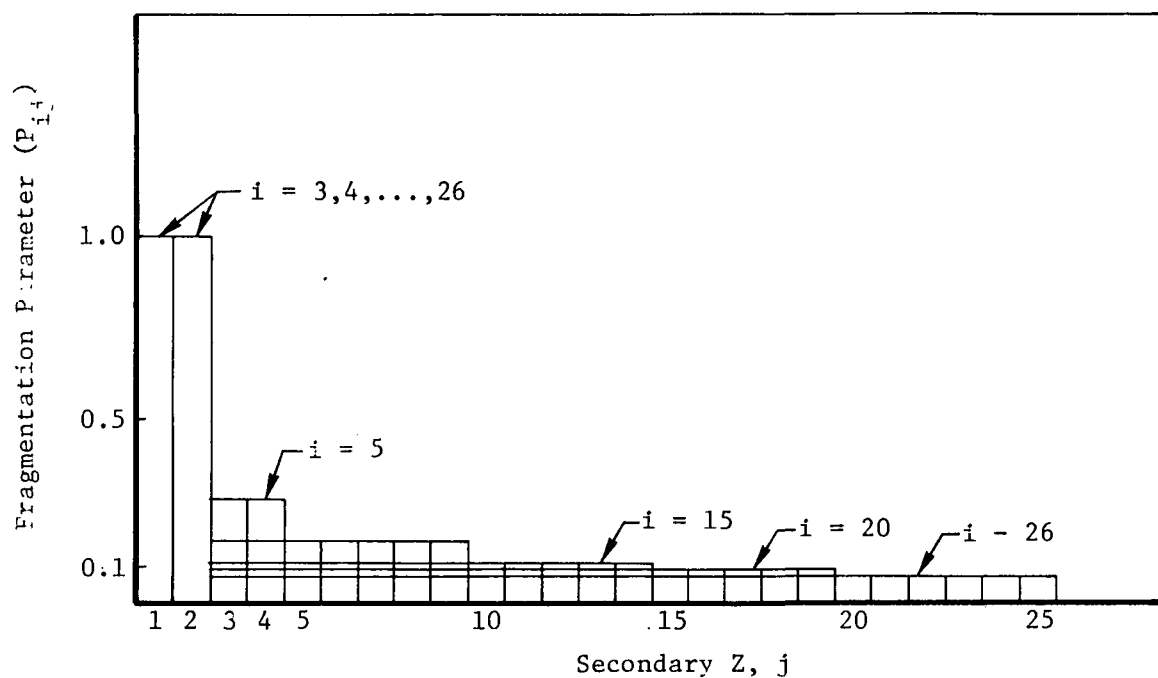


Figure 2 : FRAGMENTATION PARAMETERS---Set I, Conservation of Incident Z

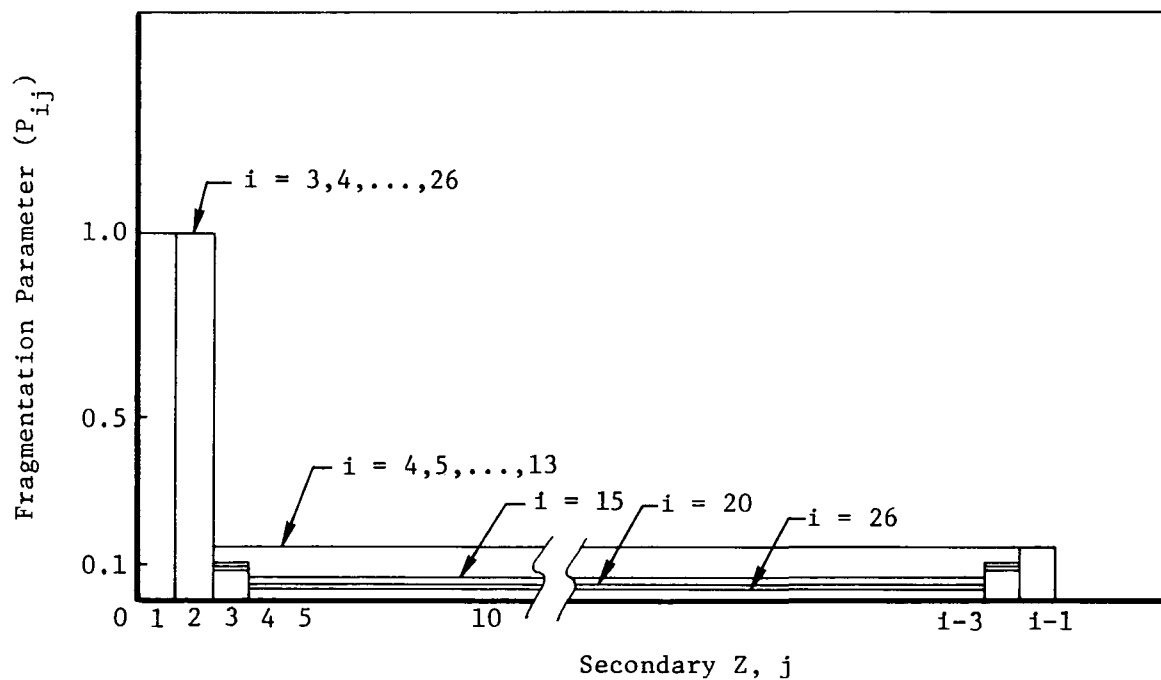


Figure 3 : FRAGMENTATION PARAMETERS---Set II

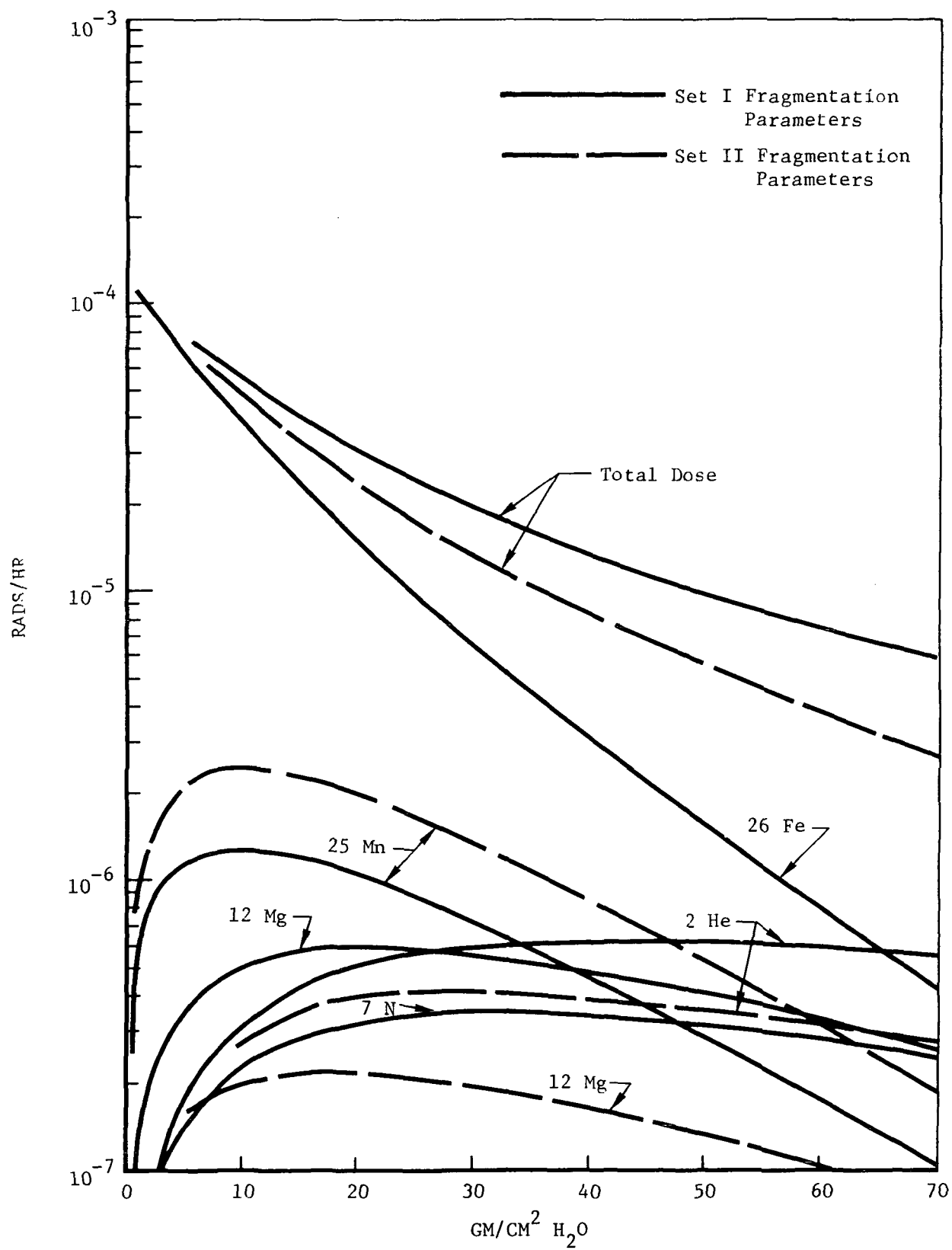


Figure 4: HEAVY GALACTIC PRIMARY VH GROUP DOSE

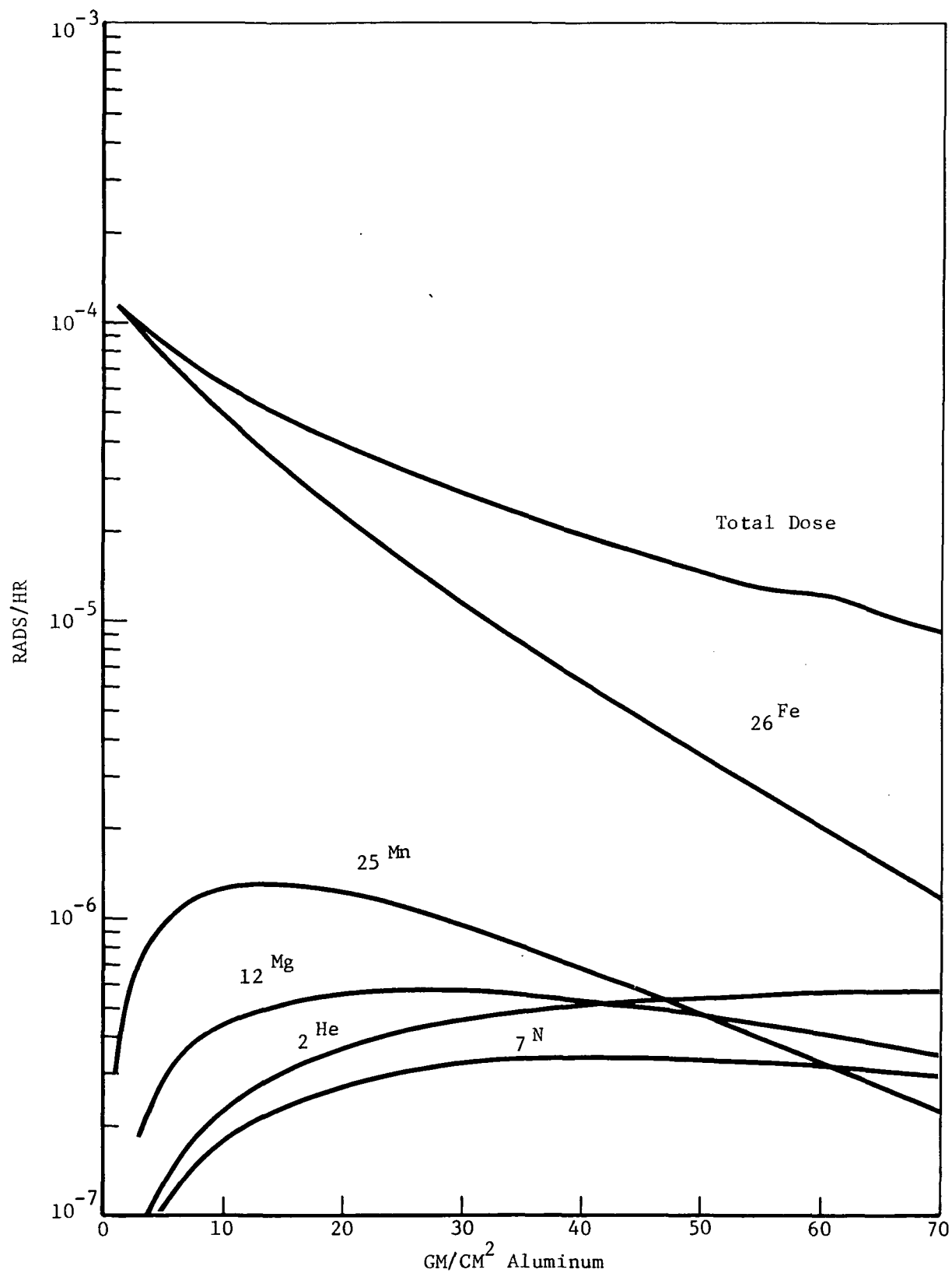


Figure 5: HEAVY GALACTIC PRIMARY VH GROUP

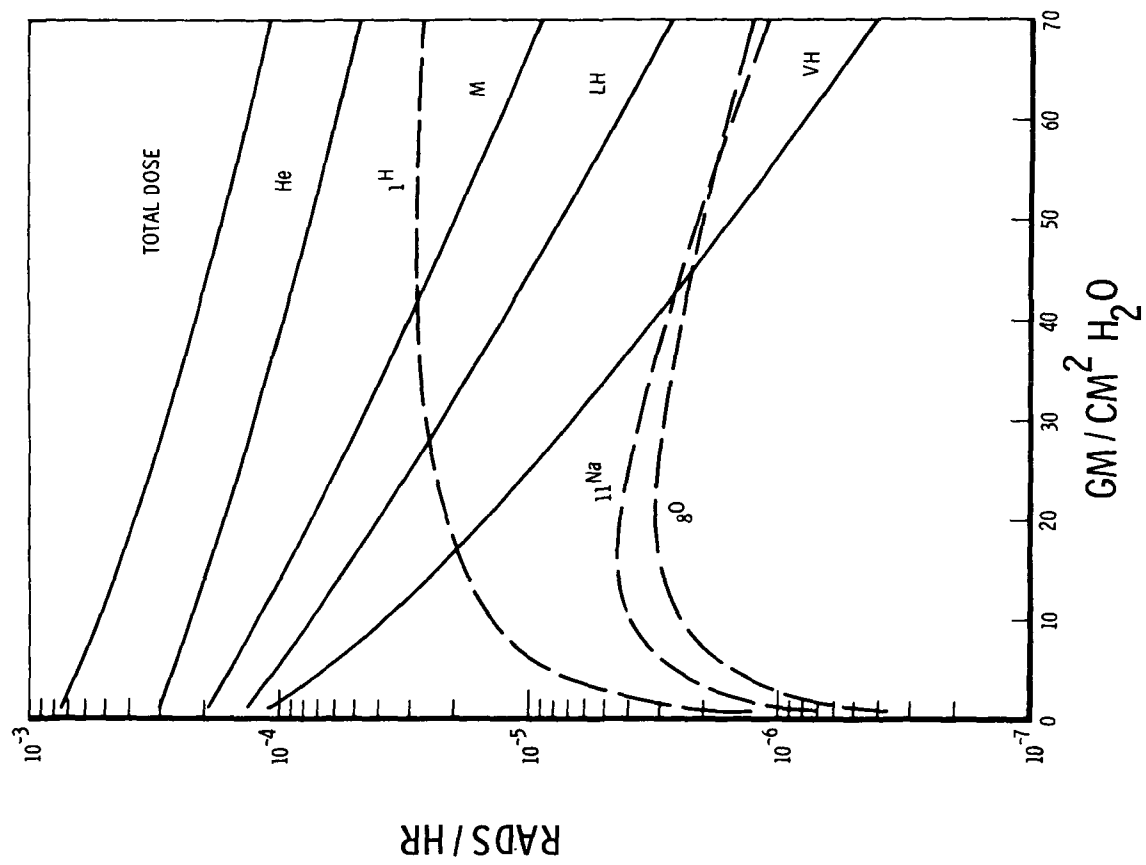


Figure 6: HEAVY GALACTIC PRIMARY TOTAL DOSE

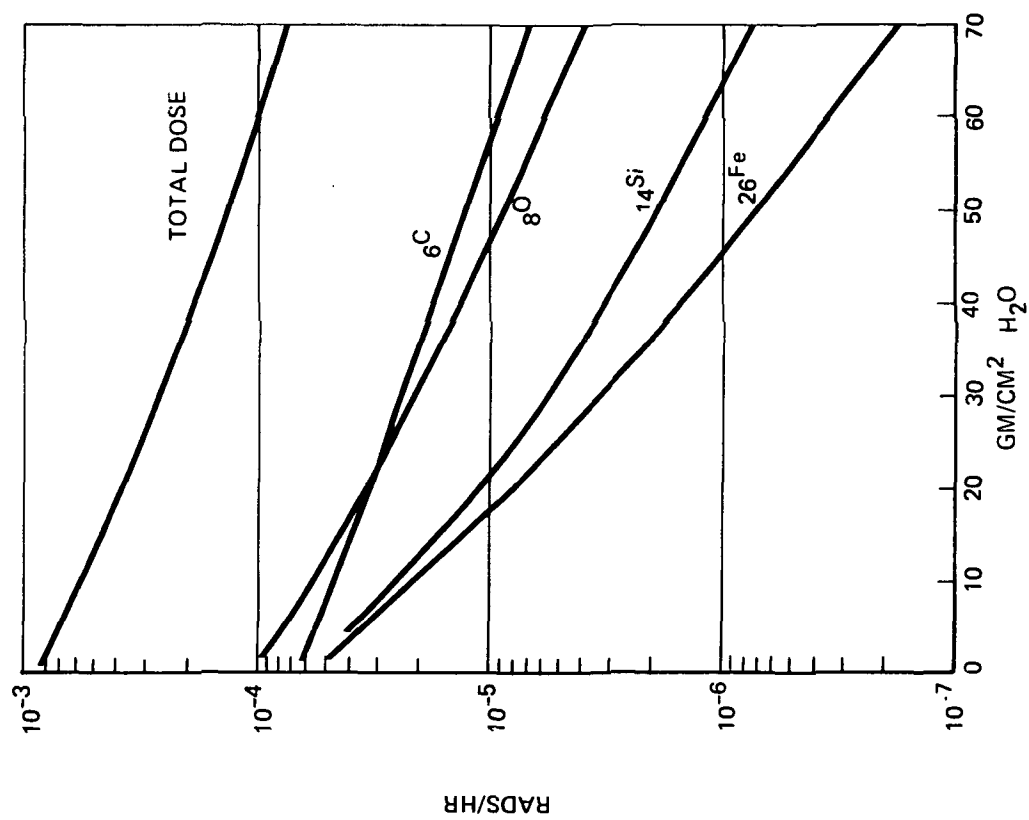


Figure 7: HEAVY GALACTIC PRIMARY TOTAL DOSE
Separate Spectra, Excluding Proton Dose

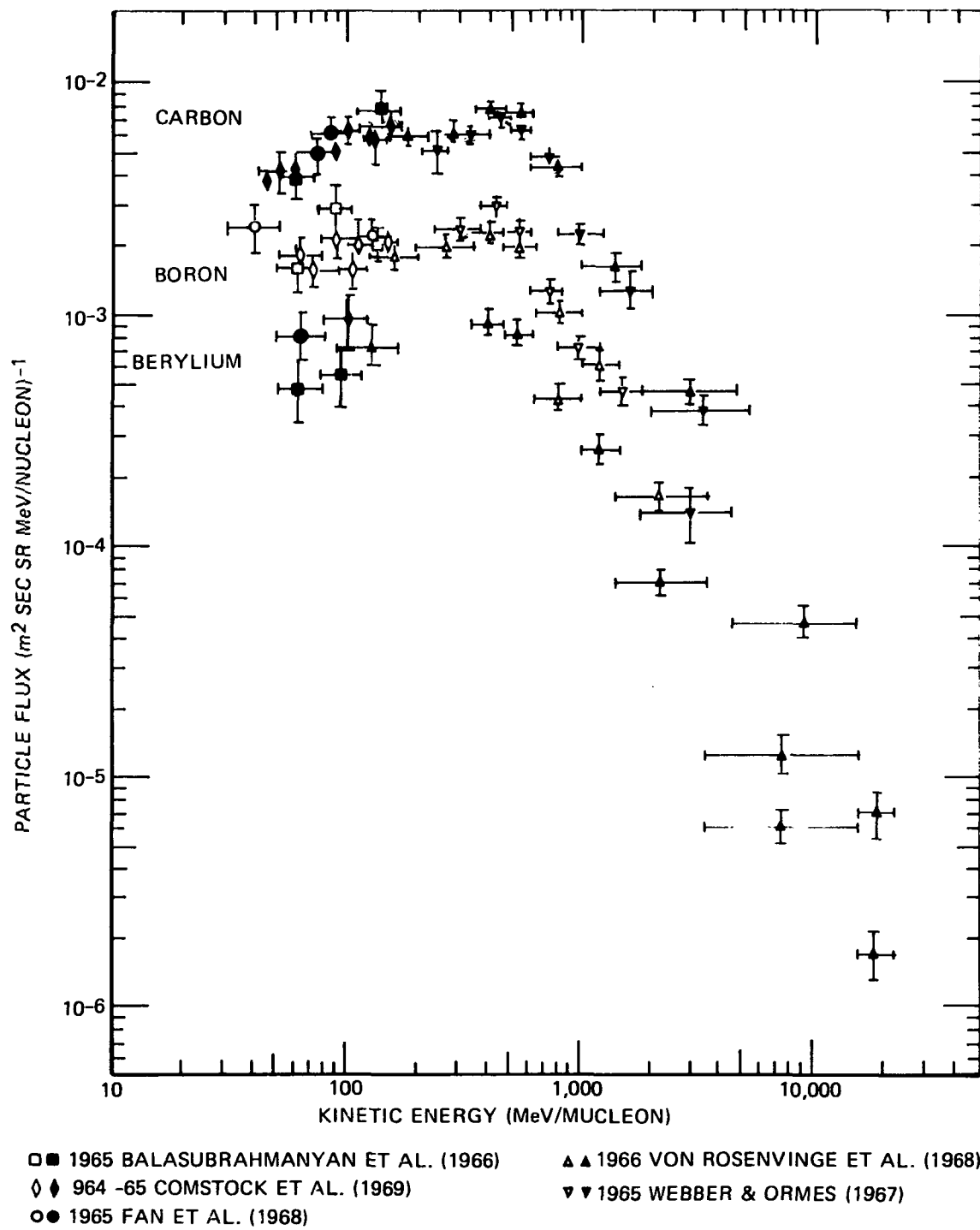


Figure 8: THE ENERGY SPECTRA OF Be, B, AND C.

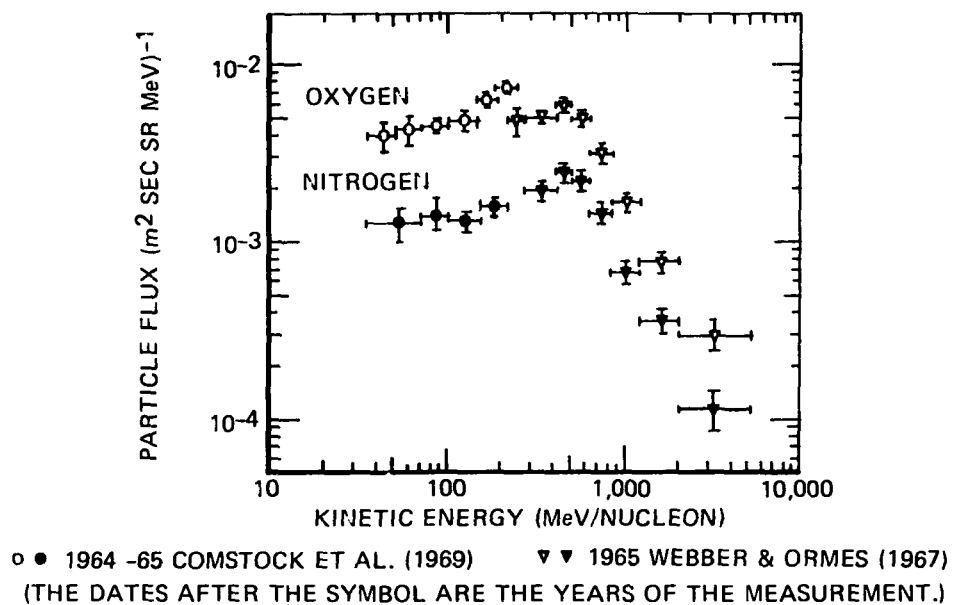


Figure 9: THE ENERGY SPECTRA OF N AND O.

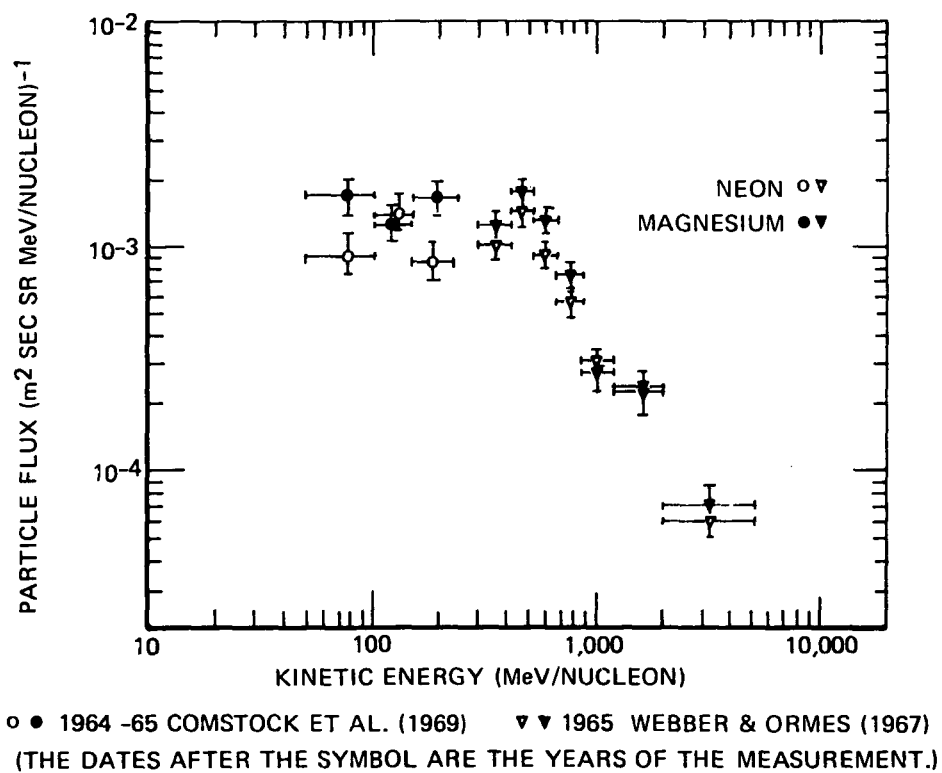
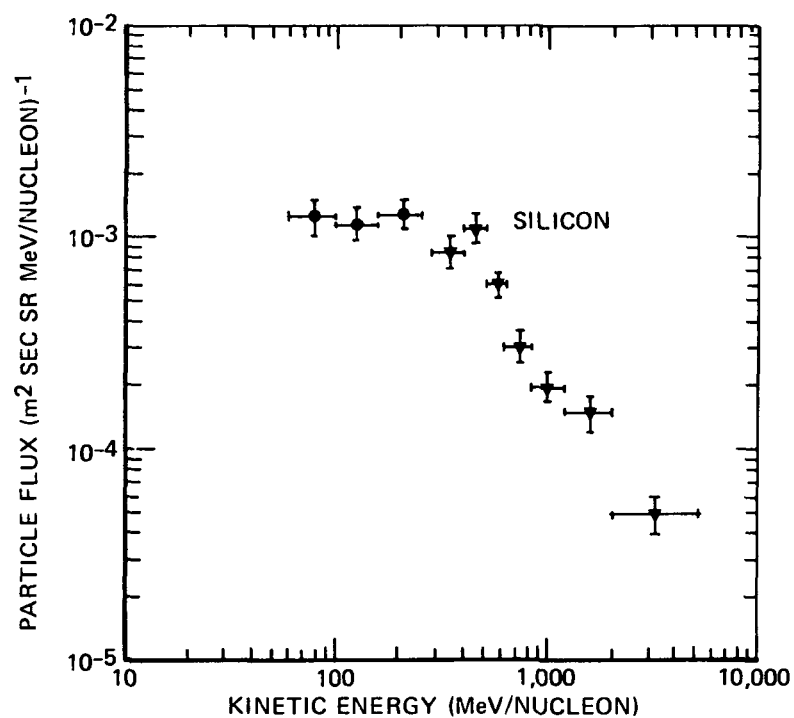


Figure 10: THE ENERGY SPECTRA OF NE AND MG.



- 1964-65 COMSTOCK ET AL. (1969) ▼ 1965 WEBBER & ORMES (1967)
 (THE DATES AFTER THE SYMBOL ARE THE YEARS OF THE MEASUREMENT.)

Figure 11: THE ENERGY SPECTRUM OF Si.

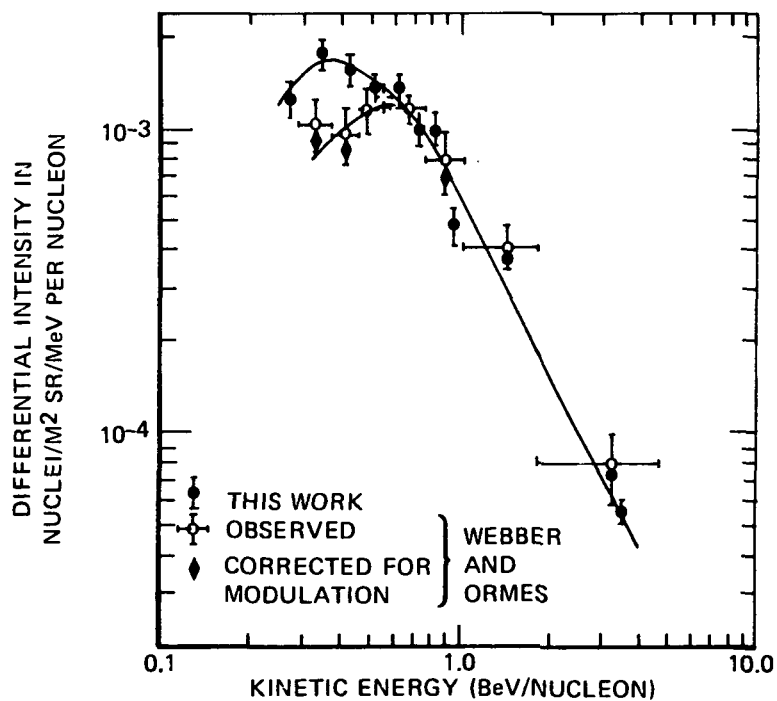


Figure 12: THE ENERGY SPECTRUM OF NUCLEI WITH $16 \leq Z \leq 30$
 (FREIER & WADDINGTON 1968b).

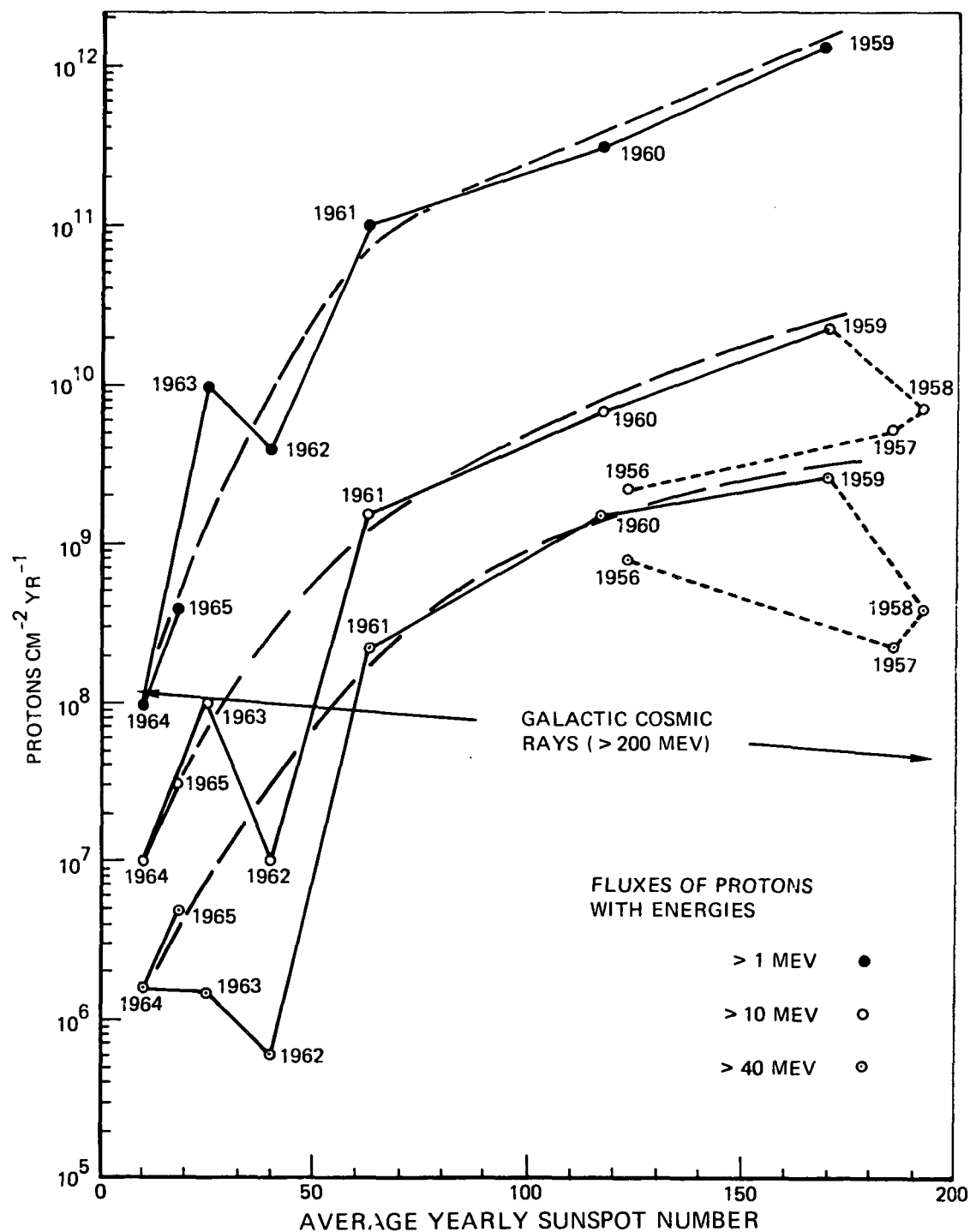


Figure 13: YEARLY FLUXES OF SOLAR COSMIC RAYS AS A FUNCTION OF MEAN ANNUAL SUNSPOT NUMBER FOR THE YEARS 1956 - 1965. THE DASHED LINES INDICATE ESTIMATED REGRESSION CURVES. THE YEARLY GALACTIC COSMIC RAY FLUX IS SHOWN FOR COMPARISON.

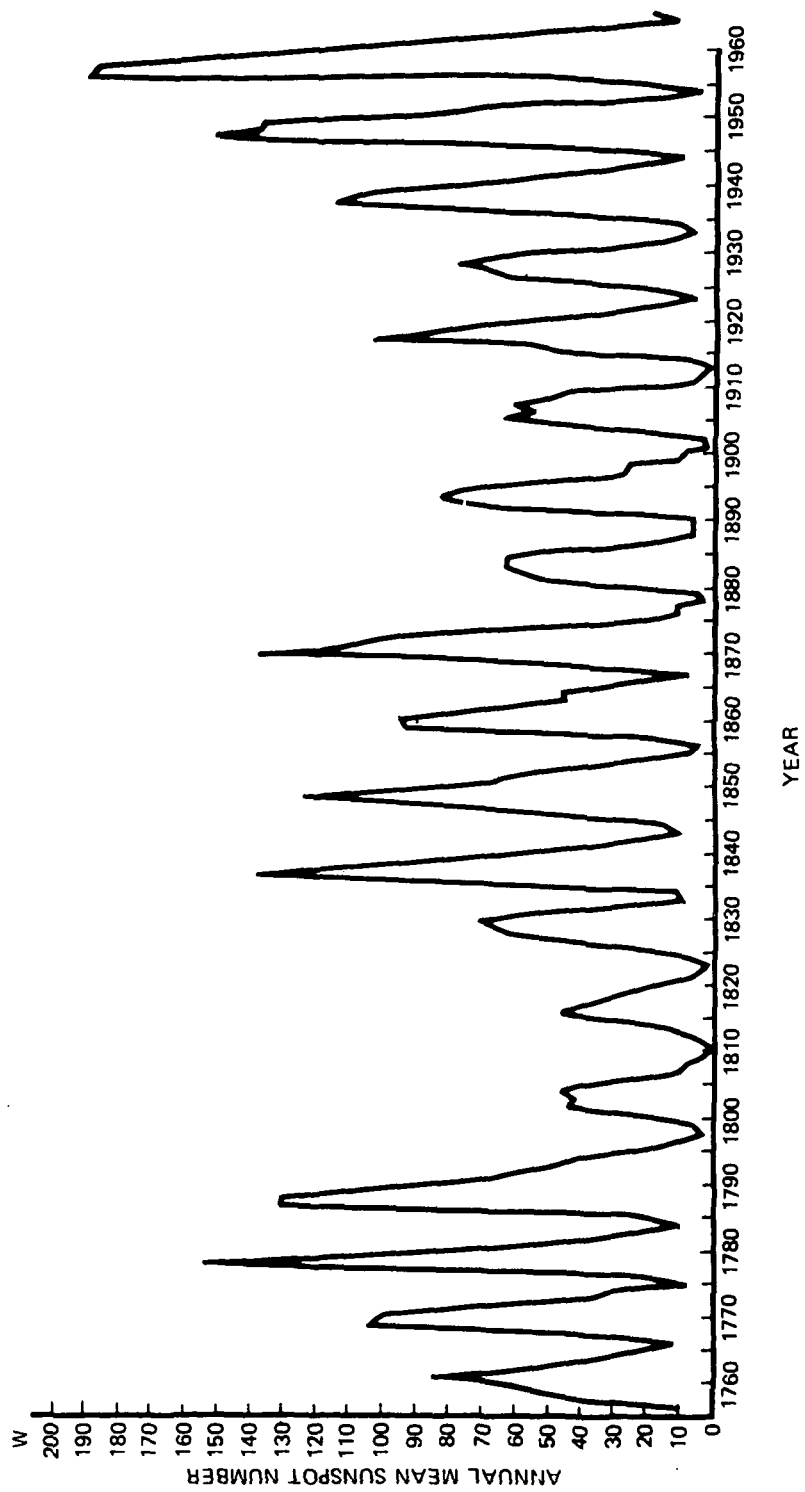


Figure 14: MEAN YEARLY SUNSPOT NUMBERS SINCE 1749

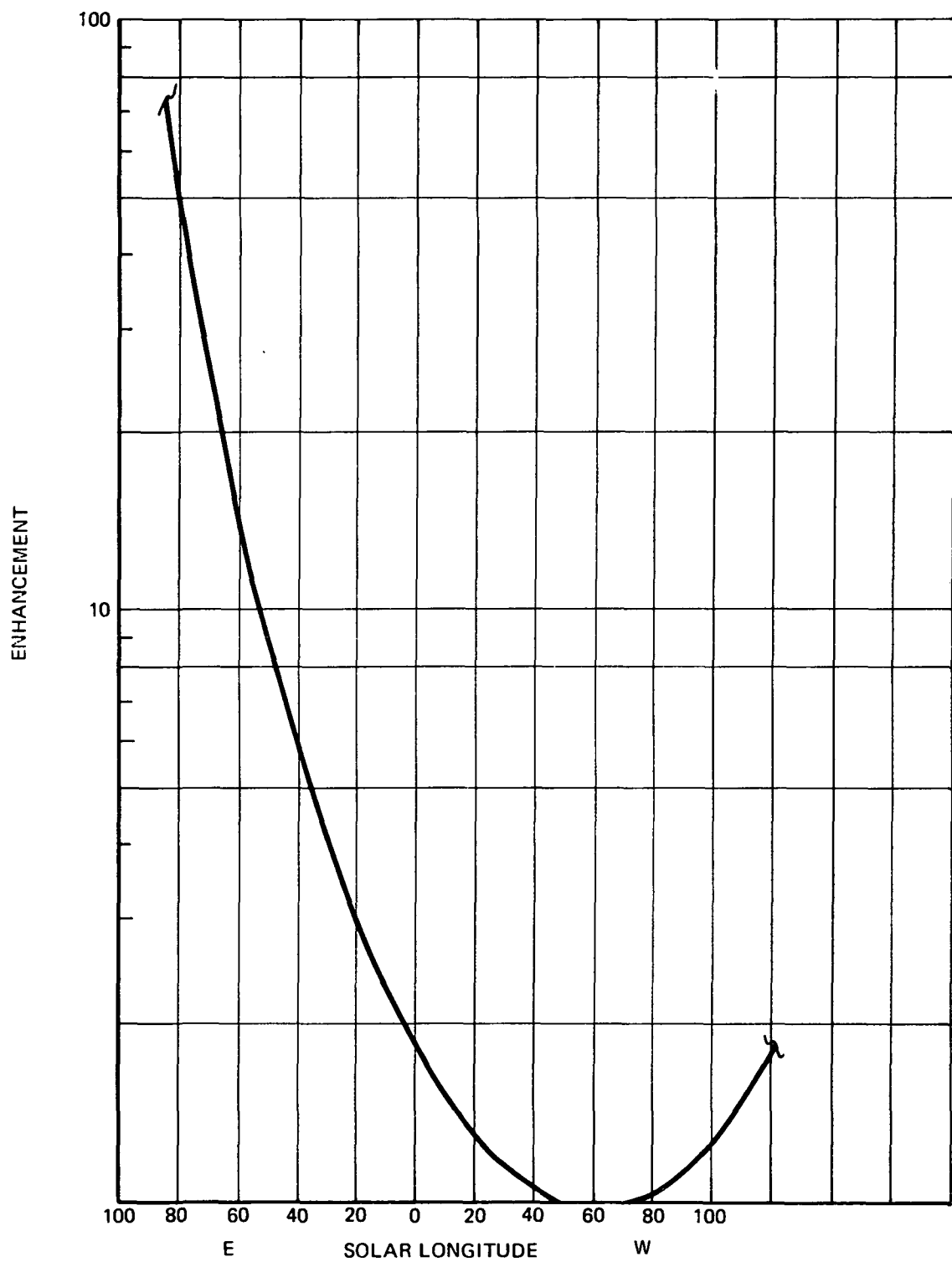


Figure 15: PARTICLE FLUENCE ENHANCEMENT VERSUS SOLAR LONGITUDE

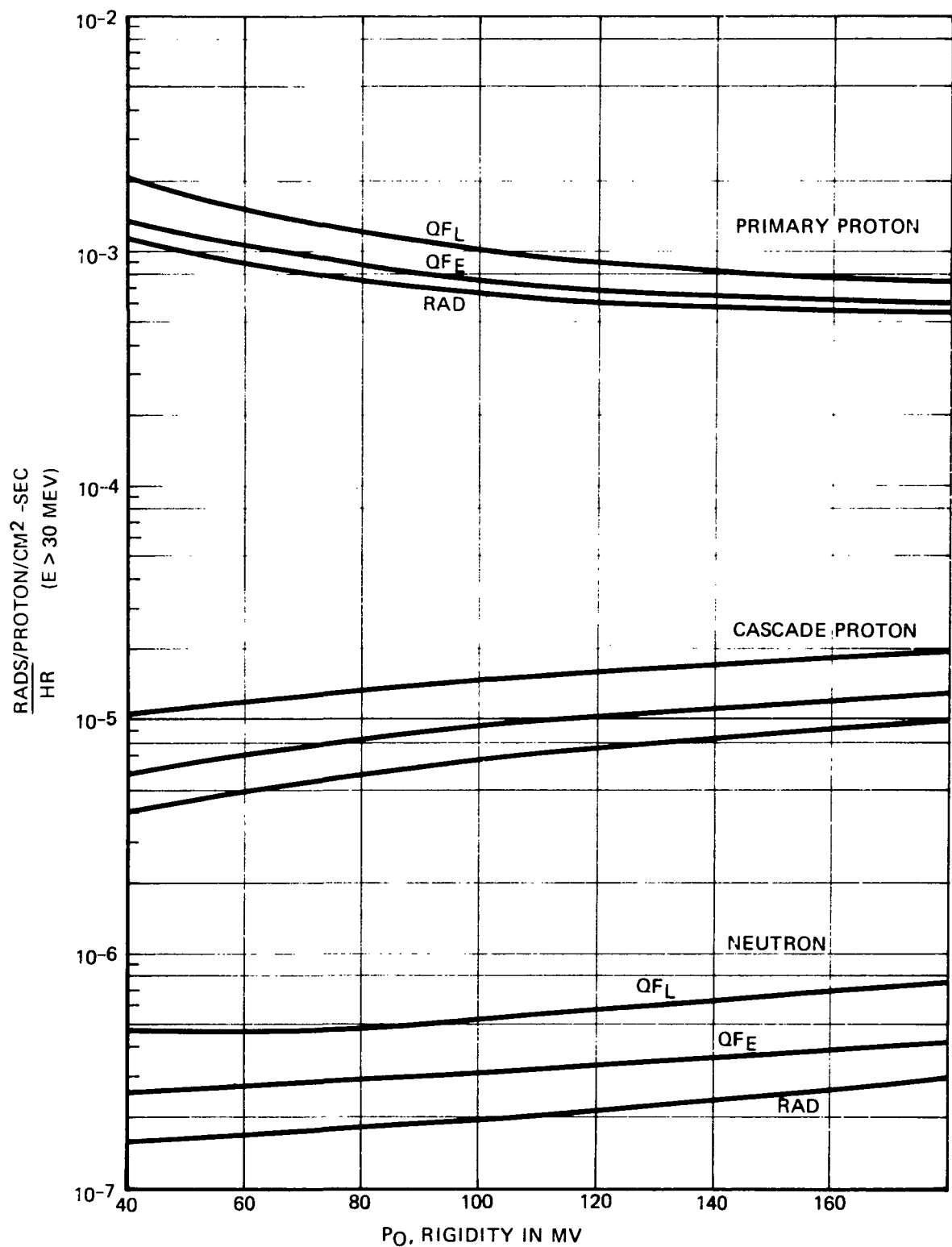


Figure 16: QFE & QFL WEIGHTED DOSES FOR EYE, 1 GM/CM² ALUMINUM

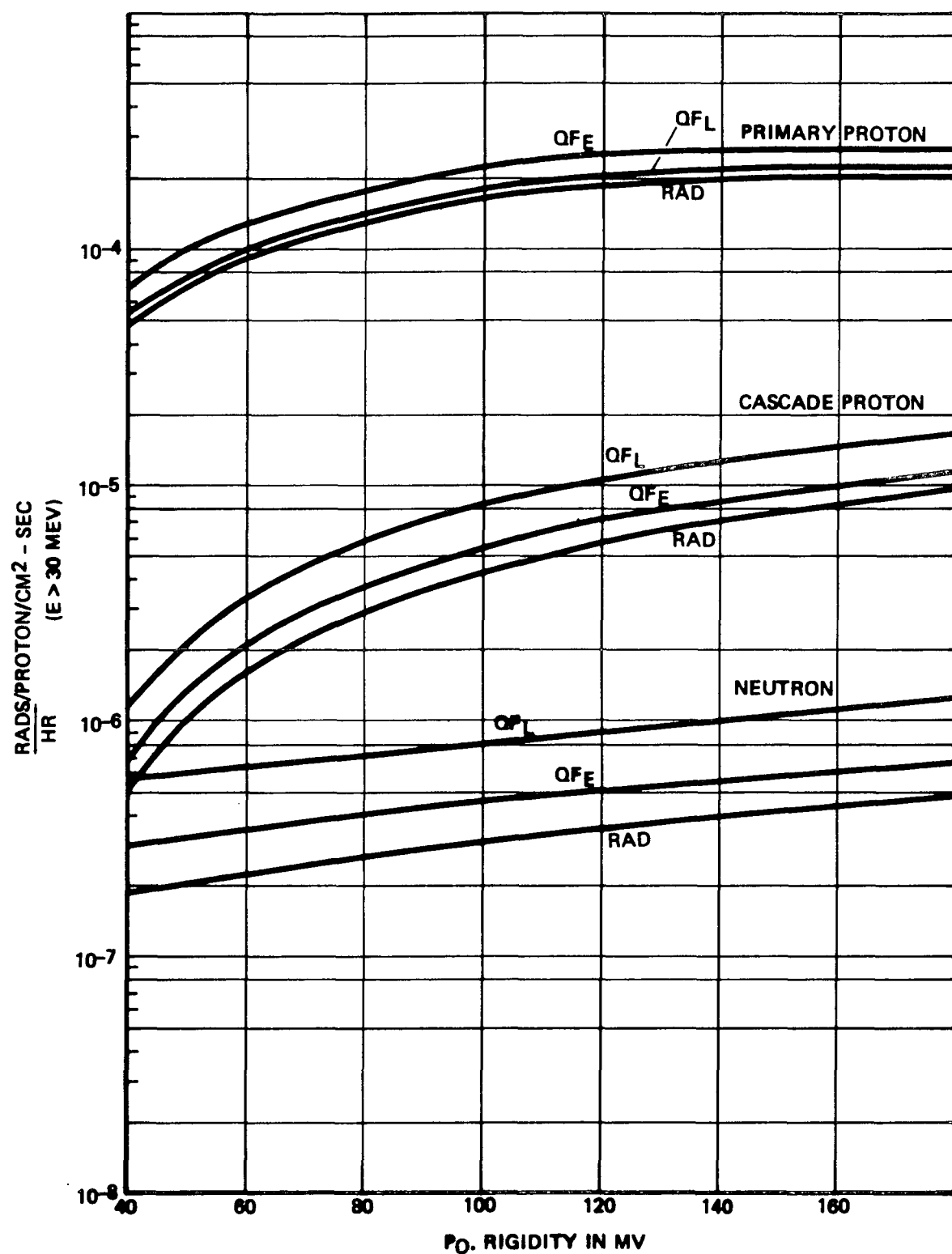


Figure 17: QFE & QFL WEIGHTED DOSES FOR EYE, 4 GM/CM² ALUMINUM

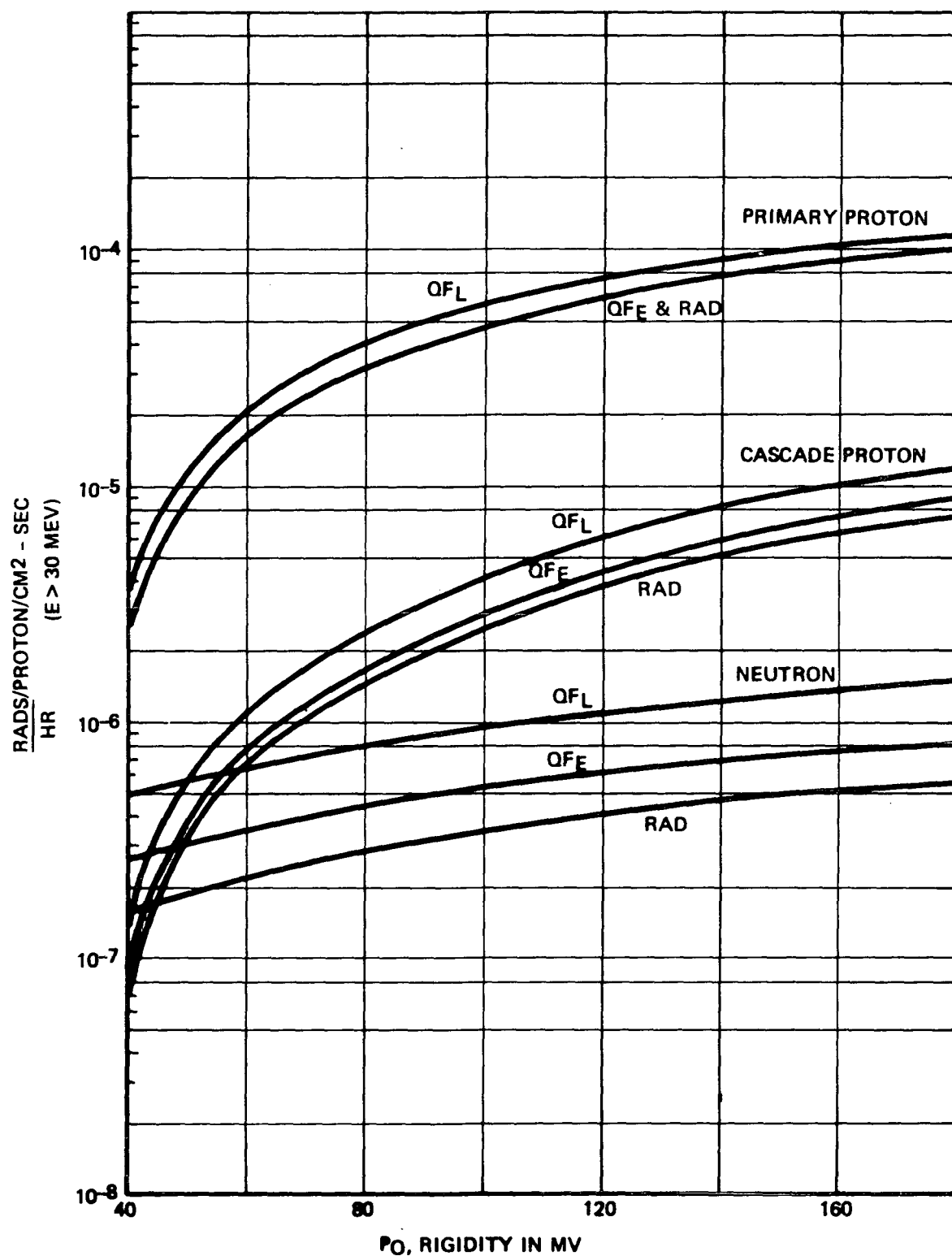


Figure 18: Q_F & Q_L WEIGHTED DOSES FOR EYE, 10 GM/CM² ALUMINUM

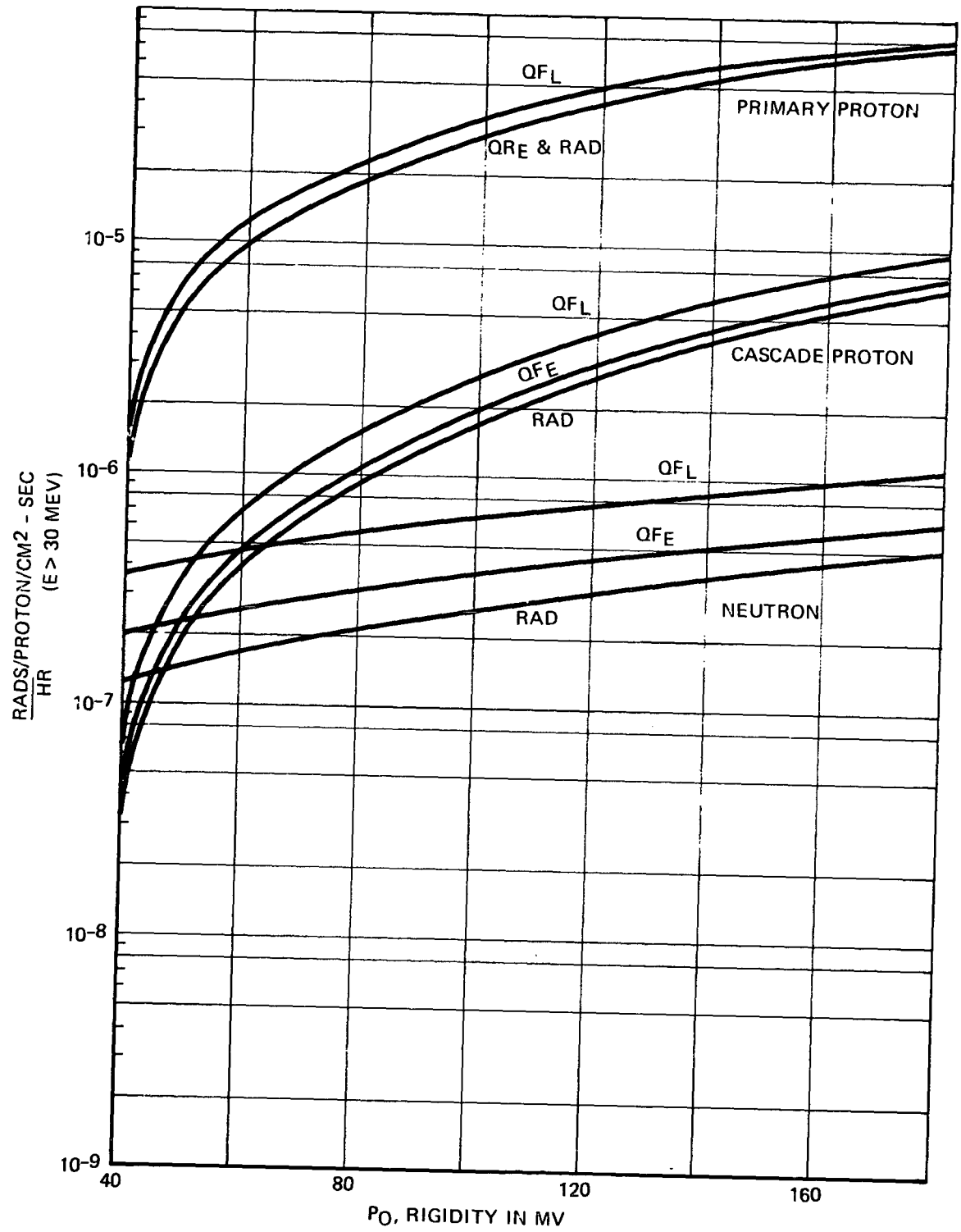


Figure 19: Q_{FE} & Q_{FL} WEIGHTED DOSES FOR WAIST 6, 1 GM/CM² AL

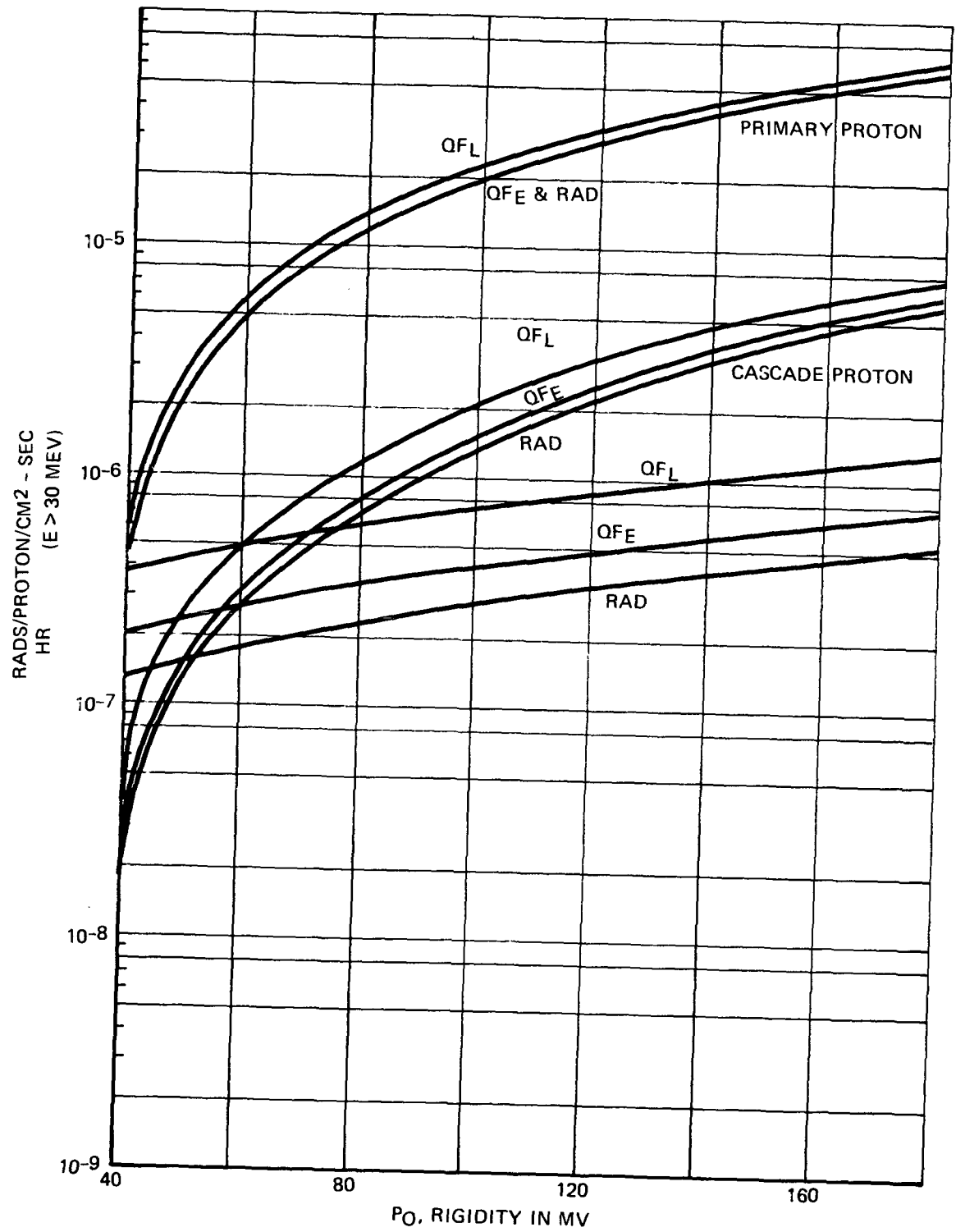


Figure 20: QFE & QFL WEIGHTED DOSES FOR WAIST 6, 4 GM/CM² ALUMINUM

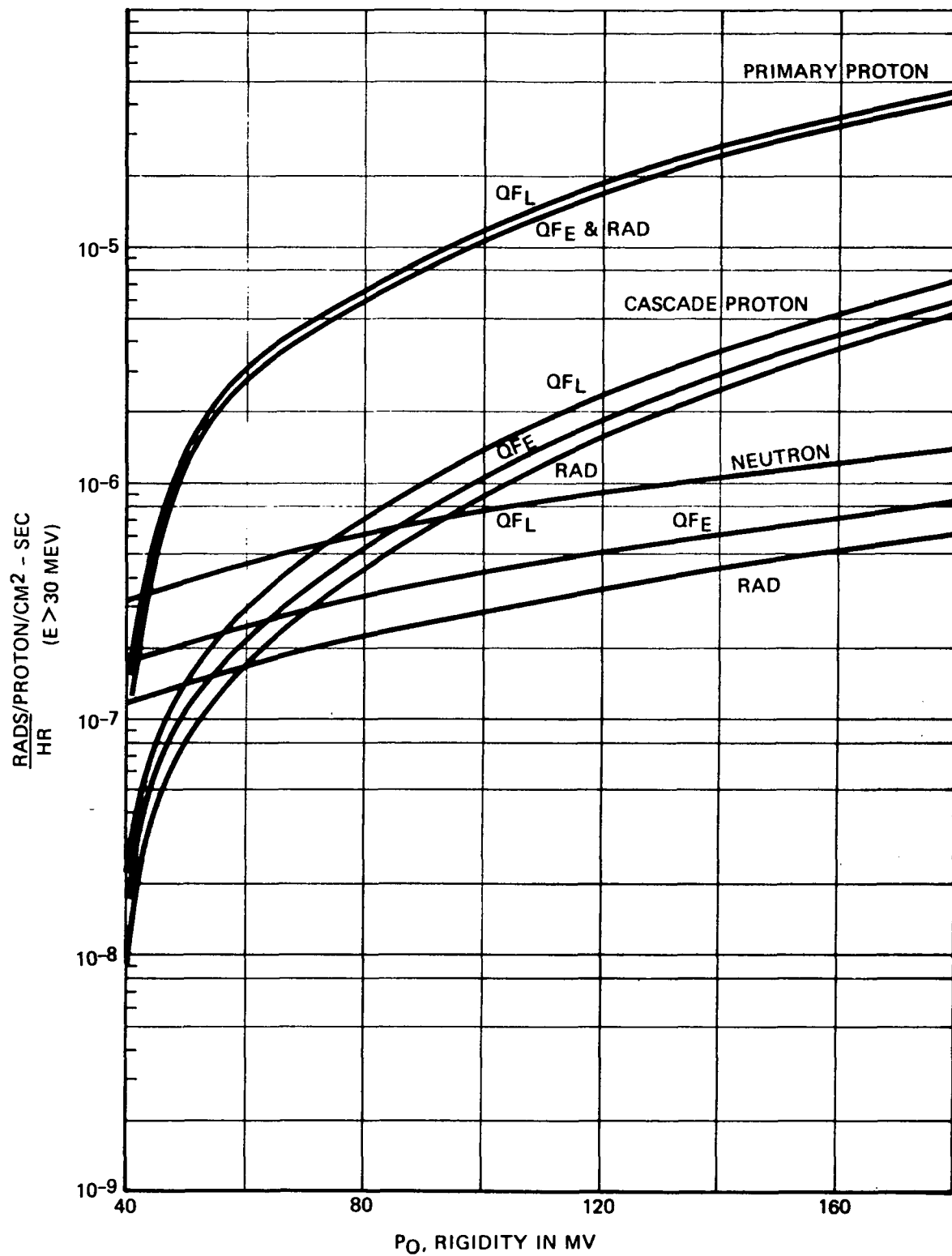


Figure 21: QF_e & QF_l WEIGHTED DOSES FOR WAIST 6, 10 GM/CM² ALUMINUM