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X-601-74-221
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NASA TM X- 70716

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(NASA-TM-X-70716) ENERGETIC SOLAR PROTON VERSUS TERRESTRIALLY TRAPPED PROTON FLUXES FOR THE ACTIVE YEARS 1977 - 1983 (NASA) ~~15~~ 16 p HC $4.00 CSCL 03B

N74-30259

Unclas
G3/29 54807

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GREENBELT, MARYLAND

X-601-74-221

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ABSTRACT

Ratios of solar to trapped proton fluences have been computed for circular-orbit, geocentric space missions to be flown during the active phase of the next solar cycle (1977-1983). The ratios are presented as functions of orbit altitude and inclination, mission duration, proton energy threshold, and the chance the mission planner is willing to take that the actually encountered solar proton fluence will exceed the design fluence provided by the statistical solar proton model used. It is shown that the ratio is most sensitively dependent on orbit altitude and inclination, with trapped protons dominant for low inclination, low- and mid-altitude orbits and for high-inclination, mid-altitude orbits. Conversely, solar protons are dominant for high-inclination, low-altitude orbits, and for low- and high-inclination, high-altitude orbits.

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ENERGETIC SOLAR PROTON VS. TERRESTRIALLY TRAPPED PROTON FLUXES FOR THE ACTIVE YEARS 1977-1983

INTRODUCTION

This note is intended to demonstrate the relative importance of solar and trapped proton fluxes in the consideration of shielding requirements for 1977-1983 geocentric space missions. Using the latest solar proton and trapped proton models, fluences of these particles encountered by spacecraft in circular orbits have been computed as functions of orbital altitude and inclination, mission duration, threshold energy (between 10 and 100 MeV), and, for solar proton fluxes, risk factor.* Ratios of solar-to-trapped proton fluences were then taken. These ratios give the relative importance of the two proton populations and indicate to the mission planner whether he must consider both or only one of these populations. To determine the absolute fluence level of either population, the mission planner must refer to one of the sources cited below.

SOLAR PROTONS

The solar proton fluences used in this study are based on the analysis of King.[1] Interplanetary 1 AU measurements of solar event fluences, taken over the period 1966-1972, were handled statistically to predict solar proton fluences for the active phase of the next solar cycle, 1977-1983, at varying probability levels and for several durations of exposure.

*Risk factor: a parameter expressing the chance a mission planner is willing to take that the actually encountered fluxes will exceed the predicted levels.

The salient features of the analysis are:

a) the grouping of events into ordinary and anomalously large (AL) events,

b) the assumption that the spectrum of all anomalously large events occurring in the 1977-1983 period will replicate the spectrum of the August 1972 event,

c) the assumption that the probability of event occurrence during the next active period is independent of time,

d) the process of estimating the frequency of future events by an extension of Poisson statistics, which compensates, to some extent, for the limited data base on which the statistical predictions are made.

An important result of the analysis is that, except for very short missions and relatively large risk factors, spacecraft design fluences can now be obtained by considering anomalously large events only, without concern for ordinary events.

Of particular interest to the present analysis is the manner by which magnetospheric solar proton fluxes are determined from the interplanetary values of King.[1] As discussed in Stassinopoulos and King,[2] the assumption was made that 10-100 MeV solar protons have a common geomagnetic cutoff (L_c) in the McIlwain shell parameter L. This is probably an adequate treatment, given the fact that diurnal and geomagnetic-disturbance-level variations in the cutoff value are greater than those variations due to energy dependence alone over the indicated range. Results based on this assumption (with L_c=5) were published in Stassinopoulos and King[2] and in King,[1] and are used in the present analysis. It should be noted that the common cutoff approximation becomes less accurate as particle energies increase above 100 MeV, causing the orbit-integrated flux of solar protons with energies

E>100 to be underestimated. However, flux levels of such energetic particles decrease markedly relative to the lower energy particles.

TRAPPED PROTONS

The models of magnetospherically trapped protons used in this analysis are AP6 in Lavine and Vette,[3] and AP7 in Lavine and Vette.[4] These models are based on data obtained by several satellite experiments between 1962-1964 and 1961-1966, respectively. In each model, the integral omnidirectional flux is given as:

$$J(>E;B,L) = J(>E_1;B,L)\ N\ (E;B,L).$$

The spectral function N was chosen as a power law for AP6

$$N = (E/E_1)^{-P(B,L)}$$

and as an exponential for AP7

$$N = \exp\ (-(E-E_1)/E_0(B,L)).$$

The model then consists of the specification of

$$J(>E_1;B,L) \text{ and } P(B,L) \text{ or } E_0(B,L).$$

Typically the models agree to within a factor of 2 with all the data from which they were generated.

Time dependences were handled by ignoring possible solar cycle variations (about which too little was known to do otherwise) and by presenting the model for periods unaffected by magnetic storms. It is now realized that, although solar cycle variations may be insignificant above 600 km, below that level they become increasingly important due to the variation in atmospheric density as discussed in Dragt.[5] Integral fluxes above 10 MeV may have a solar cycle variation amplitude of a factor of 2 to 4 at low altitudes (with largest flux at solar minimum). This question will be discussed in detail in the next trapped proton model to be published in the near future by Sawyer.[6]

Thus, the models AP6 and AP7, when applied to the solar active period 1977-1983, should be valid to a factor of 2 above 600 km and may overestimate fluxes by a factor of 2 to 4 below 600 km. These uncertainties are insignificant relative to the intrinsic statistical uncertainties in the solar proton model.

THE CALCULATIONS

It is desired to specify the ratio R:

$$R(h,i;E;\tau,Q) = \frac{S(h,i;E;\tau,Q)}{T(h,i;E;\tau)} \tag{1}$$

Here S and T are fluences associated with solar and trapped protons, respectively. The independent variables are: h and i, the altitude and inclination of the circular orbit; E, the proton energy threshold; τ, the mission duration; and Q, the risk factor. Note that, owing to the statistical and deterministic natures of solar and trapped fluences respectively, S is a design fluence which may or may not occur, while T is the trapped proton fluence which the spacecraft is actually expected to encounter.

From King,[1] we have

$$S(h,i;E;\tau,Q) = S_1(h,i)\left[S_2(E)\ S_3(\tau,Q) + S_4(E;\tau,Q)\right]. \tag{2}$$

Here $S_1(h,i)$ represents orbit-integrated effect of geomagnetic shielding (assumed energy independent), $S_2(E)$ gives the integral flux and spectrum of each anomalously large event, while $S_3(\tau,Q)$ gives the number of such events expected, and $S_4(E;\tau,Q)$ gives the fluence contributed by ordinary events. For values of τ and Q such that $S_3>0$, we may take $S_4 = 0$.

For time scales long compared to one orbital period, the trapped proton fluences are obtained from

$$T(h,i;E;\tau) = T_1(h,i;E) \times \tau \tag{3}$$

where T_1 is an annual trapped proton fluence and τ is the mission duration in units of years.

With equations 2 and 3, the ratio R may be rewritten as

$$R(h,i;E;\tau,Q) = R_1(h,i;E)\ R_2(E;\tau,Q) \tag{4}$$

where $R_1 = S_1S_2/T_1$ and $R_2 = \tau^{-1} \times (S_3 + S_4/S_2)$. The R_1 functions have the significance of being the solar-to-trapped proton fluence ratios for 1-year missions for which exactly one anomalously large event must be anticipated. R_1 functions are plotted in Figures 1a-1d in terms of iso-ratio contours in h-i space for a series of energy thresholds. The R_2 functions are R_1 modifiers, adjusting the ratios to reflect the Q, τ dependent variation in the number of AL events to be expected. Values of R_2 are inserted in matrix form into Figures 1a-1d for mission duration between 2 months and 5 years and for risk factors between .01 and 0.1 (1 and 10 percent). Note that R_2 values are independent of energy for all Q, τ matrix elements except for the 5 and 10 percent risk factors of the 2-month missions, for which no

AL event is predicted. For all other elements, $S_3>0$ and S_4/S_2 becomes insignificant.

DISCUSSION

Many features are immediately visible in Figures 1a-1d. First of all, the solar-to-trapped ratio is zero for orbits in the shaded areas where, by virtue of geomagnetic shielding, no solar particle reaches a spacecraft anywhere along its orbit. In the cross hatched region (high altitude, low inclination) the ratio is meaningless because neither solar nor trapped protons reach the spacecraft.

At a fixed altitude (below a few hundred kilometers or so) the dominant fluence source shifts rapidly from trapped to solar protons as orbit inclination is increased through the 50-to 60-degree range. Thus, for low-altitude, polar-orbiting spacecraft, solar protons are very important relative to trapped protons. As the altitude of a polar orbit mission is increased, the solar-to-trapped ratio declines and then increases again. This is mainly due to the low latitude portion of the orbit moving out to, and then beyond, the regions of maximum trapped particle fluxes. The energy dependence of R_1, apparent from a sequential examination of Figures 1a-1d, results from the variability of the trapped proton spectrum at differing spatial points and the dissimilarity of the trapped and solar spectra.

By examination of the inset matrices in Figures 1a-1d, it is apparent that for a fixed risk factor, solar particles tend to become relatively less important than trapped particles as mission duration increases. At fixed mission duration, however, solar protons become relatively more important than trapped particles as the permissible risk factor is decreased. Note, however, that as long as at least one AL event is anticipated, the variation in the solar-to-trapped ratio due to the mission duration and risk factor dependences is very small relative to the variation associated with the altitude and inclination dependences.

CONCLUSIONS

The purpose of the analysis has been to permit the space mission planner to readily determine whether he must consider solar and trapped proton fluences, or only one or the other, in his shielding requirements. The analysis is not intended to provide actual fluence values, which are available in the references cited.

The mission planner must specify orbit altitude and inclination (circular orbits only), mission duration, and the percent risk he is willing to take that the actually encountered solar proton fluence will exceed his design fluence. Then from the appropriate figure for the energy threshold of interest, he multiplies the appropriate factor from the inset matrix by the appropriate plotted R_1 value in order to determine the ratio of solar-to-trapped proton fluences he must allow for in his mission planning. Typically, interpolation will be required.

It is clear that for low-altitude polar and very high-altitude missions (any inclination), solar protons dominate trapped protons. Conversely, for low-inclination, low- and medium-altitude missions and for high-inclination, medium-altitude missions, trapped protons dominate the solar protons.

Due to the uncertainties in the models, we would recommend that if the value of the S/T ratio fell between 0.1 and 10, the mission planner ought to consider both trapped and solar proton fluences. Likewise, if the desired h, i point is in a region of rapidly changing S/T ratio, both trapped and solar fluxes should be considered.

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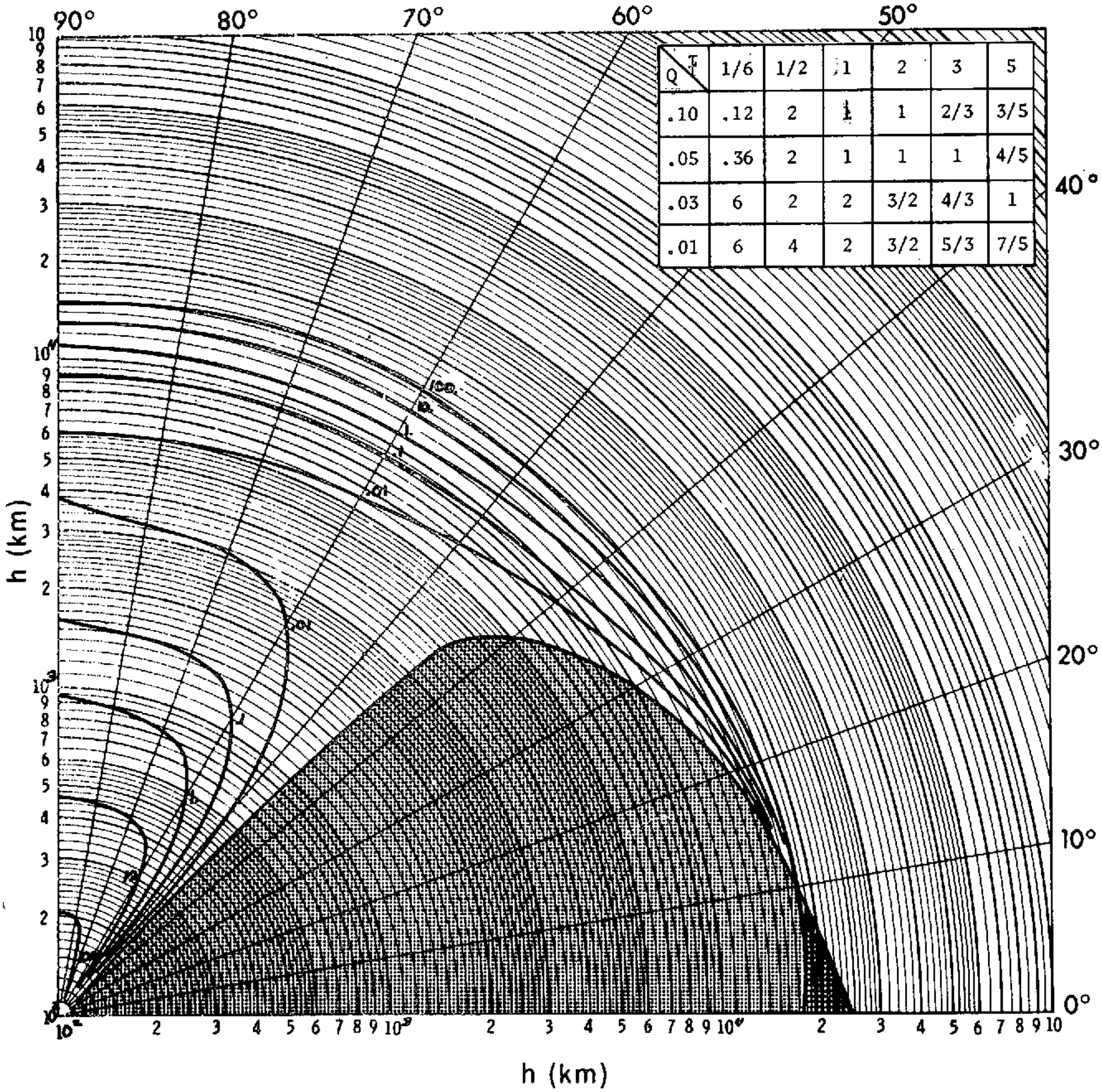
Figure 1

Constant Value Contours for Ratios of Solar-to-Trapped Proton Fluences as a Function of Orbit Altitude and Inclination for One Year Missions and for 10 Percent Risk Factor. Inset Matrix gives Multiplication Factors for Other Mission Durations (τ, in years) and Risk Factors (Q).



Q \ T	1/6	1/2	1	2	3	5
.10	.12	2	1	1	2/3	3/5
.05	.36	2	1	1	1	4/5
.03	6	2	2	3/2	4/3	1
.01	6	4	2	3/2	5/3	7/5

Figure 1a - $E_p > 10$ MeV

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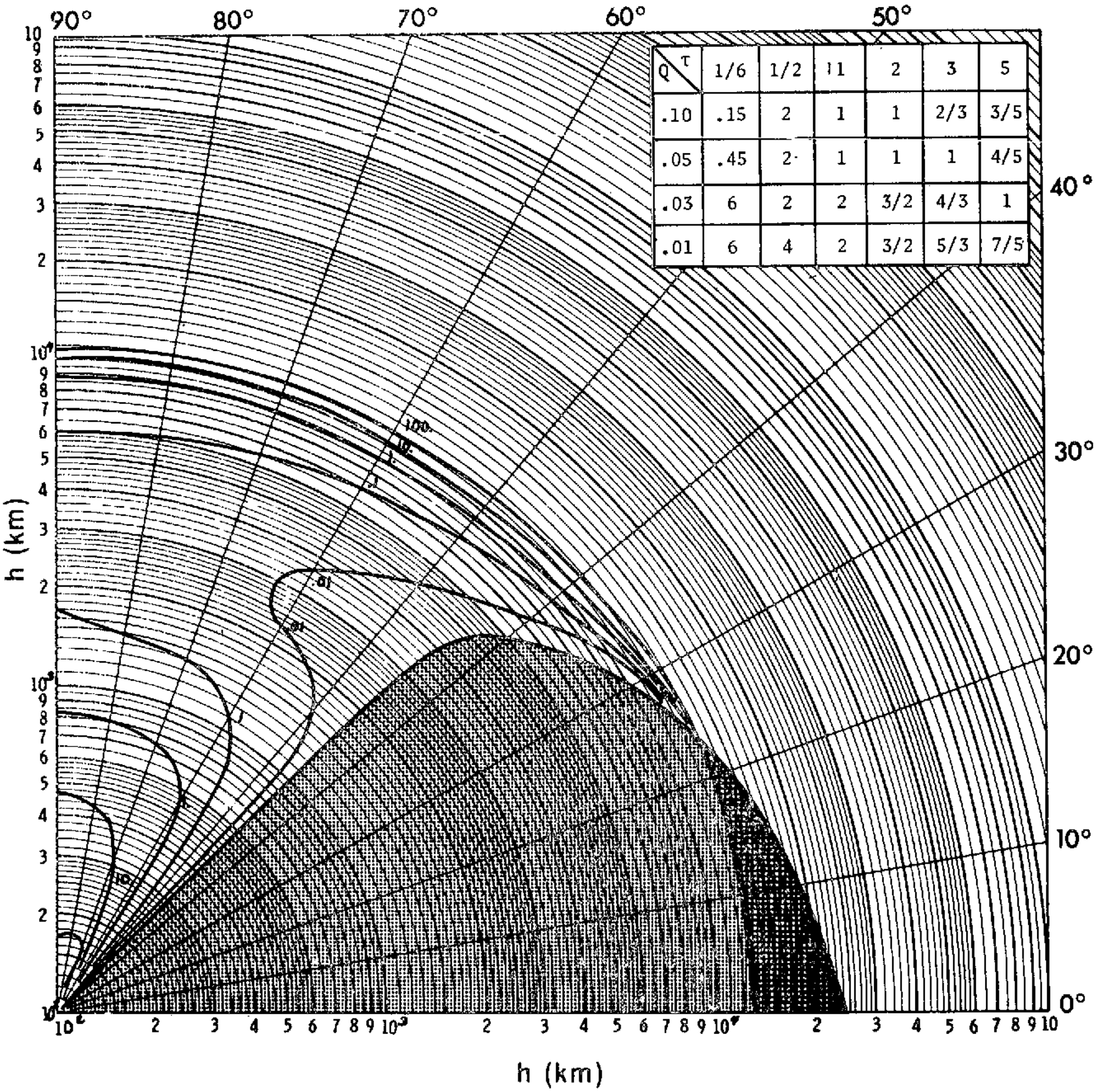

Q \ τ	1/6	1/2	1	2	3	5
.10	.15	2	1	1	2/3	3/5
.05	.45	2	1	1	1	4/5
.03	6	2	2	3/2	4/3	1
.01	6	4	2	3/2	5/3	7/5

Figure 1b - E_p>30 MeV

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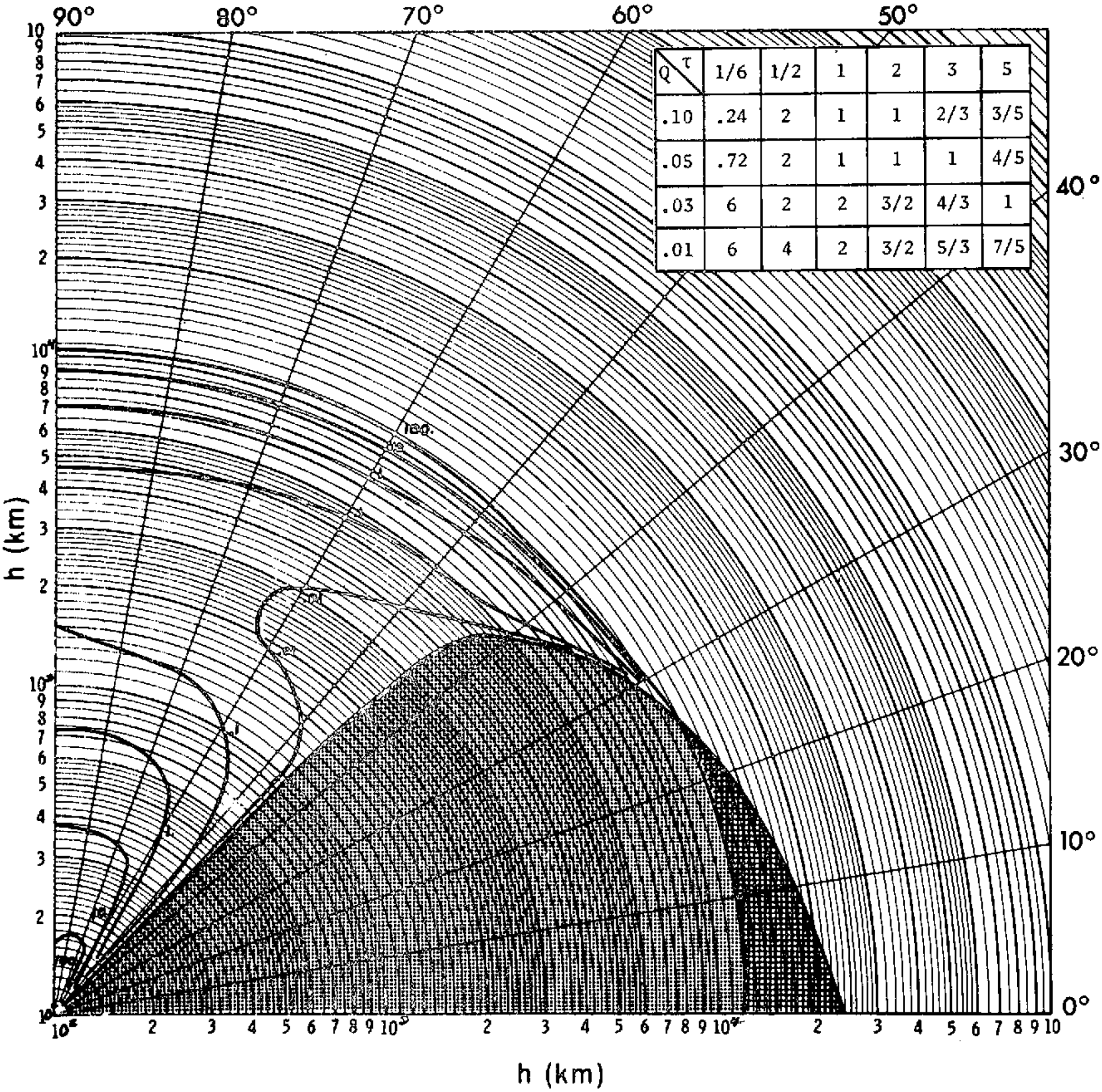

Q \ τ	1/6	1/2	1	2	3	5
.10	.24	2	1	1	2/3	3/5
.05	.72	2	1	1	1	4/5
.03	6	2	2	3/2	4/3	1
.01	6	4	2	3/2	5/3	7/5

Figure 1c - E_p>50 MeV

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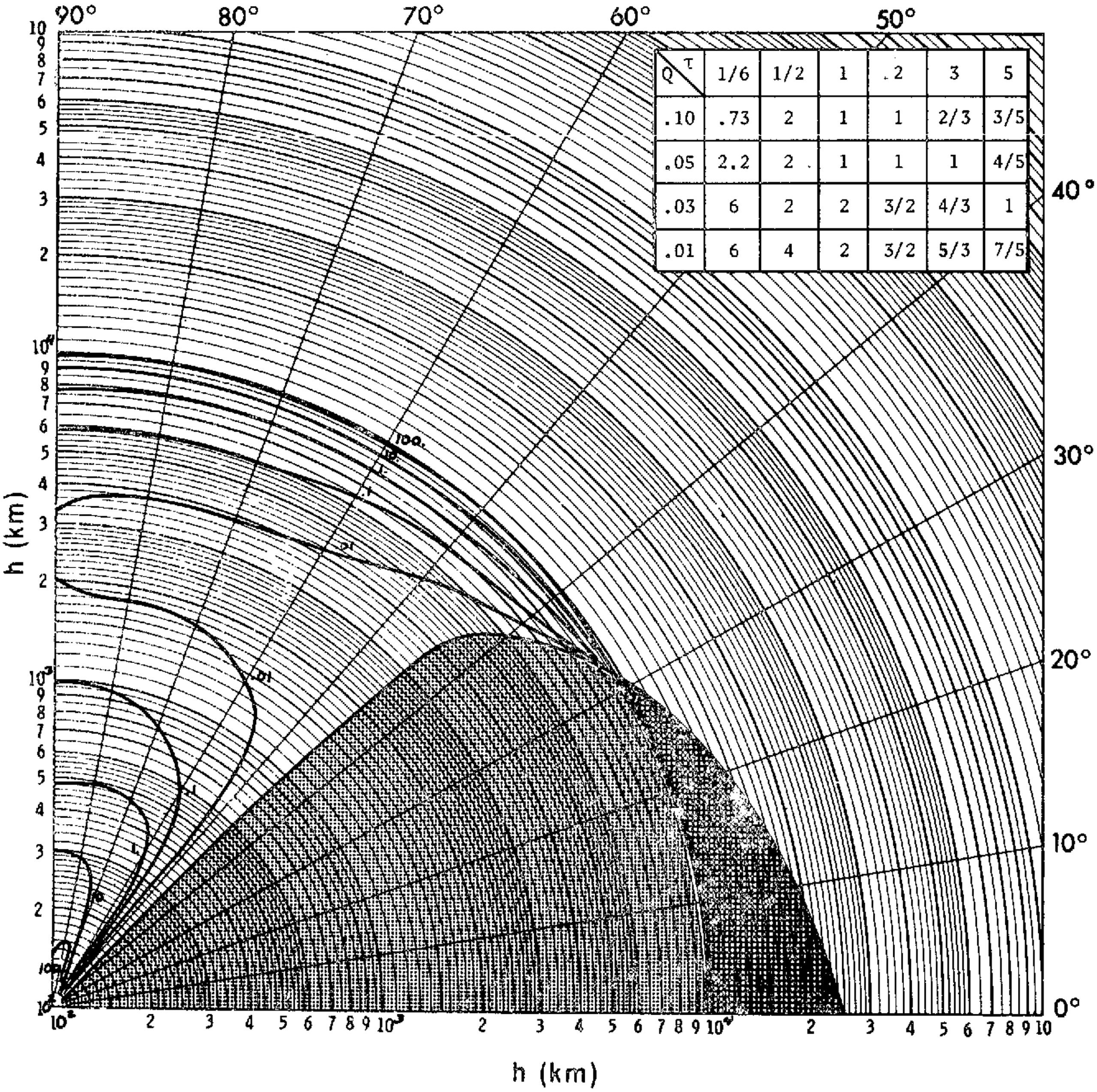

Q \ τ	1/6	1/2	1	2	3	5
.10	.73	2	1	1	2/3	3/5
.05	2.2	2	1	1	1	4/5
.03	6	2	2	3/2	4/3	1
.01	6	4	2	3/2	5/3	7/5

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Figure 1d - E_p>100 MeV

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