AFCRL-64-865
OCTOBER 1964

Air Force Surveys in Geophysics
No. 159

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Abstract

A simple calculation is done to determine the effects of an orbiting nuclear reactor on the trapped radiation belts. A SNAP-50 reactor, in an equatorial orbit at 1000 km and operating at 8 megw/thrm for a period of one year, is considered as a source of low energy electrons and protons. Neutrons escaping from the reactor decay into electrons and protons and these can become trapped in the earth's magnetic field. Hence, they contribute to the natural fluxes in the radiation belts.

Three different source problems are considered: 1.) those neutrons which decay within one kilometer of the reactor; 2.) those neutrons which decay within the entire inner radiation belt; 3.) those neutrons which decay within the entire outer radiation belt. In each region the average equilibrium of reactor-produced electron and proton fluxes at the equator are calculated after reactor operation for one year.

These fluxes are compared to the average natural electron and proton fluxes in the regions, and the reactor-produced fluxes are found to be less than 0.1 percent of the natural fluxes in all three cases.

All assumptions and calculations are presented in sufficient detail to allow updating with more recent or more exact information.

Contents

Electron and Proton Fluxes in the Trapped Radiation Belts Originating from an Orbiting Nuclear Reactor

I. INTRODUCTION

A recent paper by Carpenter[1] calculated the effects on the earth's trapped radiation belts of an orbiting nuclear reactor. Using Carpenter's basic assumption about the orbit of the reactor, we have performed the same calculation in more detail. We also extended the problem to include the effects on the entire inner and outer radiation belts whereas Carpenter only considered a small portion of the inner belt.

Neutrons escape from the reactor and decay into low energy electrons and protons which can become trapped in the earth's magnetic field. Neutrons decay throughout the entire region of the radiation belts; therefore, electrons and protons are being formed throughout the region. To consider each of these points rigorously and to determine its contribution to the total flux is beyond the scope of these hand calculations. This problem would have to be programmed for a computer. We will present what we consider a reasonable and simple approximation to this complete solution.

(Received for publication 14 August 1964)

Positions in the earth's magnetic field are generally represented by two coordinates: B and L. The quantity B is the magnetic field strength at the point in question, usually measured in gauss. The parameter L is a quantity related to the magnetic line of force at the point, measured in earth radii. Termed the L-shell, L is actually dependent upon the trapped particle's momentum along the field line, the field strength at the particle's mirror point, and the dipole moment of the field. It is accurate to 2-3 percent to say that the particle travels along the L-shell between mirror points.

In order to understand the physical significance of L, consider a simple dipole field centered at the earth's center. The L value for a particular shell would be the distance (in earth radii) from the earth's center to the point where the shell crossed the equatorial plane. This L value would have no longitude dependence, and a satellite in an equatorial orbit at a constant altitude above the earth would always be passing through the same L-shell.

If we displaced the earth so that the earth's center and the dipole field center did not coincide, the same satellite would pass through a variety of L-shells as it orbited the earth. The earth's actual magnetic field can be roughly approximated by such an eccentric dipole field, with the distance between the earth's center and the dipole center being about 420 km.

We assumed a SNAP-50 reactor, in an equatorial orbit, at 1000 km above the earth. The SNAP-50 is a fast reactor operating at a power level of 2 to 8 megw/thrm.[2] We assumed that the reactor operated at the highest power level (8 megw/thrm) for a period of one year and then examined the changes in the flux in the trapped radiation belts at the end of the year. We calculated both the reactor-produced electron and proton fluxes, and we considered each flux in three different regions of space: (a) the L = 1.11 to L = 1.28 region. This considers only those neutrons which decay within the first kilometer and is included mainly for comparison with the earlier paper.[1] (b) the L = 1.11 to L = 3.0 region. This is the entire inner radiation belt. (c) the L = 3.0 to L = 9.0 region. This is essentially the entire outer radiation belt.

The SNAP-50, operating at 8 megw/thrm, produces about 7.49×10^{17} fast neutrons/sec, and assuming a 5.5 percent leakage rate this yields 4.12×10^{16} neutrons/sec leaking out of the reactor.[2] These neutrons have an average energy of 1.4 ev and hence a velocity of 16.5 km/sec. These assumptions about the initial reactor conditions were used for all three regions.

2. CALCULATIONS

2.1. Electron Flux

2.1.1. Decay within First Kilometer – L = 1.11 to L = 1.28

It takes a neutron of velocity 16.5 km/sec only 0.06 sec to traverse the first kilometer. Since the neutron half-life is about 750 sec, the fraction of neutrons decaying in the first kilometer would be

$$1 - \exp\left[(-0.693)(0.06)/(750)\right] = 5.6 \times 10^{-5}$$

Thus we get $(5.6 \times 10^{-5})(4.12 \times 10^{16}) = 2.31 \times 10^{12}$ electrons/sec as the formation rate of electrons.

Consider the satellite orbit now. In an equatorial orbit of 1000 km the satellite would thus pass through a variety of B and L values.

The L values vary from 1.11 to 1.28 and the B values vary from 0.18 to 0.26 gauss. The average values over all longitudes are L = 1.17 and B = 0.22 gauss. Since the distance of electron formation (1 km) is small compared to the orbital altitude (1000 km), we can consider the reactor as essentially an isotropic point source of electrons, injecting electrons into L shells of 1.11 to 1.28.

We now have to consider how many of these electrons are trapped and how long they remain trapped; then we can determine the electron flux in the belt due to these reactor-produced electrons and compare it to the natural electron flux.

The basic equation for the flux (approximating the integral by a summation) is

$$\phi_{el} = T\,D\,Q \sum_i \frac{f_i g_i v_i}{V_i} \tag{1}$$

where

ϕ_{el} = reactor-produced electron flux at the equator at 1000 km at the end of one year (electrons/sec cm^2)

T = time of injection = 1 year = 3.156×10^7 sec

D = fraction of electrons which remain after decay due to the electron's energy and B-L coordinates

Q = electron formation rate (electrons/sec)

f_i = fraction of the trapped electrons which have pitch angles in the ith pitch angle group

g_i = fraction of the trapped electrons which have pitch angles in the ith pitch angle group which remain after decay due to the pitch angle

V_i = volume of space over which the trapped electrons in the ith pitch angle group will spread (cm^3)

v_i = velocity of electrons in the ith pitch angle group (cm/sec)

Each of these quantities will now be discussed separately.

The electron formation rate, Q, is just 2.31×10^{12} electrons/sec. This is the total production rate of electrons over all pitch angles.

To determine the various pitch angle groups, we considered five mirroring altitudes: 200, 400, 600, 800, and 900 km. For each mirroring altitude we used 18 different longitude values, spaced 20^o apart. At each of these longitude points the B and L values corresponding to 1000 km and 0^o latitude were determined. This L line crosses the mirroring altitude at two different B values. The lower of these two B values is the mirroring B value. The pitch angle can then be calculated by the formula

$$\sin^2 \alpha_{eq} = \frac{B_{eq}}{B_M} \tag{2}$$

where B_{eq} is the B value at the equator, B_M is the B value at the mirroring point, and α_{eq} is the pitch angle. For each mirroring altitude this gave 18 different pitch angles. These were averaged to give an average pitch angle for each mirroring altitude. The results are shown in Table 1.

The minimum value of 200 km for a mirroring altitude was chosen as this is essentially the upper limit of the atmosphere. Below 200 km particles will be rapidly lost to the atmosphere. This calculation shows that only those electrons with pitch angles greater than 55^o will be trapped and mirror at altitudes of 200 km or more.

TABLE 1

i	α_i	θ_i	r_i (km)	a_i (km)	f_i	g_i	V_i (cm^3)
1	55^o	55^o	66?0	200	0.059	0.01	2.57×10^{26}
2	61^o	59^o	6800	400	0.077	0.11	2.35×10^{26}
3	67^o	64^o	7000	600	0.096	0.29	2.08×10^{26}
4	73^o	70^o	7200	800	0.117	0.53	1.67×10^{26}
5	79^o	77^o	7300	900	0.225	0.86	1.45×10^{26}
6	---	90^o	----	---	-----	----	----------

Five pitch angle groups were thus established between 55^o and 90^o. These are shown in Table 1. Assuming the reactor emits electrons isotropitcally, it is easy to determine the fraction of electrons emitted in each pitch angle group, f_i

$$f_i = \frac{\int_0^{2\pi} d\phi \int_{\theta_i}^{\theta_{i+1}} \sin\theta \, d\theta}{2\pi} = \cos\theta_i - \cos\theta_{i+1} \tag{3}$$

where θ_i and θ_{i+1} are the lower and upper limits, respectively, of the pitch angle group. The values for f_i are given in Table 1.

Unfortunately, not much data exists on life times of trapped electrons. One reference had data from conditions similar to those we are considering: an altitude of 1000 km and an energy range of 30 kev to 1 Mev.[3] Their data was taken at a higher latitude (30^oN) and was thus at a larger L shell, however the error this contributed should not be significant in this calculation. This reference measured the angular distribution of the electron flux; it also showed that no electrons were trapped with pitch angles below about 55^o, in agreement with our number.

Our five pitch angle groups were applied to their curve of flux vs pitch angle, and an average flux in each pitch angle group was determined. This was then compared to their flux at 90^{o} and this simple ratio was used as the fraction of electrons in the ith pitch angle group which remained after decay due to pitch angle — the quantity g_i. If there was no preferential pitch-angle decay, we would expect a constant value of the flux from 90^{o} to 55^{o}, but the flux steadily decreased as pitch angle decreased. This leads us to the conclusion that there is a preferential decay as a function of pitch angle, and the quantity g_i is a rough approximation to it. The quantity g_i is shown in Table 1.

The electrons are emitted into L shells 1.11 to 1.28 during each orbit. They will be confined between these two L shells within the space above their mirroring altitudes. Since they will drift around the earth, they will occupy a volume segment around the earth. This volume can be expressed as

$$V_i = 2\int_o^{2\pi} d\phi \int_{\theta_2}^{\theta_1} \sin\theta \, d\theta \int_{r_i}^{r_2} r^2 dr + 2\int_o^{2\pi} d\phi \int_{\theta_1}^{90^{o}} \sin\theta \, d\theta \int_{r_1}^{r_2} r^2 dr \tag{4}$$

where

$r_1 = L_1 \sin^2\theta$ (km)

$r_2 = L_2 \sin^2\theta$ (km)

$r_i = r_o + a_i$ (km)

r_o = earth radius = 6400 km

L_1 = lowest L-shell = 1.11 r_o

L_2 = highest L-shell = 1.28 r_o

a_i = mirroring altitude (km)

θ_1 = angle at which $r_1 = r_i$

θ_2 = angle at which $r_2 = r_i$.

This calculation assumes the earth's field can be represented as a dipole. Equation (4) can be integrated to give

$$V_i = \frac{4\pi r_i^3}{3}\left[\sqrt{1 - \frac{r_i}{L_2}}\left(-\frac{6}{7} + \frac{6}{35}\frac{L_2}{r_i} + \frac{8}{35}\frac{L_2^2}{r_i^2} + \frac{16}{35}\frac{L_2^3}{r_i^3}\right)\right.$$

$$\left. - \sqrt{1 - \frac{r_i}{L_1}}\left(-\frac{6}{7} + \frac{6}{35}\frac{L_1}{r_i} + \frac{8}{35}\frac{L_1^2}{r_i^2} + \frac{16}{35}\frac{L_1^3}{r_i^3}\right)\right] . \tag{5}$$

At the two highest mirroring altitudes, r_i exceeded L_1. In these cases the limit on θ in Eq. (4) is from θ_2 to 90^o for the first integral and the second integral is zero. The result is that in Eq. (5) only the first four terms remain; the second four are zero. This means that the L_1 line is below the mirroring altitude and the particles are confined in the space between the L_2 line and the radius r_i.

To calculate the velocity of electrons in the ith pitch angle group, we used the formula

$$v_i = \frac{2A_i}{\tau_i} \tag{6}$$

where

A_i = length of an average (L = 1.20) L line between mirror points for particles having pitch angles in the ith pitch angle group (cm)

τ_i = period of lateral oscillation for electrons on an average (L = 1.20) L line and in the ith pitch angle group (sec).

This period is the time it takes an electron to travel from any point to one mirror point, then to the other mirror point, then back to the original point. It thus traverses twice the arc length between mirror points.

Again assuming a dipole field, the arc length can be calculated by

$$A_i = 2\,L \int_0^{\epsilon_i} \cos^2\theta\, d\theta \tag{7}$$

where

L = the L-shell along which the length is being measured

ϵ_i = angle at which the L line crosses the mirroring altitude

ϵ_i = $\arccos\sqrt{r_i/L}$.

The period of lateral oscillation is given by[4]

$$\tau_i = (0.085)\frac{L}{\beta}\,T(\alpha_i) \tag{8}$$

where

L = equatorial radius of the line of force (in earth radii)

α_i = ith pitch angle

β = v/c

$$T(\alpha_i) = 1.30 - 0.56 \sin \alpha_i. \tag{9}$$

The average energy of an electron resulting from neutron decay is about 300 kev; this corresponds to a $\beta = 0.776$.

The calculations for A_i, τ_i, and v_i were done for the five different mirroring altitudes and for three different L values: 1.11, 1.20, and 1.28. These represent the lowest, average, and highest L shells the trapped electrons will encounter. The value of A_i increased with L, as expected. The value of τ_i was relatively constant over all values of L and mirroring altitude; this constant value was about 0.1 sec. The value of v_i thus increased with increasing L, and decreased with increasing mirroring altitude. The data for the average L (L = 1.20) were used in the flux calculation. The values of ϵ_i, A_i, τ_i, and v_i for L = 1.20 are given in Table 2.

Another method of finding the velocity parallel to the L line would have been to use the formula[5]

$$v_i = v(1 - B/B_{Mi}) = v \cos \alpha_i \tag{10}$$

TABLE 2

i	α_i	a_i (km)	ϵ_i	A_i (cm)	τ_i (sec)	v_i (cm/sec)
1	55^o	200	22^o	5.616×10^8	0.111	1.012×10^{10}
2	61^o	400	20^o	5.149×10^8	0.106	9.715×10^9
3	67^o	600	17^o	4.426×10^8	0.103	8.594×10^9
4	73^o	800	15^o	3.931×10^8	0.100	7.862×10^9
5	79^o	900	13^o	3.426×10^8	0.098	6.992×10^9

where

v = total velocity of the electron (cm/sec)

B = equatorial value of B at 1000 km

B_{Mi} = value of B at mirroring altitude for pitch angle i

Equation (10) can be rewritten

$$v_i = \beta c \cos \alpha_i \tag{11}$$

where

c = velocity of light = 3×10^{10} cm/sec

Equation (11) gives very similar results to Eq. (6), with velocities ranging from 1.33×10^{10} to 4.44×10^9 cm/sec.

The decay fraction, D, is also hard to estimate, due to lack of experimental data. The best source of data seems to be the time behavior of the fission electrons released during the 1962 high altitude nuclear test series.[6-9] These results indicate that the decay of the trapped electrons depends on the L value, the B value, and the electron energy. Two different decay modes have been proposed: 1.) an exponential decay with time;[6-8] 2.) an inverse time decay.[9]

For the exponential decay we have the formula

$$\frac{dN}{dt} = -\frac{N}{p} + Q \tag{12}$$

where

N = total number of electrons (electrons)

p = decay constant (sec)

Q = formation rate of electrons (electrons/sec).

Integrating Eq. (12) and using the initial condition that at $t = 0$, $N(0) = 0$, we get

$$N(t) = Q\,p[1 - \exp(-t/p)]. \tag{13}$$

If we had assumed no decay, we would have had

$$\frac{dN}{dt} = Q\,. \tag{14}$$

Equation (14) integrates to

$$N(t) = Q\,t\,. \tag{15}$$

Thus, at time t, we have that the fraction of electrons remaining after exponential decay, D_e, is the ratio of Eq. (13) to Eq. (15)

$$D_e(t) = \frac{p}{t}[1 - \exp(-t/p)]\,. \tag{16}$$

Various values of D_e are calculated and tabulated in Table 3. These are based on different combinations of B and L values and also for different electron energies. Most of the data is measured for fission electron energies; the electrons from neutron decay are distributed in a typical beta spectrum, with a beta end-point energy of about 760 KeV and an average energy of about 300 kev.

TABLE 3

Electron Energy	L	B (gauss)	p (hrs)	D_e	D_I
Fission	1.25	0.21	480	0.055	
Fission	1.25	0.21	500	0.057	
Fission	1.25	0.21	3450	0.128	
Fission	1.25	0.21	4.2		0.500
300 kev	1.25	0.21	200	0.023	
Fission	1.25	0.20	480	0.055	
Fission	1.25	0.20	5930	0.333	
Fission	1.25	0.20	28		0.502
Fission	1.25	0.19	1200	0.137	
Fission	1.25	0.19	2400	0.065	
Fission	1.25	0.19	220		0.512
Fission	1.18	0.21	300	0.034	
Fission	1.18	0.21	480	0.055	
Fission	1.18	0.21	1500	0.171	
300 kev	1.18	0.21	100	0.011	
Fission	1.18	0.20	400	0.046	
Fission	1.18	0.20	480	0.055	
Fission	1.18	0.20	1340	0.156	
1 Mev	1.18	0.20	95		0.505

For the inverse time decay, we have, analogous to Eq. (12)

$$\frac{dN}{dt} = -\frac{N}{(t+p)} + Q. \tag{17}$$

Again with the initial condition that at $t = 0$, $N(0) = 0$, we have as the solution to Eq. (17)

$$N(t) = \frac{Qt}{2}\left[\frac{t+2p}{t+p}\right]. \tag{18}$$

Thus, after time t, the fraction of electrons remaining after inverse time decay, D_I, is the ratio of Eq. (18) to Eq. (15)

$$D_I(t) = \frac{1}{2}\left[\frac{t + 2p}{t + p}\right]. \tag{19}$$

Various values of D_I are tabulated in Table 3, based on different values of B, L, and electron energy. The values of D_e and D_I in Table 3 are calculated for $t = 1$ year.

Table 3 shows that the experimental data is in poor agreement. For this reason we considered two different values of D in the final flux calculation: 1.) the worst case, corresponding to $D = 0.51$, at $L = 1.25$, $B = 0.19$, and for fission energies; and 2.) a more realistic case, corresponding to $D = 0.011$, at $L = 1.18$, $B = 0.21$, and for 300 kev electrons. The second case was considered more realistic because the B and L values are approximately our average B and L values, and the energy is about equal to our average electron energy.

We can now combine all of these factors to calculate the average reactor-produced electron flux at 1000 km at the equator at the end of one year. The results are

For $D = 0.51$: $\phi_{e1} = 5.35 \times 10^2$ electrons/sec cm^2.

For $D = 0.011$: $\phi_{e1} = 1.16 \times 10^1$ electrons/sec cm^2.

Note that these numbers are lower than the calculations in the earlier paper[1] by a factor of 5.6×10^4 for the worst case and 2.6×10^6 for the more realistic case.

Some data exist for the natural electron flux in the range 0.5 to 5.0 Mev.[10] Although this range does not correspond exactly to our range, it is a good approximation, since the majority of the natural flux is below 1.0 MeV. These represent about the most reliable data that exist on natural electron flux in this range. These fluxes, over the B and L range of our satellite, vary from 9.4×10^7 to 9×10^3 electrons/sec cm^2. The average natural flux is 2.02×10^7 electrons/sec cm^2 over this orbit. Thus, at the end of a year, the reactor-produced flux is only 0.0026 percent of the natural flux for the worst case, and 0.00006 percent of the natural flux for the more realistic case.

If, for any reason, we wanted to change any of the initial reactor parameters, the new electron flux could be simply calculated. If we change the reactor power level, neutron leakage rate, or average neutron velocity, this only changes the number of electrons formed. From that point on the electron calculations would remain the same. If the new power level (in megw/thrm) is P, the new leakage rate (in %) is F, and the new average neutron velocity (in km/sec) is w (assuming the neutrons are still non-relativistic), then the new formation rate of electrons, Q, is

$$Q = (7.49 \times 10^{17})\,(P/8)\,(F/100)\,(5.6 \times 10^{-5})\,(16.5/w) \quad . \tag{20}$$

This would be the Q used in Eq. (1) and all other quantities in Eq. (1) would remain the same.

2.1.2. Entire Inner Belt – L = 1.11 to L = 3.0

Let us now consider the electrons produced within the entire inner belt. This belt extends out to approximately $L = 3.0$. At the equator this L shell is about 12,800 km from the earth's surface, or 11,800 km from the reactor. We will then consider all neutrons which decay within 11,800 km. It takes a neutron of velocity 16.5 km/sec about 715 sec to travel 11,800 km. Thus, the fraction of neutrons which decay in a sphere of radius 11,800 km is

$$1 - \exp\left[(-0.693)\,(715)/(750)\right] = 0.483$$

With the leakage rate of 4.12×10^{16} neutrons/sec, this means 1.99×10^{16} electrons/sec are formed in the sphere.

Not all of these neutrons will decay within the radiation belt, however. Some are emitted toward the earth, and these will be lost. Assuming the reactor is at an average distance of 1280 km ($L = 1.20$) from the earth's surface, the earth then subtends 0.244 of the total solid angle at the reactor. Then only 0.756 of the neutrons will decay within the radiation belt, and the electron formation rate within the belt is $(0.756)\,(1.99 \times 10^{16}) = 1.50 \times 10^{16}$ electrons/sec.

Not all of the electrons formed within the radiation belt will be trapped. A particle can only be trapped and mirror at points whose B value is greater than or equal to the B value of the injection point. At each point this puts a trapping limit on the pitch angles. Since we are assuming isotropic electron sources, some of the particles will have angles which do not allow them to be trapped. As this depends on the L value, the position along the L line, and the mirroring altitude, the detailed calculation is complex. To obtain an average value for this fraction lost, we considered two different L shells: $L = 1.5$ and $L = 3.0$. We calculated the fraction trapped at various positions along each L line for a minimum mirroring altitude of 200 km. These fractions were 0.57 for $L = 3.0$ and 0.48 for $L = 1.5$. We thus assumed that for all L shells about 0.50 of the electrons emitted by the source are trapped. Then $(0.50)(1.50 \times 10^{16}) = 7.50 \times 10^{15}$ electrons/sec are trapped in the inner radiation belt.

These trapped electrons will have a variety of pitch angles and over a long time we assumed that there will be some preferential decay due to the pitch angles. From our earlier calculations (see 2.1.1) we estimated this fraction to be 0.50. Thus $(0.50)(7.50 \times 10^{15}) = 3.75 \times 10^{15}$ electrons/sec remain trapped after pitch angle decay.

To obtain a value for the average electron velocity we again considered the $L = 1.5$ and $L = 3.0$ lines and used Eqs. (6-8) to calculate arc lengths, lateral oscillation periods, and velocities. These two velocities were quite similar and their average was used: 1.2×10^{10} cm/sec.

We also assumed that the electrons were distributed uniformly throughout the volume between the $L = 3.0$ line, the $L = 1.11$ line, and the 200 km mirroring altitude. From Eq. (5) we find this volume is $1.25 \times 10^{28}\,\text{cm}^3$.

The decay fraction due to the electron's energy and B-L coordinates was also hard to estimate. Even less data exists for this region than for the one we previously considered. One source[12] gives a lifetime of 16 months for $L = 1.4$ and energies approximately in this range. It[12] also gives a lifetime of 25 days for $2.4 < L < 3.6$ for electrons of energy greater than 250 kev. In our earlier calculation we used the lifetime of 100 hours for 300 kev electrons at $L = 1.18$. We then divided the inner belt into three L ranges: 1.11 to 1.3, 1.3 to 2.4, and 2.4 to 3.0. We used the values of 100 hours, 16 months, and 25 days, respectively, for the lifetimes in these three ranges. We also found the fraction of the total volume in each range and weighted these decay fractions by these volume fractions. This gave a total average value for the fraction remaining after energy and B-L decay of 0.354.

The injection time was again assumed to be one year, or 3.156×10^7 sec.

Thus, the average reactor-produced flux at the equator throughout the inner radiation belt at the end of a year is, analogous to Eq. (1)

$$\phi_{e2} = \frac{(3.75 \times 10^{15})(1.2 \times 10^{10})(3.156 \times 10^{7})(0.354)}{(1.25 \times 10^{28})}$$

$$\phi_{e2} = 4.02 \times 10^{4} \text{ electrons/sec cm}^{2} . \tag{21}$$

We again used McIlwain's data[10] to find the average natural electron flux for this region. To obtain this average we considered 16 different L values, ranging from L = 1.11 to L = 3.0, and 9 different longitude values, spaced 40^{o} apart. We found the B value at each L and longitude value; we then found the corresponding natural flux for each B-L point. This average value, again over the range 0.5 to 5.0 Mev, is 8.2×10^{7} electrons/sec cm^{2}. This agrees with the flux reported in another reference.[11]

The reactor-produced flux is only 0.049 percent of the natural flux even considering decay within the entire inner belt.

Equation (21) can be generalized as

$$\phi_{e2} = Q(2.02 \times 10^{-12}) \text{ (electrons/sec cm}^{2}) \tag{22}$$

where

$$Q = (7.49 \times 10^{17})(P/8)(F/100)\left(1 - \exp[(-0.660)(16.5/w)]\right). \tag{23}$$

The power level (in megw/thrm) is P, the leakage rate (in percent) is F, and the average neutron velocity (in km/sec) is w (assuming the neutrons are still non-relativistic). This allows the flux to be re-calculated easily for changes in the reactor parameters.

2.1.3. Entire Outer Belt – L = 3.0 to L = 9.0

The outer radiation belt extends from about L = 3.0 to L = 9.0. The L = 9.0 line is about 51,200 km from the earth's surface at the equator, or a maximum distance of 50,200 km from the reactor. Neutrons traveling 16.5 km/sec would require 3042 sec to traverse this distance. The fraction of neutrons decaying within a sphere a radius 50,200 km is 0.940. We already found that the fraction decaying in the sphere of radius 11,800 km (L = 3.0) was 0.483. Thus, the fraction decaying in the region L = 3.0 to 9.0 is 0.940 - 0.483 = 0.457. The fraction headed away from earth would be the same as found in 2.1.2: 0.756. We also assumed the same fraction (0.500) would have pitch angles which allowed them to be trapped. Due to lack of data for this region we assumed no preferential pitch angle decay.

To estimate the average electron velocity in this region, we considered an average L shell in this region: L = 6.0. Using Eqs. (6-8) for a 200 km mirroring altitude, we found an arc length of 5.84×10^9 cm, a lateral oscillation period of 0.854 sec, and a velocity of 1.37×10^{10} cm/sec. From Eq. (5) we found the volume between the L = 3.0 line, the L = 9.0 line, and the 200 km mirroring altitude was 3.52×10^{29} cm^3. Again, due to lack of data, we assumed there was no decay due to the electron's energy or B-L coordinates.

Thus the average reactor-produced electron flux at the equator throughout the outer radiation belt at the end of a year is

$$\phi_{e3} = \frac{(4.12 \times 10^{16})\,(0.457)\,(0.756)\,(0.500)\,(1.37 \times 10^{10})\,(3.156 \times 10^{7})}{(3.52 \times 10^{29})}$$

$$\phi_{e3} = 8.74 \times 10^{3} \text{ electrons/sec cm}^2 . \tag{24}$$

The average natural electron flux for this region is about 10^7 electrons/sec cm^2.[10, 13-16, 21] Thus, the reactor-produced flux is only 0.087 percent of the natural flux.

This value for reactor-produced flux is a worse-case calculation; all unknown factors were chosen to make the flux appear on the high side. For example, there would undoubtedly be some decay, as the electrons spend a large portion of their time near their mirror points and at these lower altitudes the probability of an interaction is much greater. Also the unstable nature of the outer belts was not considered. Fluctuations in the belt can dump particles which have been accumulating, and these fluctuations are rather frequent. Even neglecting these factors the reactor-produced flux is very small compared to the natural flux.

To allow for changes in the initial reactor parameters, Eq. (24) can be generalized as

$$\phi_{e3} = Q\,(4.64 \times 10^{-13})\ (\text{electrons/sec cm}^2) \tag{25}$$

where

$$Q = (7.49 \times 10^{17})(P/8)(F/100)\left\{\exp[(-0.660)(16.5/w)] - \exp[(-2.811)(16.5/w)]\right\} \tag{26}$$

The reactor power (in megw/thrm) is P, the neutron leakage rate (in percent) is F, and the average neutron velocity (in km/sec) is w (assuming the neutrons are still non-relativistic).

2.2. Proton Flux

2.2.1. Decay within First Kilometer – L = 1.11 to L = 1.28

For each electron formed in neutron decay, a proton is also created. This proton could have energy up to about 760 KeV, but the average proton energy will be much lower than this.

The formation rate of protons within one kilometer of the reactor will be the same as the electron formation rate in this volume: 2.31×10^{12} protons/sec. These protons are probably not emitted isotropically, but for simplicity we assumed that they were. The calculations here will parallel those for electrons (see 2.1.1), although there will be less detail here due to lack of information. The reactor is considered an isotropic point source of protons, injecting them into L shells of 1.11 to 1.28.

We assumed that about the same fraction (0.500) of protons as electrons would not be trapped because of unsuitable pitch angles. The volume over which these protons would be distributed would be that volume between the L = 1.11 line, the L = 1.28 line, and the 200 km mirroring altitude. This volume, which was computed in 2.1.1, was 2.57×10^{26} cm^3.

To estimate the average proton velocity, we used Eqs. (6-8) for an average L line (L = 1.20). The arc length, as found earlier, was 5.62×10^8 cm. For 760 KeV protons the value of $\beta = 0.042$. Thus the period of lateral oscillation becomes 2.04 sec, and the average velocity is 5.51×10^8 cm/sec.

The 1/e - lifetime for protons of energy approximately 1 Mev is 10^{11} sec/cm^3.[17] The atmospheric number density at 1000 km is $9.1 \times 10^5 cm^{-3}$.[18] The 1/e - lifetime is then 1.1×10^5 sec. Using Eq. (16) we obtain a B-L-energy decay factor of

$$D = \frac{(1.1 \times 10^5)}{(3.156 \times 10^7)} (1 - \exp[(-3.156 \times 10^7)/(1.1 \times 10^5)])$$

$$D = 0.0035.$$

We again assumed no preferential pitch angle decay, mainly due to lack of data. The time of injection was one year, as before.

Then the average reactor-produced proton flux at 1000 km at the equator at the end of one year is

$$\phi_{p1} = \frac{(2.31 \times 10^{12})(0.500)(5.51 \times 10^8)(0.0035)(3.156 \times 10^7)}{(2.57 \times 10^{26})}$$

$$\phi_{p1} = 2.73 \times 10^{-1} \text{ protons/sec cm}^2. \tag{27}$$

The average natural proton flux at 1000 km for protons in this energy range is about 3×10^8 protons/sec cm^2.[19] Thus the reactor-produced proton flux is only about 10^{-7} percent of the natural flux. Even neglecting the decay factor, the reactor-produced flux would still be at least five orders of magnitude below the natural flux.

Equation (27) could be written as

$$\phi_{p1} = Q\,(1.18 \times 10^{-13})\ (\text{protons/sec cm}^2) \tag{28}$$

where Q is given by Eq. (20). This allows for changes in the initial reactor parameters.

2.2.2. Entire Inner Belt – L 1.11 to L 3.0

This calculation parallels that in 1.2.2 for electrons in the same region. The formation rate of protons in the sphere of radius 11,800 km is 1.99×10^{16} protons/sec. The same fraction (0.756) decay within the belt, and we assumed the same fraction (0.500) are trapped due to their pitch angle distributions. We again assumed no preferential pitch angle decay, due to lack of data.

To obtain an average velocity for the protons, we considered two L lines: L = 1.5 and L = 3.0. Using Eqs. (6-8) we found the arc lengths to be 1.01×10^9 cm and 2.72×10^9 cm, the periods of lateral oscillation to be 3.16 sec and 7.41 sec, and the velocities to be 6.43×10^8 cm/sec and 7.34×10^8 cm/sec for the L = 1.5 and L = 3.0 lines, respectively. The average velocity was taken to be 6.9×10^8 cm/sec. The volume over which the particles are distributed is the same as found in 1.2.2: 1.25×10^{28} cm^3.

To estimate the B-L-energy decay, we assumed that there was no decay beyond 2000 km (L = 1.3) as there is little atmosphere above this. The 1/e - lifetime is 10^{11} sec/cm^3.[17] and the number density at 2000 km is 4.6×10^3cm^{-3}.[18] The 1/e - lifetime is thus 2.17×10^7 sec and the fraction remaining, from Eq. (16), is 0.527. Since the volume below the L = 1.3 line is only 2.06 percent of the total volume, and the decay fraction for the rest of the volume was assumed to be 1.000, the volume weighted decay fraction is 0.990.

Thus the average reactor-produced proton flux at the equator throughout the inner radiation belt at the end of a year is

$$\phi_{p2} = \frac{(1.99 \times 10^{16})\,(0.756)\,(0.500)\,(6.9 \times 10^{8})\,(3.156 \times 10^{7})\,(0.990)}{(1.25 \times 10^{28})}$$

$$\phi_{p2} = 1.29 \times 10^{4} \text{ protons/sec cm}^2 \quad . \tag{29}$$

The average natural proton flux for this region is about 1×10^8 protons/sec cm^2.[19,20] Thus the reactor-produced flux is only 0.013 percent of the natural flux.

Equation (29) can be generalized as

$$\phi_{p2} = Q\,(6.52 \times 10^{-13}) \text{ (protons/sec cm}^2) \tag{30}$$

where Q is given by Eq. (23). This allows for changes in the initial reactor parameters.

The flux calculated by Eq. (29) is unnaturally high. The protons would spend a good portion of their time near their mirror points and at these lower altitudes the decay factor would probably drop well below 0.990. Even so, the reactor-produced flux is still only a very small percentage of the natural flux.

2.2.3. Entire Outer Belt - L = 3.0 to L = 9.0

This calculation is similar to that (see 2.1.3) for electrons in the same region. The fraction of neutrons decaying in the region L = 3.0 to L = 9.0 is 0.457, and the fraction of these neutrons which decay within the belt is 0.756. Also we assumed the same fraction (0.500) would have pitch angles which allowed them to be trapped. We considered no preferential pitch angle decay.

To estimate the average proton velocity in this region we again used Eqs. (6-8) for an average L line (L = 6.0) and a 200 km mirroring altitude. The arc length was 5.84×10^9 cm, the period of lateral oscillation was 15.79 sec, and the velocity was 7.4×10^8 cm/sec. This value was used as the average velocity. The volume was again 3.52×10^{29} cm^3 and the time of injection was 3.156×10^7 sec. We assumed that there was no B-L-energy decay. This was based on the assumption that the protons were well above any atmosphere; also we could find no experimental data for this region.

Thus the average reactor-produced proton flux at the equator throughout the outer radiation belt at the end of one year is

$$\phi_{p3} = \frac{(4.12 \times 10^{16})(0.457)(0.756)(0.500)(7.4 \times 10^8)(3.156 \times 10^7)}{(3.52 \times 10^{29})}$$

$$\phi_{p3} = 4.72 \times 10^2 \text{ protons/sec cm}^2 \ . \tag{31}$$

The average natural proton flux for this region is about 4.8×10^6 protons/sec cm^2.[14,20] The reactor-produced flux is then approximately 0.01 percent of the natural flux.

To allow for changes in the initial reactor parameters, Eq. (31) can be written as

$$\phi_{p3} = Q\,(2.72 \times 10^{-14})\ (\text{protons/sec cm}^2)\ . \tag{32}$$

where Q is given by Eq. (26).

This reactor-produced flux is also calculated on the high side, as there would certainly be some decay and the unstable behavior of the belt would likewise cause a loss of particles. Even at that the reactor-produced flux is quite small.

3. SUMMARY

The results are summarized in Table 4. In all three regions the electron and proton fluxes produced by the SNAP-50 reactor were less than 0.1 percent of the natural fluxes. Let us again emphasize that these calculated reactor-produced fluxes are almost certainly higher than the actual fluxes which would be produced. All unknown factors in our calculations were chosen to make the flux appear higher.

TABLE 4. Average reactor-produced fluxes at the equator at the end of one year and average natural fluxes at the equator

	Decay within first kilometer $L = 1.11$ to $L = 1.28$	Inner Belt $L = 1.11$ to $L = 3.0$	Outer Belt $L = 3.0$ to $L = 9.0$
Reactor-produced electron flux	5.35×10^2	4.02×10^4	8.74×10^3
Natural electron flux	2.02×10^7	8.2×10^7	1×10^7
Reactor flux / Natural flux	0.0026%	0.049%	0.087%
Reactor-produced proton flux	2.73×10^{-1}	1.29×10^4	4.72×10^2
Natural proton flux	3×10^8	1×10^8	4.8×10^6
Reactor flux / Natural flux	10^{-7} %	0.013%	0.01%

These computations are only approximations to the rigorous calculations of the fluxes. We feel that these rigorous calculations would not differ from our numbers by more than a factor of ten, and even if our fluxes were increased by such a factor they would all still be less than 1 percent of the natural flux.

There is one point which may warrant further study. The reactor-produced fluxes are well below the average natural fluxes in these regions, but there are specific points in these regions where the natural flux is somewhat lower than the average. At these points the reactor-produced flux could become much more significant. As we stated earlier, though, to solve this problem completely and to find the reactor contribution to the natural flux at each point in the radiation belt would require the use of a computer.

Based on these assumptions and calculations, the SNAP-50 reactor seems to be an insignificant source of contamination to the trapped radiation belts.

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