JUPITER RADIATION BELT ELECTRONS AND THEIR EFFECTS ON SENSITIVE ELECTRONICS

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MR. DIVITA: I will discuss specifically the electron environment trapped at Jupiter; testing performed to simulate the effects of electrons on MJS77 (Mariner Jupiter-Saturn 1977) sensitive piece parts, and test results from those simulations.

I was pleased to see a preliminary analysis presented on the proton radiation effects because I am not going to address protons. However, I think the proton environment eventually may have a significant impact on the design of Jupiter probes.

The data base used which is now a significant data base is from the Pioneer 10 observations. At this point in time the emphasis is predominantly on electrons. The proton data base which includes protons above 35 Mev, protons above about 65-70 Mev and lower energy protons (∿1 to 20 Mev) are currently being developed into an engineering model. Considerable uncertainty exists in both low-energy protons, below 35 Mev, and their extent. Therefore, I will specifically address the electron problem. The Pioneer project is providing a current summary of the low-energy protons observations.

Figure 9-34 is an introductory slide which will give you a reference to the spatial distribution of the trapped electrons. The reference is a set of isoflux contours mapped on a Jupiter fixed-dipole coordinate plot using the magnetic polar, Z, axis measured along the planet offset dipole and the L-shell, R_J, axis measured along the magnetic equator in the radial direction.

We have taken the model from the February, 1974 Workshop, which was held at ARC by the Pioneer 10 Project. This map is for electrons having energy E greater than 3 Mev. The workshop data allow us to map as is done for the Earth Van Allen Belts,

CONTOURS OF CONSTANT FLUX J (CM^{-2} S^{-1}), 1974 WORKSHOP ELECTRON DATA, E_e >3 MeV;

JOVIOMAGNETIC COORDINATES (ASSUMING LONGITUDINAL SYMMETRY)

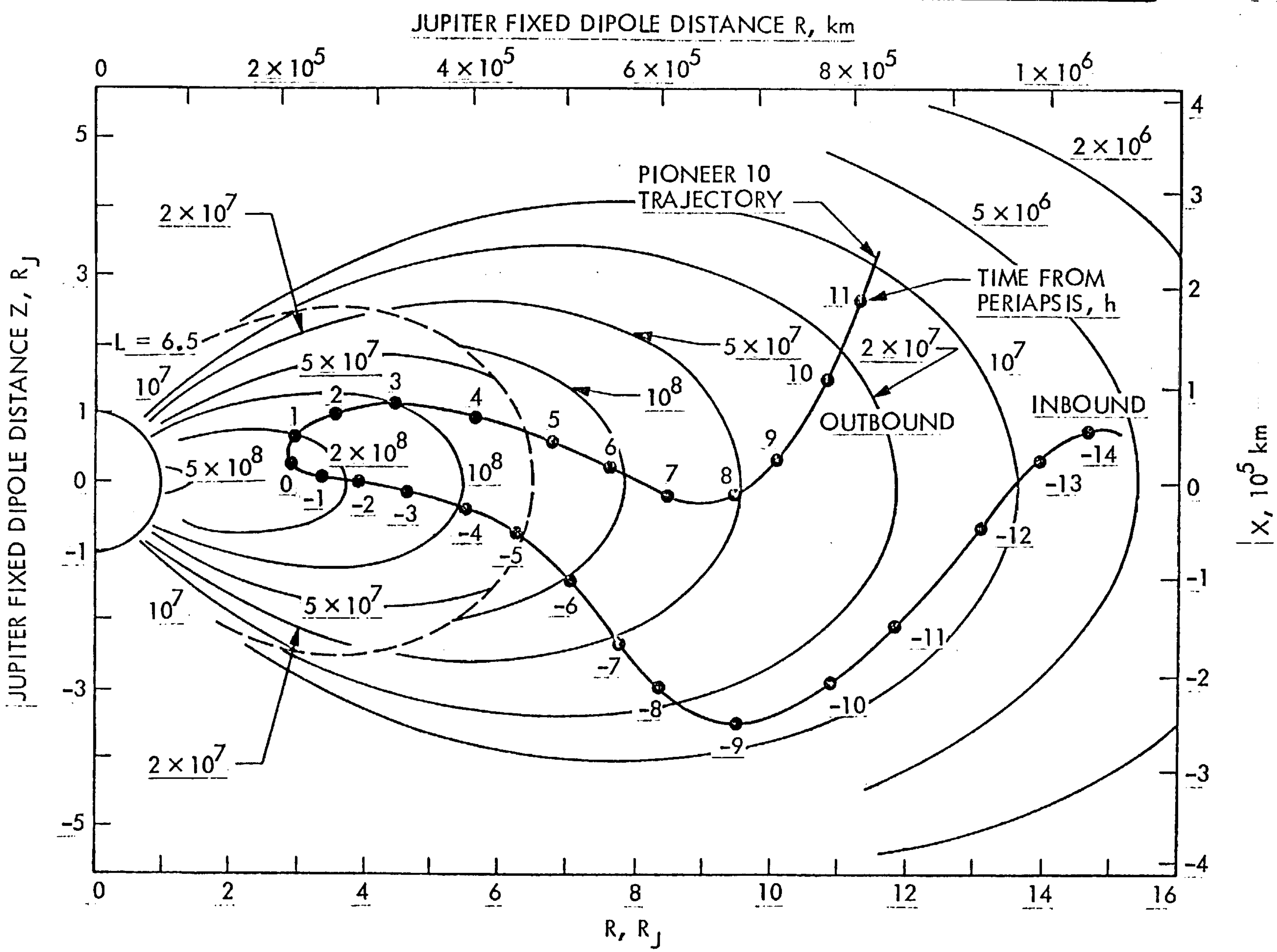

FIGURE 9-34

with symmetry, a set of contours about the planet Jupiter. Based on available observations, we can map for lower energies down to 550 Kev, and for higher energies up to 31 Mev.

The contour map in Figure 9-34 is used to address some of the important features of the Belt. These electrons peak near a little more than on R_J from the center of the planet at 5×10^8 electrons per square centimeter per second above 3 Mev. This level is a significant flux and it potentially can interfere with sensitive science instruments and sensitive materials. From about 3 R_J to about 12 to 14 R_J the reduction is about a factor of 1/50 decrease in flux along the magnetic equator - this small decrease emphasizes the extensiveness of the trapped radiation belt.

The next feature in Figure 9-34 is the fluence accumulated by Pioneer 10. The flight path shown indicates that it was significant with a peak flux of 3×10^8 e/cm^2-s. Science measurements taken along this flight path allowed good mapping of the trapped particles.

The flux and fluence data presented for candidate MJS '77 flybys are determined as described for Pioneer 10. A family of flight paths with various perijove distances were used to evaluate fluences accumulated along those flight paths. Figure 9-35 shows the results of this evaluation as a set of accumulative fluences based on using several contour plots corresponding to different integral energies. The integral fluence is given as a function of energy for selected perijove distances, 5.0, 8.8, and 12 R_J. This range essentially encompasses the region of interest to MJS '77.

An important feature is the significant change in slope of the integral fluence at 3 Mev. For the 5 R_J perijove case the fluence level is about 5×10^{12} electrons per square centimeter above 3 Mev. Pioneer 10, based on using the same model, and the flight path shown in Figure 9-34 encountered about 7×10^{12} elec-

INTEGRAL ELECTRON FLUENCE ENERGY DISTRIBUTION FOR SELECTED PERIJOVE DISTANCES

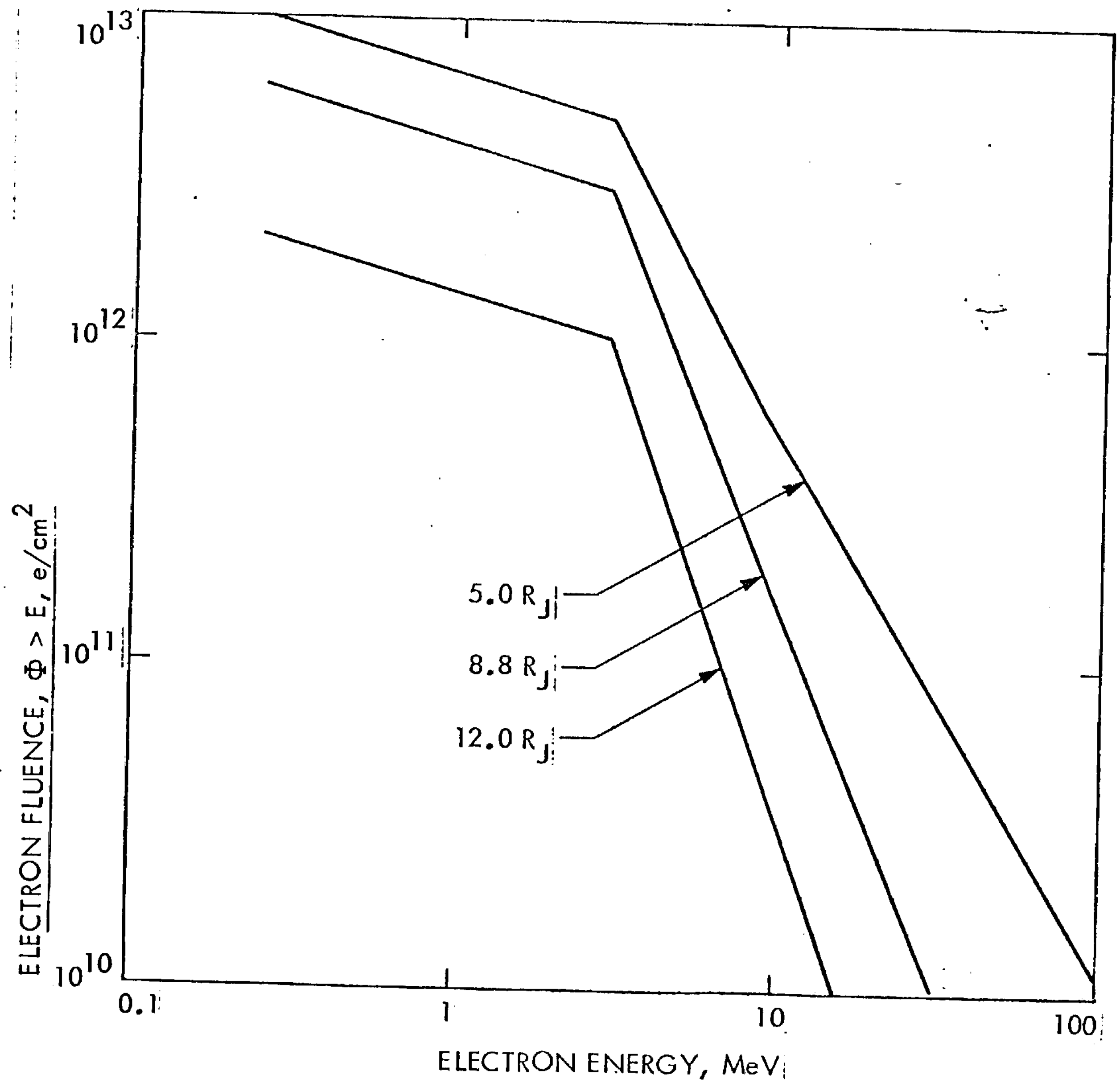

FIGURE 9-35

tron/cm^2 (E>3 Mev). Therefore, at 3 Mev the integral fluence for a 5 R_J perijove encounter is essentially the same as that which Pioneer 10 accumulated.

To specify test levels based on these spectra it is necessary to collapse the spectra to single energy equivalents of the spectra. This is accomplished by accounting for either one or both of the two major types of damage resulting from radiation: one, ionization; the other, displacement. To perform reasonable and practical tests, and to test with the facilities that are available, it is necessary to use cyclotrons (D.C. steady state or pulsed accelerators) to produce the desired high-energy electrons. In either case, using a mono-energetic electron is a practical simulation. The use of gammas as a substitute for electrons to simulate ionization is also generally acceptable provided that only ionization degradation is expected to dominate. Gamma substitution is the most practical test method. The predominant degradation mechanism for electrons at these fluences is ionization. The equivalency for ionization is performed on a total dose basis.

Figure 9-36 displays a plot of the fluence-to-dose conversion for the ionization produced by electrons as a function of energy. This dose conversion is an absolute conversion and it was evaluated using the energy loss dE/dx (Mev-cm^2/gm) in silicon.

Figure 9-36 also contains a curve which defines the other type of degradation displacement damage. In order to generate a set of test levels to simulate displacement requires energy equivalencing. This is required because displacement varies significantly with energy and depends on the types of materials and, as well, what happens in the material itself. The displacement damage curve in Figure 9-36 is specified as a relative displacement damage because it is the relative differences between energies that validate the assumption for its use. The spectra (see Figure 9-38) are weighted by the normalized values to yield a spectrum equivalent the 3 Mev level.

ELECTRON IONIZATION ENERGY DEPOSITION
AND
RELATIVE DISPLACEMENT DAMAGE IN SILICON

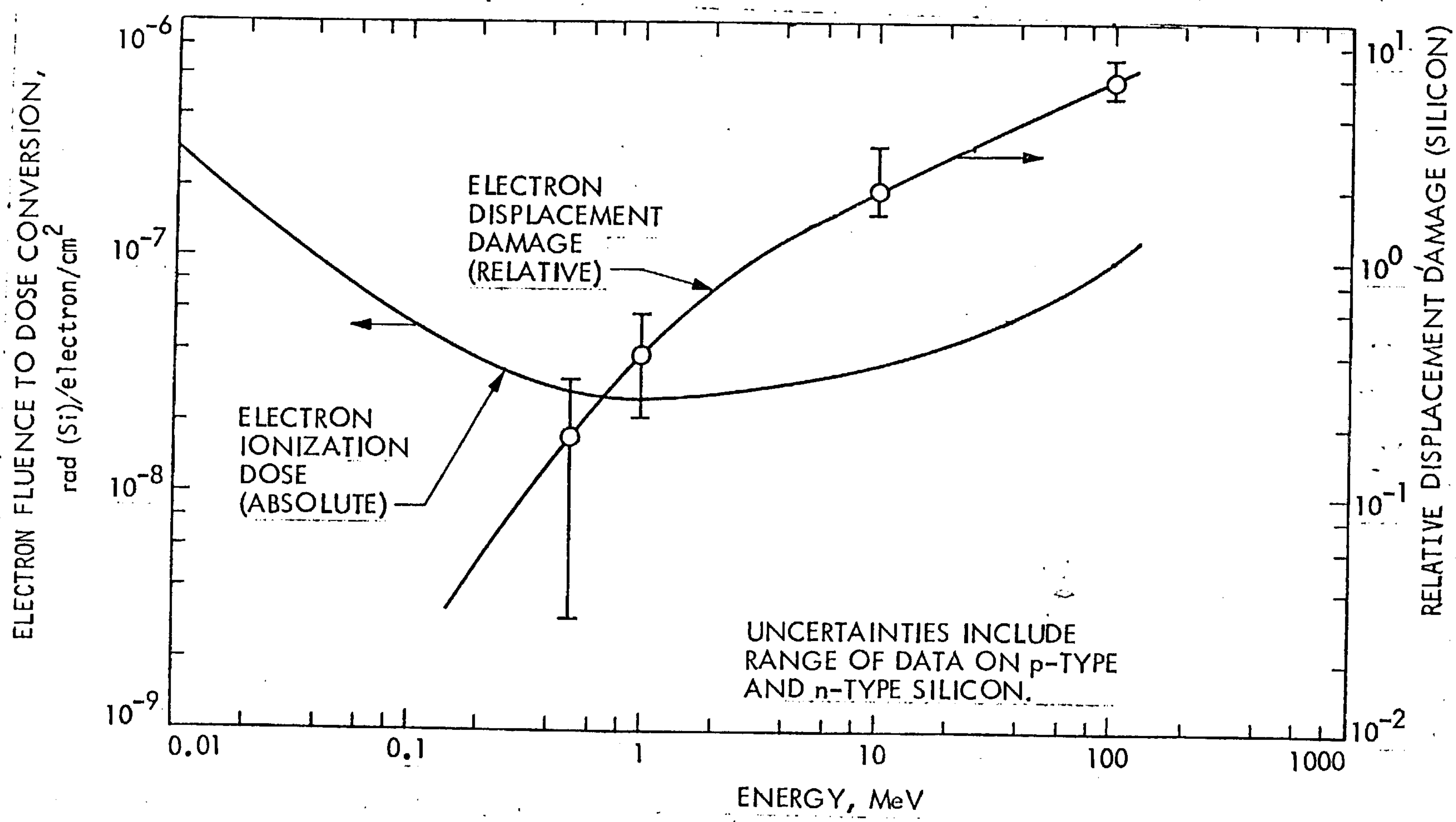

FIGURE 9-36

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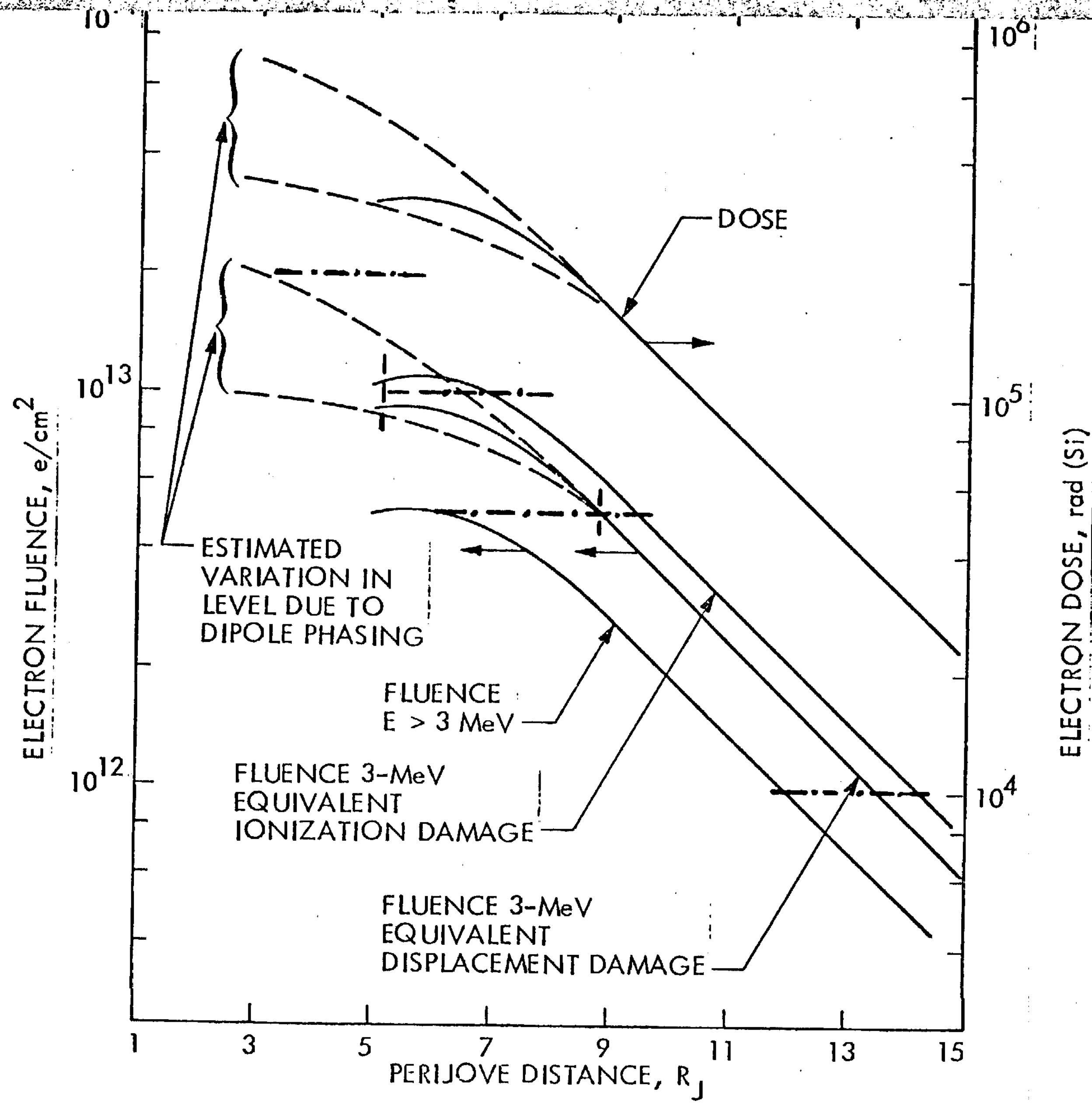
These uncertainty bars in Figure 9-36 simply have to do with whether the material is P-type or N-type silicon. There are other uncertainties that should be factored in but the important feature of this curve is its relative distribution. The slope and not the absolute amount is the important parameter at this stage; however, variation in slopes should be anticipated.

Note in Figure 9-36 that the low-energy contribution of the electrons has very little influence on the accumulation of displacement degradation. However, the low-energy ionization dose contribution has a sizable influence on ionization dose. Our problem, with sensitive electronics on MJS, is primarily an ionization problem.

For comparison purposes, the MJS '77 proton environment, if as large as expected, will not achieve as much ionization as expected with the electron environment as defined. However, the displacement from protons would be at least as much as the electron environment. As a result, the displacement problem may be twice as large which is still not as critical, from our understanding of the sensitive electronics, as is the ionization. Proton ionization at exposed surfaces are expected to be significant.

Figure 9-37 displays the results of folding the energy and dose equivalent degradation data (see Figure 9-36) into the spectra in Figure 9-35. The results include 3 Mev equivalent fluences, 3 Mev equivalent doses, and E>3 Mev fluences. A major feature displayed in Figure 9-37 includes phasing of the flyby with planet rotation and magnetic axes. For the current model no significant variations in phasing occur beyond about 6 R_J. Probe mission design, therefore, should consider this feature as significant and more detail study should be followed and correlated with Pioneer 11 data.

The curve of fluence with E greater than 3 Mev is constructed using data points taken from Figure 9-36 at the integral fluence points at E greater than 3 Mev. The fluence, curve of 3 Mev equi-



ELECTRON FLUENCE AND DOSE ACCUMULATION IN A POINT DETECTOR FOR FREEFIELD ENVIRONMENT AND FOR SELECTED TRAJECTORIES VERSUS PERIJOVE DISTANCE

FIGURE 9-37

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valent ionization damage, is constructed using the ionization data normalized to a 3 Mev equivalent. The fluence, 3 Mev equivalent displacement damage, is constructed using the displacement data normalized to a 3 Mev equivalent. The difference in levels between these two curves, the one for ionization and the other for displacement, 3 Mev equivalent for comparable R_Js are essentially insignificant.

Furthermore, the total ionization dose is used to simulate the ionization radiation environment. Because ionization degradation can be effectively evaluated by assuming that the dose-damage concept applies, the influence of electron energies can be neglected within the first approximation. So the tests simply use the total dosage due to the spectrum taken at 3 Mev. With this assumption we can account for both ionization and displacement in the same test and as well provide test data as a function of R_J for mission design assessment.

Four fluence levels on Figure 9-37 are highlighted with dash-dot lines to indicate derived test levels. The levels, 2×10^{13}, 1×10^{13}, 5×10^{12}, and 1×10^{12} are the test levels used for our quick-look tests. An extention of the quick-look tests is planned for parts identified as significantly influenced by this test environment. The evaluation will be made: (1) to determine whether the parts are potentially usable, which means more radiation data as a function of critical parameters are required, and (2) to determine whether the parts will work in circuits having specific input/output characteristics.

Table 9-1 contains a tabulation of a set of qualified test results. The qualifiers are: (1) these are quick-look test results of limited measurements and interpretations; (2) degradation is rated slight, moderate and critical, and should be related to statements: about parameter changes as noted, e.g., slight: component/circuit operates within specification limits, application should be reviewed. Moderate: significant parameter shifts, one parameter out of specification, component/circuit

TABLE 9-1

TEST RESULTS

Components / Type		3 MEV e/cm^2		20 MEV	Comments
	1×10^{12}	5×10^{12}	2×10^{13}	3×10^{12}	
Integrated Circuits					
★DGM 111	Critical	Critical	Critical	Critical	All devices catastrophic failure if used in neg current drain mode
DG 125	Moderate	Critical	Critical	Critical	Same as above at 5×10^{12} and 2×10^{13}
★LM 108A	Moderate	Critical	Critical	Critical	Slew rate okay; gain severe degrad
HA 2520	Slight	Slight	Critical	Slight	Catastrophic failure at 2×10^{13} in gain and off-set and bias currents
HA 2700	Slight	Slight	Moderate	N.T.	
DAC-01	Slight	Slight	Slight	Slight	
AD-550	Slight	Slight	N/A	Slight	

TABLE 9-1

TEST RESULTS (CONT)

Components / Type	3 MEV e/cm^2			20 MEV	Comments
	1×10^{12}	5×10^{12}	2×10^{13}	3×10^{12}	
CMOS					
CD4012AD	Slight	Moderate	Critical	N/A	
CD4049AD	Slight	Moderate	Critical	N/A	
CD4014AD	Slight	N/A	N/A	N/A	Still analyzing results
★ CD4011AK	Moderate	Critical	Critical	Slight	
CD4061A	Slight	Critical	Critical	Critical	Some devices survived and operated within spec at above 2×10^{13} (670K rads)

Note: All CMOS devices have shown a significant dependence on date code with respect to their sensitivity to radiation. Later devices appear to be significantly softer. Under investigation by Sandia and RCA.

TABLE 9-1

TEST RESULTS (CONT)

Circuits / Types	10^7 e/cm^2/sec	10^8 e/cm^2/sec	10^9 e/cm^2/sec	1×10^{12}	5×10^{13}	2×10^{13}	Comments
IRU Integrators	Slight	Slight/Mod	Critical	Slight	Moderate	N/A	
Power Shunt Regulators	Slight	Slight	Slight	Slight	Slight	N/A	
Power Under Voltage Det	Slight	Slight	Slight	Slight	Slight	N/A	Tested at 20 MEV to 5×10^{12} with only slight effects
FDS Master OSC	N/A	N/A	N/A	Slight	Slight	Signifi-cant	Failed at 2×10^{13} and then recovered 18 hrs. later; same results at 20 MEV
FDS Countdown Ckt	No results due to test equipment malfunction						

still operates, applications of component/circuit must be checked. Critical: two or more critical parameters out of specification, failure may be catastrophic, all applications must be reviewed, circuits utilizing components should be tested. These qualifiers are important because generally the worst-case measurement condition was followed.

The simulations were performed using a LINAC. It is used to produce the accumulated test fluence only, because it is a pulsed accelerator. Rate interference testing is not performed with a LINAC. All rate interference test data presented was accomplished using a continuous-wave DC machine (Dynamitron) producing electron energies between 2 to 3 Mev.

Test levels identified in Table 9-1 are 1×10^{12}, 5×10^{12}, 2×10^{13}. For some piece-parts a 20 Mev electron simulation of the spectra was performed to make sure that we didn't have a significant difference in the 20 Mev displacement compared with 3 Mev displacement. The displacement curve was larger at 20 than at 3 Mev, resulting in an equivalent amount about 2/3 of the equivalent amount at 3 Mev.

The starred entries include transistors which are low power and potentially low current usage devices. The 2N2484 was identified as critical at all fluences indicating a very sensitive part showing DC current gain out of spec at all levels. However, proper interpretation is required because the device was tested in a low-current mode, 10 microamps. When the device was operated at higher currents, then only moderate degradation occurred. Moderate degradation is, typically, acceptable within the gain change. Note that the degradation which occurred at low current is estimated to be practically all ionization degradation. The displacement degradation which occurred throughout but is dominant at the higher current level was not significant enough to fail the 2N2484. The same kind of appraisal applies to the other transistors (typically, these devices are general-purpose transistors). At the higher fluence levels, the critical parameters have moderate degradation.

Sensitive Integrated Circuits which are starred in Table 9-1 e.g., the analog switches, are devices which are tentatively identified as critical: these switches showed catastrophic failure when used in a negative current drain mode. That simply says that you can't turn the device on, so it can't be used in a bilateral switching mode.

The LM 108A is an operational amplifier whose characteristic offset voltage may be the critical parameter. It was identified as moderate degradation at 1×10^{12} and critical at the higher levels 5×10^{12}, to 2×10^{13}. The point made using LM 108 data is that there is a tremendous spread in the amount of degradation in that device for a given level. Therefore, applications in circuits, especially at 5×10^{12} and higher should be properly designed to accommodate radiation.

The CMOS devices, for example, the CD 4011 Dual Quad Nand Gate, essentially contains two P-channel and two N-channel type transistors. It was rated as moderately damaged at 1×10^{12} e/cm^2; but critically damaged at the higher levels ($\geq 5 \times 10^{12}$ e/cm^2, 3 Mev equivalent) as shown on Table 9-1. For 20 Mev electrons the damage assessment at 3×10^{12} which is assumed equivalent to the 3 Mev fluence of 5×10^{12} e/cm^2 indicated less degradation. Therefore, we assume the degradation to be dominated by ionization degradation.

The point in this assessment is that 4011's are ionization damage sensitive; and, as well, the range on degradation levels is wide and the degradation depends on part type, process and the manufacturer. There are a number of things that are being done to close-up the uncertainty range on the damage level as well as to harden the devices. Manufacturers, processes and controls are being reviewed and, as well, some of the available "hardened" CMOS is being evaluated.

Notice what happens to circuits which use these parts. The IRU integrator shown in Table 9-1 uses the LM 108 operational amplifier. The rate interference was slight to moderate at rates as high as 10^8 e/cm^2-s. For the MJS '77 mission, the rate is more like about 5×10^8 e/cm^2-s (see Figure 9-34). At this design rate there is a concern about rate interference. The detailed test data indicate that there is an adequate function at 5×10^8 e/cm^2-s. Only moderate damage to the IRU occurred at 5×10^{12}, which satisfies the MJS '77 design requirement. These quick-look test results help us identify those parts that are potentially too sensitive to the Jovian electrons, allow us to selectively generate characteristic performance data for the sensitive parts, and circuits that use the sensitive parts. In addition, the test results will be used to do radiation design analysis on the circuits.

The test results and design analysis will be used in spacecraft design trade-offs. Spacecraft design trade-offs include the use of inherent shielding, location and orientation of sensitive devices and, as well, the use of some additional shielding. Mission trade-offs, essentially, include selecting the perijove flyby distance and satellite positions most compatible with science objectives.