Radiation Effects on Science Instruments in Grand Tour Type Missions*

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The extent of the radiation effects problem is delineated, along with the status of protective designs for 15 representative science instruments. Designs for protecting science instruments from radiation damage is discussed for the various instruments to be employed in the Grand Tour type missions. A literature search effort has been undertaken to collect science instrument components damage/interference effects data on the various sensitive components such as Si detectors, vidicon tubes, etc. A small experimental effort is underway to provide verification of the radiation effects predictions.

The various experimenters whose instruments are used as models have made available some of their own radiation effects experience for this study.

In response to the rare opportunity afforded by the multiplanet flyby or "Grand Tour" missions, the Jet Propulsion Laboratory has been examining mission problems and developing a practical design for an outer-planets spacecraft. The evolving spacecraft, TOPS (Thermoelectric Outer Planets Spacecraft), will be exposed to several new hazards. Two of the more difficult hazards are the requirement for long component life due to the mission duration of approximately ten years, and the subjection to Jupiter's severe trapped radiation environment. The total radiation environment includes gamma, neutron, proton, and electron fluxes. There are two dominant sources of the radiation, the Jovian trapped charged particles and the neutrons and gammas from the radioisotope thermoelectric generators (RTG). The trapped charged particles have been indirectly observed around the planet Jupiter and possibly radiation belts surround other planets. Jupiter must be used for a gravitational assist in Grand Tour type missions and, thus, the trajectory is fixed for any particular mission. The RTG is a nuclear electrical power supply which emits both gamma and neutron fluxes. It is needed for outer planets missions, because solar panel electrical power requires more kg/W than RTG power beyond ~3 AU.

Figure 1 shows the current TOPS baseline configuration (for perspective, this configuration has a 4.3 m reflector). The experiment requirements have been considered during the preliminary system design phase so that the design of the spacecraft itself permits meaningful science experiments. Configurations are under study which may further improve RTG radiation shielding of the science area. Table 1 shows representative science instruments used in the design study. Although the specific instruments for the actual mission payload have not yet been selected, the instruments listed in Table 1 form a set which adequately represents typical instrument integration problems. Table 2 is a list of radiation sensitive components being considered in this study.

The radiation problems are not equally severe. Gamma interference and proton damage are the two most critical problems and therefore will be considered in detail. The neutron fluence for the mission is expected to be about $10^{10} n/cm^2$ in the science area for the 10 year mission (ref. 1), and although interference is expected, only slight damage may occur. For example, this fluence level may be somewhat degrading to currently available components such as Si(Li) detectors in that a few percent resolution loss may occur. But this should not cause severe problems to flight instruments which generally do not require extreme resolution. Electrons are expected to contribute damage, but to a lesser degree than protons. Also, as J. Barengoltz (ref. 2) has shown, shielding would be beneficial for reducing electron damage, where as practical amounts of shielding may not adequately reduce proton damage. Thus, I will not consider electron or neutron effects.

Table 1. Representative instruments used in radiation effects study

Instrument	Principal experimenters	Institution (or mission)
Charged Particle Telescope	J. A. Simpson	(Pioneer F/G)
Cosmic Ray Detector	F. B. McDonald	(Pioneer F/G)
Imaging	TOPS	JPL
Infrared Multiple Radiometer	TOPS	JPL
Meteoroid Astronomy Detector	R. K. Soberman	(Pioneer F/G)
Micrometeoroid Detector	O. E. Berg W. H. Kinard	GSFG (Proposed for Pioneer F/G)
Plasma Probe	Wolfe Bame Bridge	(Pioneer F/G) LASL-(MVM) MIT-(MVM)
Plasma Wave	F. L. Scarf	(Proposed for Pioneer F/G)
Radio Astronomy Experiment	J. K. Alexander	(Proposed for Pioneer F/G)
Trapped Radiation Detector	J. A. Van Allen	(Pioneer F/G)
Trapped Radiation Instrument	R. W. Fillius	(Pioneer F/G)
Ultraviolet Photometer	D. Judge	(Pioneer F/G)
Vector Helium Magnetometer	E. J. Smith	(Pioneer F/G)
X-Ray Detector	K. A. Anderson G. Garmire	(Proposed for Pioneer F/G) CIT

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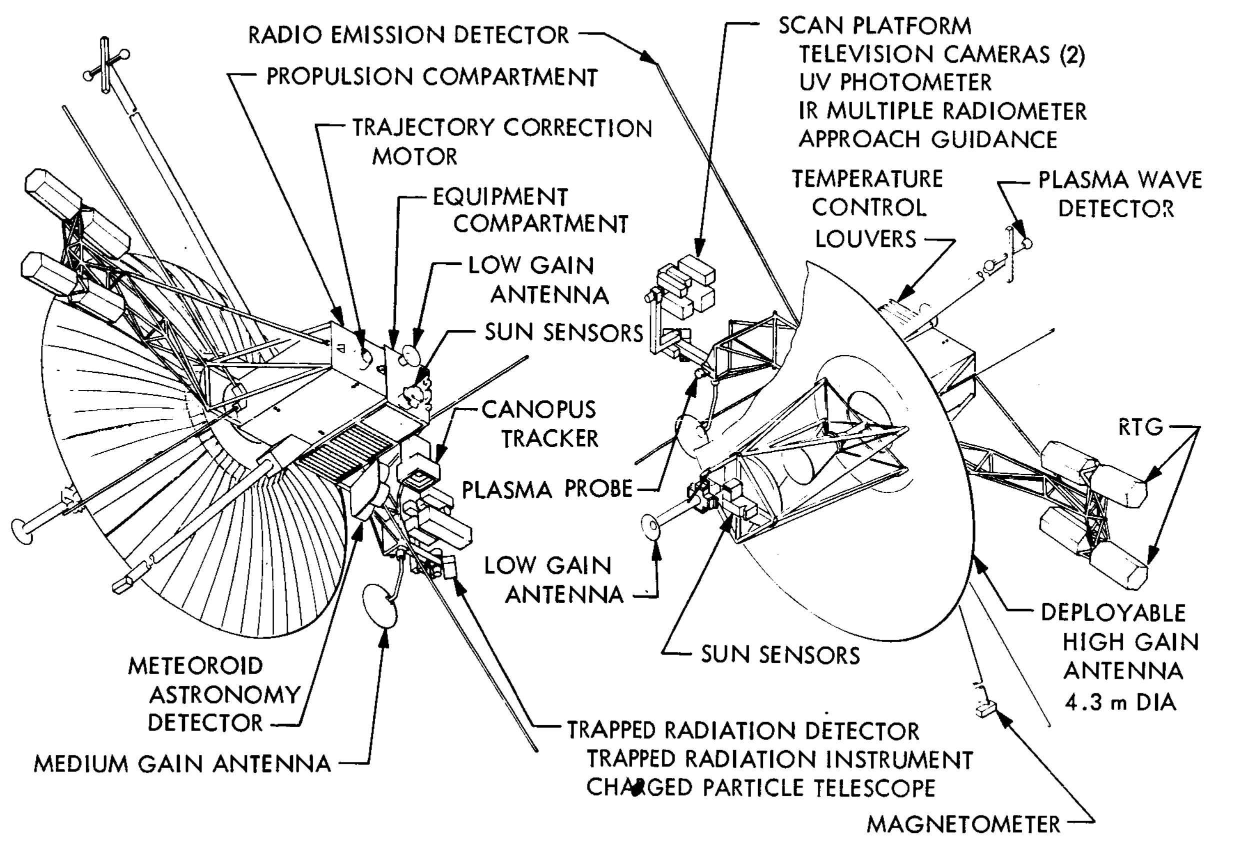


Figure 1. Thermoelectric Outer Planets Spacecraft, configuration 12L (with representative payload)

Table 2. Radiation sensitive components which limit instruments either from permanent damage or interference effects

- Solid state detectors
  - Si surface barrier
  - Si(Li)
  - Ge(Li)
- Scintillators
  - Na I (Tl)
  - Cs I (Na)
  - Plastics
  - Organics
- GM tubes
- Proportional counters
- Photomultiplier tubes
- Continuous channel multipliers
- Vidicon tube
- Emissive and optical materials for
  - UV (e.g., S_iO_2 etc., overlap with visible detector materials)
  - Visible (e.g., S20, etc., ···, > 10 types)
  - IR (e.g., HgCdTe; CdS, MgO, ···, > 20 types)
- Electronics

Melvin Reier (ref. 3) has detailed the gamma spectrum expected from the RTG and the spectral variations, with time, impurities, and orientation, are well known. Reference 1 also establishes the design restraint gamma dose of about 300 rad in the science area for the mission. Although this dose level will not cause damage problems, interference from approximately 1600 γ/cm^2-sec of a few keV to a few MeV must be considered as a time dependent background problem. For this reason in-flight calibration is highly important to many instruments.

The University of Chicago original Charged Particle Telescope (CPT) design for Pioneer F/G, which is shown in Fig. 2, is considered to provide a typical evaluation of interference problems. The CPT instrument uses a cylindrical anticoincidence scintillator around a six element telescope. The RTG contribution to the background under various coincidence requirements is shown for both the Pioneer F/G situation (ref. 4) and the unshielded TOPS situation. By "unshielded" it is meant that the shielding effects of the electronics bay and propulsion bay are not included. Davis and Koprowski (ref. 5) have analytically shown that about one order of magnitude

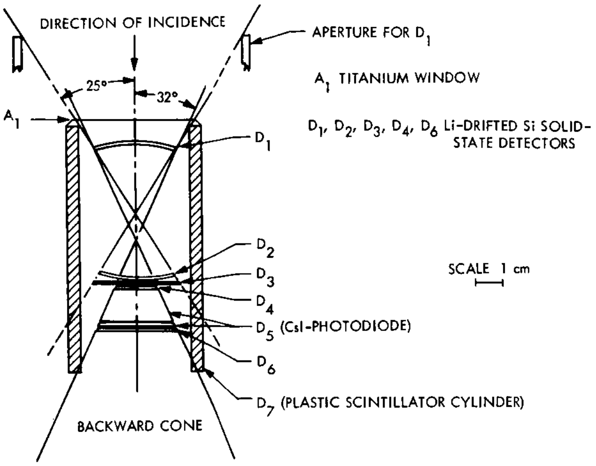


Figure 2. Charged Particle Telescope, proposed for the Pioneer F/G missions (This is a cylindrical scintillator shield around a six-element telescope.)

attenuation may be available in some areas on the spacecraft due to this shielding. This may allow instruments similar to the Pioneer F/G CPT and the Cosmic Ray Detector, to be located in regions where no additional passive shielding is required. In fact, experiment instruments as sensitive as an x-ray detector using proportional counters may be accommodated. This is possible since the projected number-flux levels without additional shielding may be as low as a few γ/cm^2-sec, most of which will be above 500 keV (i. e., above the energy region of interest to x-ray investigations) and therefore easily discriminated electronically. Background levels which would be acceptable for an x-ray instrument observing Jupiter are less than 0.04 counts/cm^2-sec (ref. 6). Figure 3 clearly shows the radiation improvement of the TOPS design which indeed should be further improved both from the revised design and reduced uncertainties using more sophisticated analysis and experimental verification of gamma number-fluxes. Additional spacecraft shielding may be provided to some instruments to reduce the radiation fluences from the RTGs. Initial instrument shielding calculations were based on unidirectional gamma and neutron fluxes from the RTG with no shielding or scattering effects due to intervening spacecraft materials. This was done as a worst case calculation to see what the limit of radiation shielding requirements might be. With the exception of the x-ray instruments (not considered in the baseline), the total shadow shield weights were less than 5 kg of tungsten or depleted uranium. The largest baseline shield was given to the Charged Particle Telescope and weighed about 2.27 kg. As Davis showed, this approach of neglecting spacecraft shielding and scattering, is pessimistic for flux magnitude calculations, but, optimistic for flux direction calculations. This means that shields will be thinner, but, must cover larger areas than unshielded calculations predict.

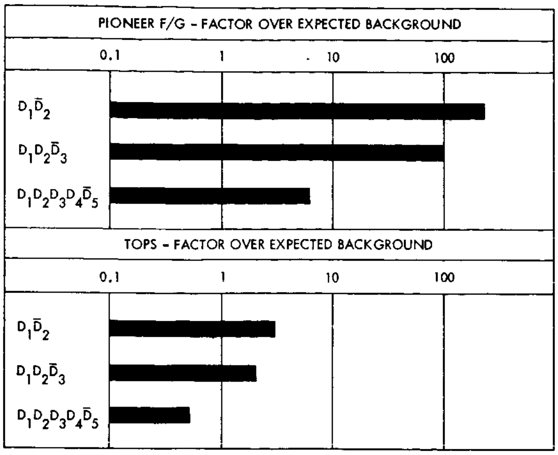
Table 3 shows the preliminary shield weights which are spherical surfaces that are thinned in the antenna direction, built up in the RTG direction, and made integral parts of the instrument. The specific electronic shielding (e. g., pulse amplitude discrimination, coincidence requirements, etc.), are included as well as specific geometrical configurations and experimental objectives. The x-ray detector shield weight is extremely sensitive to changes in flux levels since such a large area (~180 cm^2) must be shielded. There is a possibility that an area may be sufficiently shielded by the spacecraft electronics bay to accommodate this type of instrument without additional shielding. However, conclusive data will require radiation mapping around a prototype spacecraft.

Although the RTG radiation problem is serious, it is greatly overshadowed by the highly uncertain natural Jovian radiation environment. Many studies have been undertaken in recent years to resolve the uncertainties in the Jovian trapped radiation. Unfortunately due to the lack of experimental verification, the proton models are still highly uncertain. This will not be resolved until after Pioneer F/G results are known. The Pioneer results will not be available in time to establish spacecraft design constraints and thus we are dependent on models alone.

Table 3. Preliminary shield weights*

Experiment	Acceptable RTG fluxes	Shield weight, kg	Experiment	Acceptable RTG fluxes	Shield weight, kg
CPT	8 γ/cm^2 sec (on D1 and D2) (1500 γ/cm^2-sec on scintillator shield) 150 $^n/cm^2$-sec	1.1	PWD	0.1 Rads/hr 3000 $^n/cm^2$-sec	0
			RA	0.1 Rads/hr 3000 $^n/cm^2$-sec	0
IMR	15 γ/cm^2-sec 3000 $^n/cm^2$-sec	0.7	TRD	45 γ/cm^2-sec 150 $^n/cm^2$-sec	0
MAD	0.1 Rads/hr 3000 $^n/cm^2$-sec	0	TRI	45 γ/cm^2-sec 150 $^n/cm^2$-sec	0
MAG	0.1 Rads/hr 3000 $^n/cm^2$-sec	0	TV	0.1 Rads/hr (55,000 γ/cm^2-sec) 300 $^n/cm^2$-sec	0
MD	0.1 Rads/hr 3000 $^n/cm^2$-sec	0	UVP	0.1 Rads/hr 3000 $^n/cm^2$-sec	0
PP	15 counts/cm^2-sec 300 $^n/cm^2$-sec	~1.0	XRD	2 γ/cm^2-sec 3 $^n/cm^2$-sec	-13.6

*The shield weights include specific experiment geometries and electronics shielding. Underlined levels are for damage, the others are for interference.



'igure 3. RTG gamma interference in the Charged Particle Telescope (the expected ackground is an estimate without any RTG radiation). All the detectors not indicated re in anticoincidence, e.g., $D_1 \bar{D}_2 \equiv D_1 \bar{D}_2 \bar{D}_3 \bar{D}_4 \bar{D}_5 \bar{D}_6 \bar{D}_7$. The TOPS numbers do include the self-shielding of the spacecraft.

The best model in my opinion is the one developed by Neil Divine (ref. 7). Although, even this model has large uncertainties associated with it. Since the TOPS conservative design philosophy demands a design restraint model which includes the uncertainty and a safety margin, the design restraint levels for protons and electrons are quite severe. Table 4 shows both the electron and proton TOPS design restraint fluxes and fluences. The proton fluence levels are approximately four orders of magnitude above the nominal Divine model predictions for critical proton energies. Although the table includes particles from all sources such as the earth's Van Allen belts, solar wind, solar flares, and galactic cosmic radiation, essentially the source above 1 MeV for protons and 0.25 MeV for electrons is the Jovian trapped radiation prediction. J. Barengoltz (ref. 2) has detailed the design restraint model and what effect it will have on semiconductor devices.

In some science instruments electronics will be the sensitive components and the radiation effects on electronics obviously are inherent in all the instruments. In general, however, the damage tolerance is more restricted for science instruments and electronics which have delicate linear analog front ends as opposed to digital circuitry which in many cases can be over designed (ref. 8). Circuit design, to overcome this hazard, must be tailored to the individual instrument and this detailed work is not yet underway.

Figure 4 shows the effects on proton fluence of shielding on a Grand Tour trajectory. The weights of a sphere with radius equal to the shield thickness is shown as an indication of the weight involved. Obviously if fig. 4 represents the spectral shape even though shielding will reduce the total number fluence, the "softer" proton spectrum has more protons with energy below ~20 MeV than the unshielded spectrum. Protons in the energy region below ~20 MeV are considerably more damaging than the higher energy protons (ref. 2) and thus the shielded spectra are more hazardous than the unshielded for reasonable weight shields.

Table 4. Radiation design characteristics and restraints*

Radiation type	Energy interval (MeV unless otherwise noted)	Maximum flux (particles/ cm^2-sec)	Fluence (particles/ cm^2)
Proton	~3 keV	1.2×10^8	5×10^{15}
	1-3	3.7×10^8	5.7×10^9
	3-10	2.9×10^7	8.0×10^{10}
	10-30	3.8×10^6	9.6×10^{11}
	30-100	3.1×10^6	3.9×10^{12}
	100-300	2.4×10^7	1.6×10^{12}
	300-1000	9.1×10^7	6.1×10^9
	1000-3000	3.0×10^7	4.7×10^8
	3000-10000		2.0×10^8
	E >10000		9.9×10^7
Electron	0-0.25	4.3×10^9	8×10^{10}
	0.25-3	2.6×10^9	6.4×10^{10}
	3-10	1.2×10^8	5.1×10^{10}
	10-30	2.2×10^7	2.2×10^{11}
	30-100	3.2×10^7	3.2×10^{11}
	100-300	2.5×10^8	2.5×10^{10}

*These levels include all sources such as solar wind, GCR, solar flares and Van Allen belts. Levels above 1 MeV for protons and 0.25 MeV for electrons are essentially due to Jovian trapped radiation.

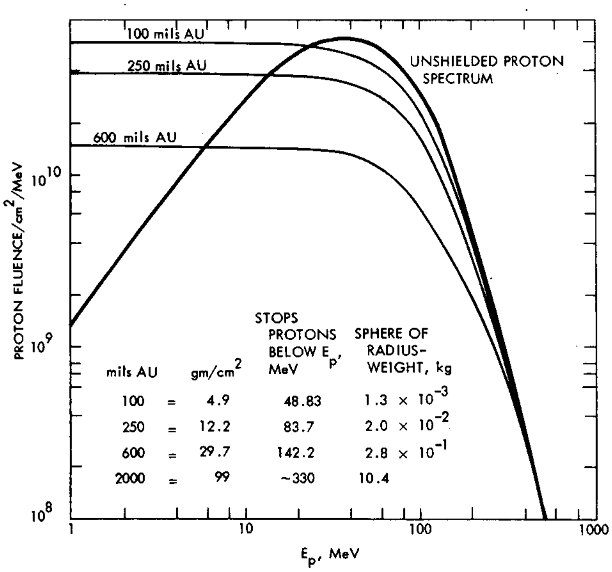


Figure 4. The effects on proton fluence of shielding on a Grand Tour trajectory (The heavy line shows the unshielded Jovian trapped proton fluence for a Grand Tour trajectory with a $3R_J$ periapsis.)

Proton damage will occur in science instruments exposed to the fluence levels required by the TOPS design restraints. This can be seen by comparing the design restraint levels to damage threshold levels for various components. Since many authors have investigated the various components, a bibliography would be excessively long. A typical example of published data however is illustrated by some work with the Si surface barrier detector. Singh and Rind (ref. 9) have obtained an empirical formula in the 5 to 40 MeV proton range. For a factor of 2 resolution degradation of the P^{210} peak width they find the fluence to be

$$\Phi = (2.94 \pm 1.20) \times 10^{10} \left(\frac{E}{E_d}\right)^{1/2}$$

$$\exp\left(-7.3 \pm 2.3 \times 10^{-5}_{\rho}\right)$$

where E is the proton energy, E_d is the energy loss in the sensitive regions (depletion region) of the detector and ρ is the original resistivity of the detector.

Thus for a 5000 μ detector irradiated by 30 MeV protons the fluence limits range from 2×10^{10} p/cm^2 to 2×10^{11} p/cm^2 for an original resistivity of ~20k Ω-cm.

Coleman, et al. (refs. 10 and 11) have looked at lower energy proton effects in the two separate experiments and together with reference 9 all of the critical energy region is covered for Si surface barrier detectors.

Figure 5 shows several proton damage thresholds for typical components. In considering these values, one must remember that experimental objectives and requirements can affect the damage threshold value of a particular component by as much as an order of magnitude. Thus, if the purpose of an experiment is to resolve two closely spaced lines, 5% or 10% resolution changes could seriously degrade the instrument. On the other hand, if one merely wants a number flux with crude energy resolution factors of 2 to 10 resolution, degradation may not be significant. For the Outer Planets Missions, the experiments are all designed for survey instruments to cover large ranges of information, but with only moderate resolution. Factors of two degradation in the resolution have been assumed as a limit for the baseline instruments.

It is apparent from Fig. 5 that most components will be affected. Presently available Ge(Li) detectors should not be considered as flightworthy on these missions unless in-flight redrifting is possible. The relatively new continuous channel multipliers are in a period of rapid development and recent indications are that at least two manufacturers expect to have significant lifetime increases available within a year. All instruments will need inflight calibration to assess the proton effects.

Experimental verification of radiation interference and, if possible, radiation damage will be quite important for science instruments as well as the entire spacecraft on Grand Tour type missions. Experiences in the Pioneer F/G radiation program have been quite enlightening and although problems still exist, one can realistically expect significant scientific results which will advance the understanding of the origin of our solar system.

The individual experimenter however must follow one or more of several options. If the instrument will survive due to lower actual levels (the probable situation) the experiment continues as planned. If his instrument is not "hard" enough to withstand the radiation, but significant data can be obtained before destruction, then he can simply monitor the instrument to destruction. A third alternative is to trade off resolution or some experimental objectives for more shielding, redundancy, harder but less desirable components in flight calibration, etc. A fourth option is to try to alter the mission such that the environment is less severe. A fifth option, and the most unpleasant, is to remove the particular experiment from the mission.

Designers of science instruments for outer planets Grand Tour missions, must consider radiation effects at all phases of the instrument development and the mission in order to be able to unfold pertinent data from radiation interference and/or radiation induced instrument degradation.

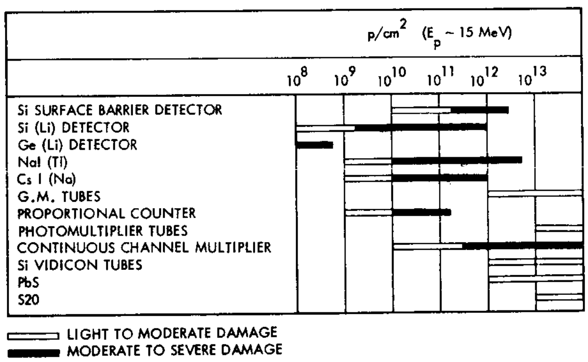


Figure 5. Science instruments' components typical damage levels (These damage levels depend strongly on the particular experimental requirements and objectives.)

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