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Space Weather Biological and System Effects for Suborbital Flights

31 October 2008

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Volpe National Transportation Systems Center
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14. ABSTRACT

The Aerospace Corporation was tasked to assess the impacts of space weather on both RLVs and ELVs operating at suborbital altitudes from launch sites located in the low (equatorial regions), middle, and high latitudes. The present report presents a broad overview of the space environment, seeks to quantify radiation exposure, and describes the potential hazards that a suborbital RLV, including passengers and crew, can expect to encounter during a suborbital flight from launch points located in the low, middle, and high latitudes.

Owing to the short duration of flights (~30 minutes, or less), the even shorter exposure at altitudes where all but the most energetic particles may penetrate with significant fluxes (~ 5 minutes) the exposure of crew and passengers is minimal, except under circumstance such as Solar Particle Events (SPEs) occurring less than ~ 5% of the time. Under typical conditions the radiation exposure to crew and passengers on a suborbital flight is less that for a long duration airline flight.

Avoiding exposure to potentially harmful radiation associated with solar or geophysical disturbances can be achieved by locating launch sites at middle latitudes, or lower or by delaying flights when there are indications that an SPE is in progress or is imminent. It is most likely that the lower intensity primary and secondary radiation environments below some latitudes are benign enough that launch can occur at any time, including the ~5% of the time when particular events associated with potentially significant risk occur. In the case of a high-latitude site, such as the site considered here, a possible launch commit criterion could be based on event probability distributions. Forecasts and monitoring (now-casting) support is available from NOAA’s Space Weather Prediction Center.

Although the radiation risk for crew and passengers is minimal except possibly at high latitudes and during solar and geomagnetic disturbances, crew and passengers should be monitored for radiation exposure. This is because of the potential for litigation and the possibility, however remote, that the onset of an event such as an unanticipated SPE could occur during flight. Passengers should also be briefed on the radiation risks in the spirit of informed consent.

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Abstract

The Aerospace Corporation was tasked to assess the impacts of space weather on both RLVs and ELVs operating at suborbital altitudes from launch sites located in the low (equatorial regions), middle, and high latitudes. The present report presents a broad overview of the space environment, seeks to quantify radiation exposure, and describes the potential hazards that a suborbital RLV, including passengers and crew, can expect to encounter during a suborbital flight from launch points located in the low, middle, and high latitudes.

Owing to the short duration of flights (~30 minutes, or less), the even shorter exposure at altitudes where all but the most energetic particles may penetrate with significant fluxes (~ 5 minutes) the exposure of crew and passengers is minimal, except under circumstance (Solar Particle Events, SPEs) occurring less than about 5% of the time. Under typical conditions the radiation exposure to crew and passengers on a suborbital flight is less that for a long duration airline flight.

Avoiding exposure to potentially harmful radiation associated with solar or geophysical disturbances can be achieved by locating launch sites at middle latitudes, or lower, or by delaying flights when there are indications that an SPE is in progress, or is imminent. It is most likely that the lower intensity primary and secondary radiation environments below some latitudes are benign enough that launch can occur at any time, including the ~5% of the time when particular events associated with potentially significant risk occur. In the case of a high-latitude site, such as the site considered here, a possible launch commit criterion could be based on event probability distributions. Forecasts and monitoring (now-casting) support is available from NOAA’s Space Weather Prediction Center.

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Acknowledgments

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Dr. Richard L. Walterscheid served as the Principal Investigator at The Aerospace Corporation, and Mr. Robert W. Seibold served as Program Manager. Coauthors are Dr. Ronald E. Turner and Mr. Thomas A. Farrier, Analytic Services Inc. (ANSER) and Dr. Joseph E. Mazur, The Aerospace Corporation. The authors are grateful for guidance and support of Dr. Fan Lei, QinetiQ, for providing access to the QinetiQ Atmospheric Radiation Model (QARM) radiation exposure model, and Ms. Susan Murray, ANSER, for compiling results from that model.

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1. Executive Summary

1.1 Introduction

The Aerospace Corporation was tasked by the DOT Volpe National Transportation Systems Center to provide technical support to the Federal Aviation Administration, Office of the Associate Administrator for Commercial Space Transportation (FAA/AST), in assessing the impacts of space weather on Reusable Launch Vehicles (RLVs) operating at suborbital altitudes from launch sites located in low, middle, and high latitudes. This document presents an overview of the space environment, seeks to quantify radiation exposure, and describes the potential hazards that a suborbital RLV, including passengers and crew, can expect to encounter during a suborbital flight from representative launch sites.

Aerospace is pleased to submit this final report, in accordance with the requirements delineated in Section F.2, Deliveries or Performance, of Contract No. DTRT57-05-D-30103, Task 13B.

1.2 Radiation Environment

The crew and passengers on commercial suborbital space ventures may be exposed briefly to a radiation environment made up of radiation trapped in the Earth's magnetic field, background galactic cosmic radiation (GCR) and, occasionally, to brief but intense solar energetic particle events (SPEs).

Galactic Cosmic Rays (GCRs) comprise a low flux of highly energetic and extremely penetrating ions. They can penetrate tens to hundreds of centimeters of shielding. The GCR flux is greatest near solar minimum and is least at solar maximum (CERS, 2008).

SPEs occur intermittently throughout the solar cycle, are not well understood and cannot be predicted. Dramatic increases in the intensity of penetrating particles (with ranges from millimeters to tens of centimeters) can begin within minutes to tens of minutes of the onset of an SPE and have the potential to produce elevated flux for many successive days. A few times per Solar Cycle these events have very large fluxes at very high energies beyond ~100 Mega electron Volts (MeV). These events give the most severe radiation environment to which suborbital flights may be exposed (CERS, 2008).

Particles trapped in the Earth's magnetic field comprise the third major component of the near-Earth ionizing radiation. They surround the Earth and include electrons, protons, and heavier ions. (CERS, 2008).

Near-term forecasts provide estimates of the probability of an event within the next few hours to days. Now-casts attempt to forecast the evolution of flux, fluence, and duration of on-going events. The NOAA Space Weather Prediction Center (SWPC) and the United States Air Force Weather Agency (AFWA) are responsible for providing space weather forecasts; The SWPC provides SPE forecasts to U.S. civil users. The Air Force serves specialized DoD needs, but its forecasts are also available to commercial space launch providers through the SWPC. Even after an SPE has been observed to be under way, forecasts of peak flux are good only to within an order of magnitude, at best (CERS, 2008).

Energetic solar and galactic cosmic rays pass through shielding material and body tissues. Biological damage results from interactions of the transported radiation at the organ or tissue site. The internal environment depends on the thickness and composition of the spacecraft walls. Dosimetric quantities related to biological risk can be estimated from calculated particle fluxes and energies in tissues or organs. These radiation transport methods can also be used to assess damage to spacecraft electronics (CERS, 2008).

1.3 Biological Hazards of Radiation Exposure

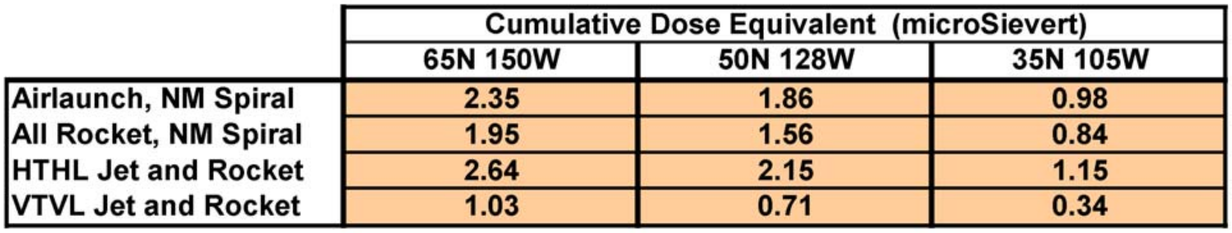
The crew and passengers of suborbital commercial space flight will experience enhanced exposure to cosmic radiation as they reach altitudes up to 100 km. However, because of the short duration of suborbital missions, they will likely get a lower dose than the crew and passengers of long duration commercial air flights. Nonetheless, it would be prudent to require the providers of commercial suborbital missions to provide crew and passengers with a briefing of the effects of radiation and exposure they could experience. In addition, the providers should have the tools and expertise to monitor forecasts and measurements of the radiation environment.

Long term health risks due to exposure to the radiation environment—in particular, the increased risk of fatal cancer—last for the life of the flight participant. Crew with repeated exposure to low doses during suborbital flights also face the possibility of accelerated development of cataracts, skin damage, central nervous system damage, and impaired immune systems.

Most radiation health research to date has focused on the increased risk of cancer. There is substantial uncertainty in translating results from impact on cells to impact on tissue, from impact on tissue to impact on the body, and from animal populations to humans or even from “population average” to “healthy” adults. Due to all of the variables and unknowns, risk calculations carry large uncertainties. A rule of thumb, that should be used with caution, is that twenty cSv (effective dose) increases the probability of a fatal cancer by one percent [NCRP 1989, 1993a, 2000].

A model of the radiation environment from the surface to 100 km was used to estimate the radiation exposure at three locations spanning 35 N to 65 N chosen to represent low mid-latitude, mid latitude and high-latitude launch sites. Dose Equivalent was calculated for various trajectories at each location for quiet solar conditions at solar minimum (maximum GCR contribution) and two SPE conditions. The radiation model used was the QinetiQ Atmospheric Radiation Model (QARM) constructed using Monte Carlo simulations of particle transport through the atmosphere. This model is optimized for aircraft altitudes and has been validated up to 40 km. Since less than five minutes on each trajectory is above 40 km, QARM should provide a reasonable representation of exposure. The QARM does not include vehicle shielding in its calculations. Table 1.1 shows the dose equivalent for four trajectories and the three launch locations for quiet solar conditions, solar minimum and GCR maximum. Note the range is roughly from 0.3 μSv to about 3 μSv. The dose increases with increasing latitude.

Table 1.1 Cumulative Dose Equivalent for suborbital trajectories for quiet solar conditions, solar minimum, GCR maximum from the QARM model (NM = New Mexico Spaceport)



	Cumulative Dose Equivalent (microSievert)		
	65N 150W	**50N 128W**	**35N 105W**
Airlaunch, NM Spiral	2.35	1.86	0.98
All Rocket, NM Spiral	1.95	1.56	0.84
HTHL Jet and Rocket	2.64	2.15	1.15
VTVL Jet and Rocket	1.03	0.71	0.34

Solar storm exposure can be orders of magnitude greater than exposure experienced during quiet geomagnetic and solar conditions. The QARM was used to estimate the impact of a solar storm on suborbital missions at high latitude. The dose equivalent versus altitude was generated for two representative storms, one from 29 September 1989 and one from 24 October 1989. Figure 1.1 shows the dose equivalent versus altitude at 65 N 150 W for 29 Sept 89, 24 Oct 89, and for comparison, the quiet GCR. For the active cases there is a rapid increase in dose up to around 40 km altitude where it becomes nearly constant. For the quiet case the increase halts at around 20 km.

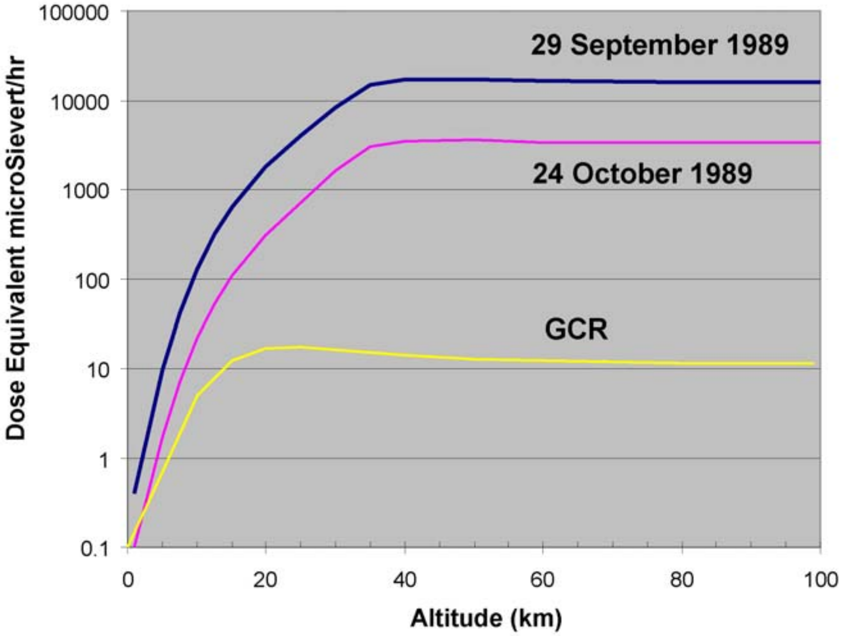


Figure 1.1. Dose equivalent versus altitude from QARM at 65 N 150 W for 29 Sept 1989, 24 Oct 1989, and for comparison, the quiet GCR used earlier.

If a suborbital mission were to launch at high latitude during the peak of a solar storm, the exposure could be as much as 2 to 3 orders of magnitude greater than for the same mission launched during quiet solar conditions at peak GCR. However, the exposure drops rapidly with decreasing latitude for latitudes less than about 60 °N, dropping to less than GCR exposures below 45 N°. Note that while solar storms cannot be forecast even hours in advance, they can be reliably detected minutes to tens of minutes in advance. Even this short notice should be adequate to cancel or delay suborbital missions

Figure 1.2 shows the dose versus latitude at 20 and 40 km altitude for the September storm. Also shown is the quiet case for 20 km. For the September case, there is a rapid drop in exposure as latitude decreases from 65 N to 50 N and below, dropping below GCR exposures below 45 °N. The exposure for crew and passengers during a solar storm would be very sensitive to the exposure duration, timing relative to event onset and peak, geomagnetic conditions, flight profile, latitude, and shielding provided by vehicle.

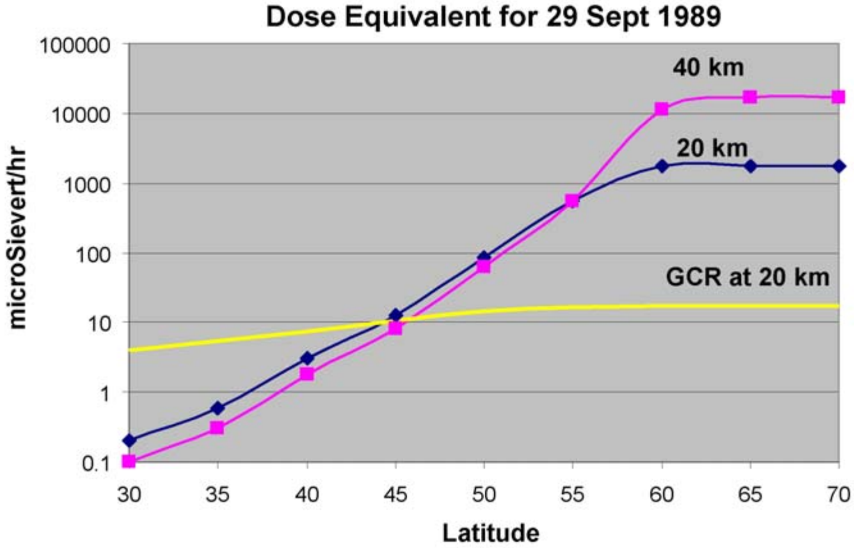
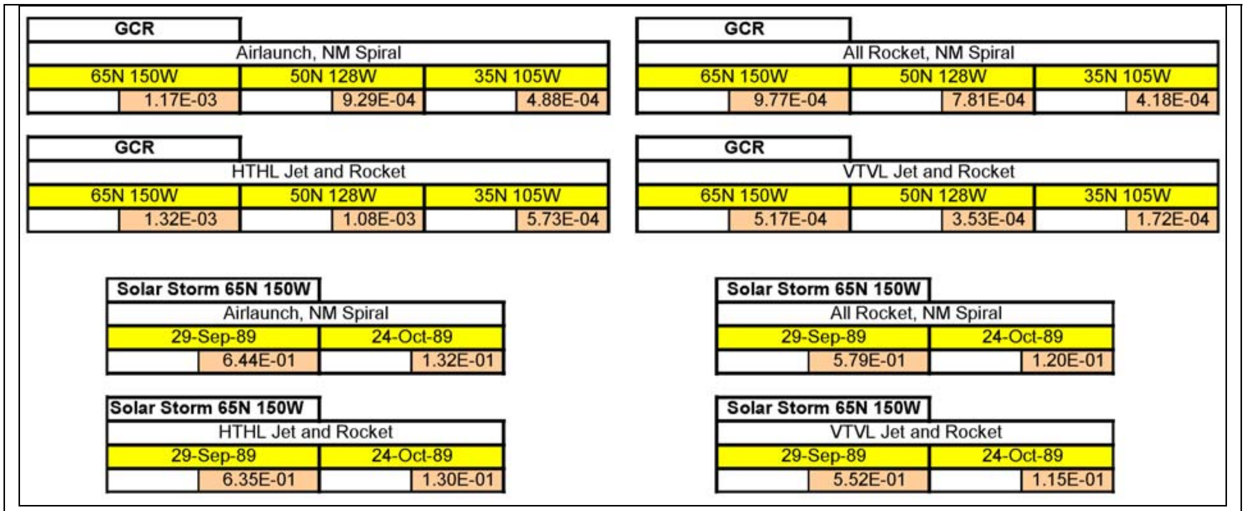


Figure 1.2. Variation of dose equivalent versus latitude from QARM along the 150 W longitude line at 20 and 40 km for 29 Sept 89 and for comparison, the 20 km quiet GCR used earlier. Note the dose equivalent from solar storms increases rapidly with latitude up to a flat maximum above 60 degrees.

With caution, the rule of thumb that a 20 μSv effective dose causes a one percent increase in lifetime fatal cancers can be applied to the calculated dose equivalents (NCRP, 1993b). The results obtained assuming that one μSv leads to 0.0005 excess lifetime fatal cancers in a population of 10,000 exposed individuals are shown in Table 1.2. If this is true, then quiet GCR lifetime fatal cancer rates will be less than .001 per 10,000 exposures, but during a severe solar storm there may be one excess fatal cancer per 10,000 exposures. Even the larger number is small compared to the expected natural rates, for example, 150 cancer occurrences and 20 fatal cancers within 10 years for 10,000 30-year old race-averaged females.



GCR		
Airlaunch, NM Spiral		
65N 150W	50N 128W	35N 105W
1.17E-03	9.29E-04	4.88E-04

GCR		
All Rocket, NM Spiral		
65N 150W	50N 128W	35N 105W
9.77E-04	7.81E-04	4.18E-04

GCR		
HTHL Jet and Rocket		
65N 150W	50N 128W	35N 105W
1.32E-03	1.08E-03	5.73E-04

GCR		
VTVL Jet and Rocket		
65N 150W	50N 128W	35N 105W
5.17E-04	3.53E-04	1.72E-04

Solar Storm 65N 150W	
Airlaunch, NM Spiral	
29-Sep-89	24-Oct-89
6.44E-01	1.32E-01

Solar Storm 65N 150W	
All Rocket, NM Spiral	
29-Sep-89	24-Oct-89
5.79E-01	1.20E-01

Solar Storm 65N 150W	
HTHL Jet and Rocket	
29-Sep-89	24-Oct-89
6.35E-01	1.30E-01

Solar Storm 65N 150W	
VTVL Jet and Rocket	
29-Sep-89	24-Oct-89
5.52E-01	1.15E-01

Table 1.2. Excess fatal cancers per 10,000 passengers. The table assumes in a population of 10,000 exposed individuals one μSv leads to 0.0005 excess lifetime fatal cancers. However, this "rule of thumb" may not apply at low dose rates.

Effective implementation of a policy of informed consent might require that the providers have as part of their support staff experts familiar with:

- The space environment
- Techniques to monitor measurements and forecasts of the radiation environment
- Techniques and models to estimate the doses within the body under realistic shielding
- Biological effects of radiation

Effective monitoring of the environment during flight and would require providers to include instrumentation in the vehicle to measure the radiation environment within. Comparisons of the flight data with model predictions would increase confidence in the environment and transport calculations and help improve the models.

1.4 Systems Effects

The radiation effects on vehicle electronics are of interest. The flight path will include typical aircraft altitudes, where there is a large body of research on hazards to avionics (e.g., Normand 1996), and could briefly reach altitudes where the primary particle environment can be similar to that for low-Earth orbits for satellites.

The total radiation dose due to the GCR and SPE environments is probably not relevant for suborbital vehicle systems because of the relatively low doses involved. For example, assuming a quality factor of 10 appropriate for high-energy protons and the entire neutron environment, the cumulative dose for the 29 September 1989 SPE in is on the order of 100 Gy. However, commercially-available off the shelf electronics may fail at doses on the order of a few tens Gy (e.g., Winokur et al. 1999). A complete assessment of the total dose on the actual suborbital vehicle electronics is outside the scope of this report.

Flights up to ~100 km will traverse the D region of the ionosphere (50-90 km) where high energy electrons of the auroral distribution create the ionization (e.g., Whalen 1985). The altitudes at which one needs to consider the effects of charging in auroral arcs are probably not relevant for suborbital flights. However, the D region absorbs high-frequency radio signals (3-30 MHz), so the short duration (15 min) increases of D-region absorption that occur during geomagnetic activity at high latitudes (>60 deg) could be relevant. Another hazard to HF communication through the D-region is increased absorption during solar flares (e.g., http://www.swpc.noaa.gov/dregion/dregionDoc.html).

In single-event effects in microelectronics a charged primary or secondary particle deposits enough energy within a device, such as random-access memory, to affect the state of a memory location, or an atmospheric neutron collides with material to create energetic and ionizing particles which then interact with electronics. As suggested by total dose calculations with the QARM model, the hazards for vehicle avionics will depend on solar and geomagnetic activity and launch location. Figure 1.3 plots the geomagnetic cutoff for two primary proton energies in terms of latitude and longitude. On the scale of the plot, there is no significant change in the locus of points with altitudes considered in this study. Primary protons with higher energies (500 MeV in Figure 1.3) have access to lower latitudes and the access can be as much as 10 degrees lower during geomagnetic storms.

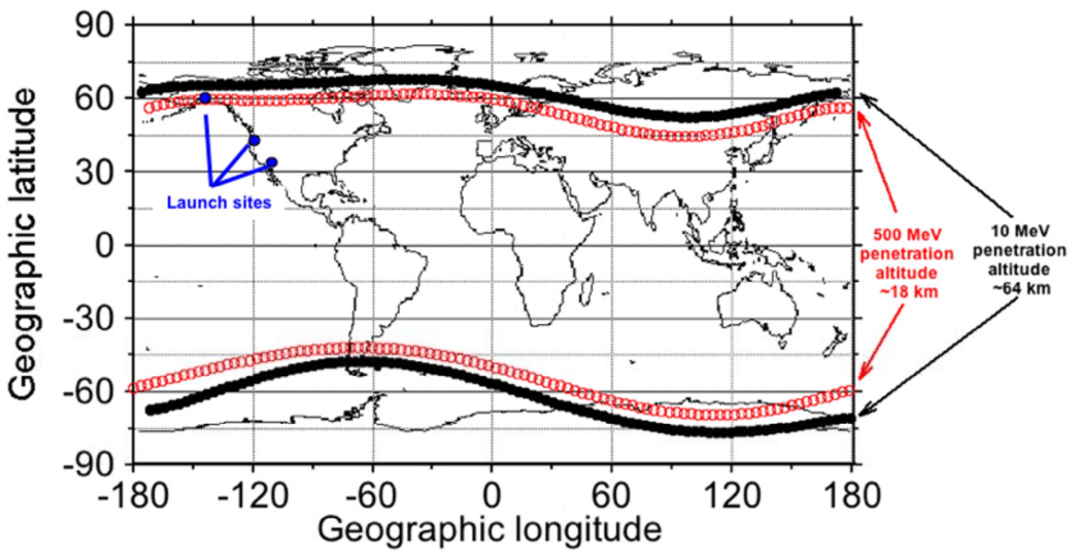


Figure 1.3. Geographic coordinates of the geomagnetic cutoffs for 10 and 500 MeV primary protons.

Some techniques that are used in the satellite and aircraft avionics industries might also be applied to suborbital missions. An example is predicting upset rates given ground-based measurements of single-event cross sections and the flight environment and then determining if additional error handling logic is required. Delay of launch is another mitigation technique that is possible in the case of non-time critical missions if some vehicle part has too high an upset probability. The only way to determine if delay would be necessary is through analysis of the part and the systems it supports.

It is most likely that the lower intensity primary and secondary environments below some latitudes are benign enough so that launch can occur at any time, including the ~5% of the time when SPEs occur. In lieu of detailed parts analysis, one could place a threshold at, say, the 99% worst-observed value of an index of geomagnetic activity such as the planetary 3-hourly magnetometer-based index Kp and SPE environments and delay launch until these indices fall below a threshold. Figure 1.4 shows the resulting delay times. For the SPE hazard, the resulting delay could be a day or more.

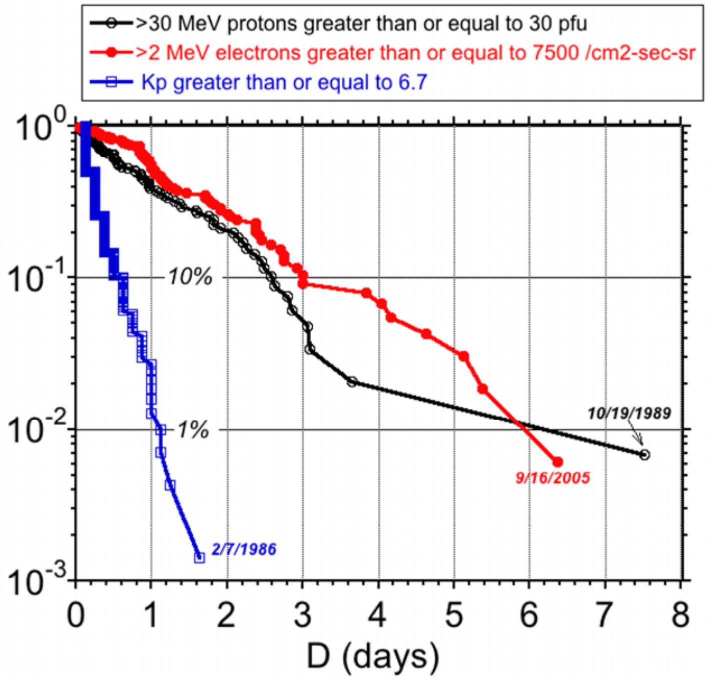


Figure 1.4. Probability that launch would be delayed D days if thresholds on the SPE (black) and geomagnetic activity (blue) were at the 99th percentile. Here pfu denotes peak flux unit and /cm2-sec-sr denotes counts per square cm per second per steradian

1.5 Potential Need for Space Weather Safety Regulations

The intent of Congress appears to be to promote space tourism as an industry, and to address the safety of participants in tourist-oriented suborbital and orbital flights by providing notice regarding the hazards associated with such operations. This report expands on this presumed intent, since space weather *per se* is not a hazard associated with launch or re-entry, the only phases of flight that are explicitly addressed in applicable legislation.

Further analysis will be needed in assembling a defensible foundation upon which future rulemaking can be based. However, it seems evident that three sets of regulatory guidance will be required to properly protect both crewmembers and tourists:

- A standard hazard communication briefing, incorporated into regulations in a format similar to that provided in 14 CFR §121.571 for airline passenger pre-flight briefings.
- A set of requirements for launch operators to limit cumulative exposure to crewmembers including radiation monitoring and mission scheduling and flight planning standards.
- Crew compartment shielding design sufficient to give crew a comparable level of protection to that for passengers accounting for the greater exposures over time for crew.

Additional research in all three areas would be appropriate, as would closer alignment with analogous regulations issued by the Associate Administrator for Aviation Safety (AVS). In addition, research and development aimed at improved means of monitoring of solar activity, of modeling and monitoring the environment inside the vehicle, and of processing and disseminating actionable and timely knowledge related to such activity should be explored.

Congress has created a framework within which the government's regulatory discretion is somewhat limited. The relevant legislation, incorporated into 49 U.S.C. §70102 *et seq*. creates the construct of a "space flight participant – an individual who is not crew carried within a launch vehicle or reentry vehicle." These individuals must be advised of hazards and protected from gross harm, but for whom it is not clear that Congress wishes to regulate exceptional protections.

Any spacecraft certification process developed to support the manned commercial space market will use some variation on current FAA and NASA criteria to protect all occupants against system-related catastrophic hazards encountered during launch, mid-flight, and recovery. This leaves environmental conditions (i.e., space weather) as the principal hazard requiring consideration for abatement.

Except in the highly unlikely event of a sudden change in solar activity after launch, a single sub-orbital flight will not expose space flight participants to unsafe doses of ionizing radiation. Part of the overall hazard communication process consistent with the intent of Congress would be to inform space flight participants formally of the exposure they received during their flight. It would also support an understanding of exposure upon which post-flight decisions regarding subsequent medically required or employment-related exposures could be based.

From a regulatory perspective two aspects of crew safety and health could draw Occupational Safety and Health Administration (OSHA) interest in space operations and operators:

- OSHA's "General Duty Clause" may figure in discussions regarding crew protection.
- The "grandfathering" that limits OSHA's ability to regulate exposures of aircrew members may not be applicable in space flight, since it may be argued that pre-existing regulatory standards are not in place.

The General Duty Clause criteria may be relevant to health risks arising from radiation exposures, even though it is not yet clear as to the radiation dose that could be experienced on sub-orbital flights.

The question addressed here is of what should space participants be warned, and to what extent can a warning facilitate a truly informed acceptance of risk. The hazards associated with prolonged or intense exposure to ionizing radiation are generally well understood, and there already are some noteworthy guidelines in place that may be applied, such as are contained in the European Union's "Basic Safety Standards Directive." It is essential to require operators to track factors relating to exposure(such as flight hours) in combination with exposure data, since reducing flight hours remains the only proven solution for reducing ionizing radiation exposure.

Space weather phenomena are virtually impossible to predict with any degree of accuracy. This limits mitigation options to three basic strategies:

- Crew scheduling to minimize individual annual exposures
- Crew compartment shielding to protect the most frequently exposed occupants
- Sufficient operational flexibility and event warning timely enough to employ last minute launch abort or early flight termination as a means of avoiding excessive exposures

Crafting suitable regulations regarding exposures requires predicted and actual exposures. The former may be used to build crew rosters, while the latter should form the basis for modifying them based on the actual cumulative doses experienced by each individual.

1.6 Summary and Conclusions

Owing to the short duration of flights (~30 minutes, or less), the even shorter exposure at altitudes where atmospheric shielding is significantly reduced (~ 5 minutes) the exposure of crew and passengers is minimal, except under circumstances (SPEs) occurring less than about 5% of the time. Under typical conditions the radiation exposure to crew and passengers on a suborbital flight is less than that for a long duration airline flight.

Avoiding exposure to potentially harmful radiation associated with solar or geophysical disturbances can be achieved by locating launch sites at middle latitudes, or lower, or by delaying flights when there are indications that an SPE is in progress or is imminent. For a high-latitude site a possible launch commit criterion could be based on event probability distributions.

Although the radiation risk for crew and passengers is minimal, except as noted, crew and passengers should be monitored for radiation exposure because of the potential for litigation and the possibility, however remote, that the onset of an event such as an unanticipated SPE could occur during flight. Passengers should also be briefed on the radiation risks in the spirit of informed consent.

2. Introduction

Space tourism, a concept that even a few years ago was perceived as science fantasy, is now appears to be on course to be a viable industry. Five individuals have paid up to $25 million to spend time on the International Space Station, and a sixth has started the process.

Bigelow Aerospace [http://www.bigelowaerospace.com/news/] has begun development of a prototype scale-model version of a full-scale habitable orbital module that may be launched in the 2010–2012 timeframe. Other space tourist companies have also reported making progress towards first launch. For example, Rocketplane Kistler is developing and building a fully reusable, two-stage orbital launch vehicle, capable of serving multiple markets [www.rocketplane.com]. Virgin Galactic is reportedly on the verge of launching suborbital flights and has already sold tickets for the first flights. Virgin Glactic has collected over $25 Million of customer deposits and plans to begin flying private passengers as early as 2009 [www.virgingalactic.com]**.** Futron Corporation, a market analysis firm that specializes in space commerce, recently released a report suggesting that the world-wide market for suborbital flight would exceed 10,000 people by 2020 [Futron, 2006**]**. In light of this, the Federal Aviation Administration's Office of Commercial Space Transportation (AST) released regulations in December 2006, authorizing the transportation of commercial passengers for the first time [CFR, 2006.].

The emergence of space tourism now presents new opportunities and new responsibilities for the commercial space weather community because the launch operators will benefit from accurate and timely space weather forecasts.

Adverse space weather can interfere with communications and could damage sensitive electronics. With adequate consideration, preparation, and caution, none of these potential impacts need to be severe. General techniques for commercial missions designed to ensure communications, minimize hardware failure, and maintain optimal orbit can be drawn from the extensive experience of the aerospace community.

Protecting passengers and crew from harmful radiation is of paramount concern to those overseeing space tourism. This report focuses on potential radiation-induced human health risks inherent in space tourism and suggests appropriate countermeasures to mitigate these risks.

2.1 Overview of Space Radiation

Operational space weather monitoring support to government sponsored human space flight is the domain of government entities such as the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) and the NASA Space Radiation Analysis Group, with help from a wide range of other government and industry resources. Products prepared by the NOAA SWPC would be readily available to the commercial space flight industry. These groups watch for three distinct natural sources of space radiation that will affect the crew and passengers of commercial space missions: trapped radiation in the Earth's magnetosphere**;** high-energy, low-flux galactic cosmic radiation (GCR), and periodic, lower-energy, extremely high-flux solar particle events.

Particles within the trapped radiation belt peak in density at altitudes significantly above the normal altitude region for sub-orbital human space flight. Nonetheless, trapped radiation from the South Atlantic Anomaly (SAA) is a significant source of exposure to astronauts on orbital missions.

Suborbital missions, with peak altitudes near 100 km, will only briefly sample the lower fringes of the region affected by trapped radiation. They will not likely be anywhere near the SAA.

GCR comprises very energetic, but very low flux particles that originate outside our solar system. While GCR is attenuated by the Earth's magnetic field at low orbital altitudes, this radiation and the secondary particles it generates as it penetrates the atmosphere, including backscattered neutrons will be the largest contributor to suborbital radiation exposure.

The Earth's magnetic field tends to shield low-Earth-orbiting spacecraft from the impact of Solar Particle Events (SPEs). However, the poles are accessible to incoming energetic solar particles. High inclination orbits and suborbital flights at high latitudes would expose the crew and passengers to these particles.

A further discussion of the radiation environment is provided in Section 3.

2.2 Biological Impact of Radiation Exposure

The typical US population's annual exposure to radiation is less than 5 mSv per year. Radiation worker limits are generally less than 50 mSv per year, and until recently, astronaut limits were 500 mSv per year. The exposure rate in a commercial suborbital mission will vary with altitude, mission duration, solar cycle, solar activity, vehicle shielding, and location within the vehicle. Total exposure is not likely to exceed a few μSv, less than a typical cross country air flight. In contrast, mission exposure for US astronauts has ranged from 1 to 100 mSv. Mission-averaged rates for astronauts have ranged from 0.1 to 4 mSv per day [Cucinotta, 2007].

The effect of exposure to ionizing radiation is a function of total dose, location and distribution of the dose within the body, rate of accumulation of the dose, and types of ionizing radiation that produce the dose.

High dose over a short period can lead to acute effects such as headaches, nausea, and skin burns. In extreme cases, the effects of high dose rates can be severe, either directly through radiation sickness or indirectly, as from vomiting in a space suit. However, the exposure expected in a suborbital mission will be far below the levels that cause acute effects.

A lower dose over a prolonged period may have long-term impact, including increased risk of cancer, effects on genetics or fertility, development of cataracts, and cumulative damage to tissue (particularly the central nervous system, digestive system, cardiovascular system, and immunological system).

While there is no doubt that exposure to significant levels of radiation will increase the probability of cancer, there is substantial uncertainty in quantifying the details, largely in the biological effects of radiation. Sources of uncertainty include but are not limited to a lack of understanding of the causative chain of events from exposure to cancer; the difference between the space environment and terrestrial exposure experience, and a lack of directly relevant data (most case histories are based on weakly ionizing radiation, as opposed to the highly destructive ionizing particles in the space environment).

For further discussion of the radiation hazards, see Section 3.

2.3 Space Flight Regulations

The Federal Aviation Administration recently established requirements for human space flight as mandated by the Commercial Space Launch Amendments Act of 2004, including rules on crew qualifications and training, and informed consent for crew and space flight participants [CFR, 2006]. The requirements, effective February 13, 2007, provide an acceptable level of safety to the general public and ensure individuals on board are aware of the risks associated with a launch or reentry.

Section 14 CFR Part 460.45 requires an operator to inform each space flight participant in writing about the risks of the launch and reentry, including the safety record of the launch or reentry vehicle type.

In addition, an operator must present this information in a manner that can be readily understood by a space flight participant with no specialized education or training, and must disclose in writing:

- For each mission, each known hazard and risk that could result in a serious injury, death, disability, or total or partial loss of physical and mental function
- That there are hazards that are not known
- That participation in space flight may result in death, serious injury, or total or partial loss of physical or mental function

Further, before flight, an operator must provide each space flight participant an opportunity to ask questions orally to acquire a better understanding of the hazards and risks of the mission, and each participant must then provide consent in writing that indicates that the participant understands the risk, and his or her presence on board the launch vehicle is voluntary. Note these rules are specifically for launch and reentry, not the orbital phase, as it is not yet clear which regulatory organization is responsible for regulations for the time in orbit.

The radiation environment of space is not explicitly handled in the FAA regulations. The closest reference is in a discussion of the Environmental Control and Life Support Systems (ECLSS). Among the factors that should be considered are: severity of the hazards, likelihood for catastrophic or critical consequences of exposure; potential for rapid or large changes in conditions, and availability of practicable in-flight measurement techniques and devices.

The FAA has much less stringent requirements for the crew. 14 CFR Part 460.9, *Informing crew of risk*, says only “an operator must inform in writing any individual serving as crew that the United States Government has not certified the launch vehicle and any reentry vehicle as safe for carrying flight crew or space flight participants.”

In presentations at NOAA’s Space Weather Week [2006 and 2007] and at the interagency Space Weather Enterprise Forum held in Washington, DC, in April 2007 Dunstan [2007] made the case, after reviewing the recently released regulation, that the commercial space tourist industry “will be on its own when it comes to safety issues related to space weather.” He went on to suggest that the space tourist industry needs the following:

- An inexpensive and reliable way to receive information concerning current space weather conditions, including “go/no-go” safety instructions just prior to launch
- A full characterization of the nominal space environment for their normative flight profile, including nominal radiation dosages that passengers can expect, given the particular vehicle properties, as well as any predictable variances from those norms

- The ability to track actual radiation dosages obtained over a number of flights to verify the theoretical calculation of radiation exposure
- Monitoring devices that, to the extent possible, can provide accurate post-flight data of each passenger's individual exposure during the flight

Such forecasts could be accomplished by monitoring alerts and warnings from the NOAA Space Environment Center, along with a commercially provided space-weather interpretation specific to the launch operator

Characterizing nominal expected exposure prior to the mission and validating these estimates may be the most difficult tasks, as these require good environmental models and observations at difficult altitude and latitude ranges and a good radiation transport code with an adequate representation of the vehicle geometry. The model will need sufficient precision to represent the relatively small dose expected. There are a variety of detectors that could be used for the validation.

There are several radiation monitoring devices that could be worn by the passengers and crew to meet the need for personal monitoring. To be most useful, these devices should provide more than an integrated dose, but rather should be able to produce a dose history.

Clearly a system to provide space weather prediction and *in situ* radiation monitoring will be needed in the era of commercial orbital space flight when the exposure, while tractable, will far exceed terrestrial background levels. While the risk for suborbital flights is much less, a similar system could be envisioned, if only for due-diligence and consistency with a policy of informed consent. Monitoring systems may also be a valuable resource should lawsuits be filed claiming that the radiation exposure during flight was the cause of a subsequent cancer or other health issue.

3. Radiation Environment

The crew and passengers on commercial suborbital space ventures may be exposed briefly to a hazardous radiation environment made up of radiation trapped in the Earth's magnetic field, the background galactic cosmic radiation (GCR) and occasionally to brief, but intense, solar energetic particle events (SPE). Accurate and timely information about this environment is required in order to plan, design, and execute commercial suborbital missions.

NOTE: The text in this section (except subsection 3.6) is largely adapted from the National Research Council report "Managing Space Radiation Risk in the New Era of Space Exploration," (CERS, 2008). Any references to this text should cite that source.

3.1 Galactic Cosmic Radiation

Interplanetary space is bathed by a low flux of essentially uniformly distributed, highly energetic, and extremely penetrating ions that are believed to be accelerated by supernova shocks in our galaxy. These ions make up the Galactic Cosmic Rays (GCRs). The highest intensities of GCRs are found between a few tenths and a few tens of a GeV/nucleon, where the particles can penetrate tens to hundreds of centimeters of shielding. Every naturally-occurring element in the periodic table is present in the GCR: nearly ninety percent are protons (hydrogen), close to ten percent are helium; the remaining are elements heavier than helium, with a relative abundance roughly similar to that found in our solar system. GCRs also include electrons and positrons, but their intensities are too low to be of practical concern.

The GCR flux outside the solar system may be regarded as constant. However, to get to Earth, these particles must penetrate the heliosphere, the magnetic plasma that surrounds the Sun and prevents the charged constituents of GCR from entering the interplanetary space. The interplanetary magnetic field varies with the solar cycle; the GCR flux near Earth is at a peak near solar minimum (when the interplanetary magnetic field is weakest) and at its low point at solar maximum (when the interplanetary magnetic field is strongest). The magnitude of the fluctuation varies with the energy of the GCR particles and with the intensity of the solar maximum in an understood and approximately predictable way, given accurate forecasts of the solar cycle. In the energy range of less than a few GeV/nucleon the flux decreases from solar minimum to solar maximum by thirty to fifty percent (Figure 3.1).

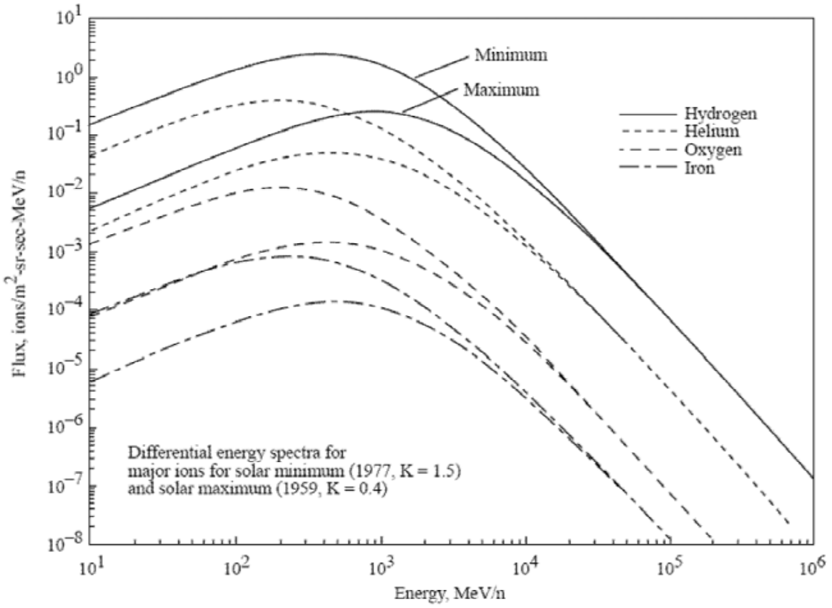


Figure 3.1 Differential Solar Energy Spectra at solar minimum and solar maximum. SOURCE: NRC 2008 and references therein.

3.2 Solar Particle Events

Energetic particles, occasionally with energies exceeding several GeV, are accelerated in sporadic events at the Sun. These energetic particles are produced by processes whose details are still being studied. SPEs occur intermittently throughout the solar cycle, although less frequently near sunspot minimum, and presently cannot be predicted. In addition to the particles themselves, signatures of SPEs also include significant increases in solar radio emissions, x-rays, and, occasionally, detectable levels of gamma rays and neutrons from the Sun.

A large body of research in the 1980s led to the classification of SPEs into two types, “gradual” and “impulsive.” These terms are now generally understood as shorthand for two distinctive particle acceleration mechanisms. In gradual SPEs, which have large intensities at energies relevant to radiation safety, shocks driven by fast coronal mass ejections (CMEs) are the dominant accelerator. The particle acceleration in impulsive SPEs, on the other hand, is believed to be due to magnetic reconnection processes, similar to those that go on in solar flares. Compared to gradual SPEs, impulsive SPEs are characterized by small intensities, short durations, low energies that do not penetrate typical shielding, and observability only over a narrow range of solar longitudes. Impulsive SPEs are also characterized by distinctive patterns of enhancements in heavy ions. Impulsive SPEs are too low in flux and fluence (time-integrated flux) to contribute substantially to the exposure of a commercial space tourist or crew member. All further discussion of SPEs in this report refers to gradual SPEs.

Dramatic increases in the intensity of penetrating particles (with ranges of millimeters up to tens of centimeters) can begin within minutes to tens of minutes of the onset of solar activity. During these early minutes, the particle flux is generally anisotropic, meaning more particles come from one direction than another. The peak direction is not necessarily toward the Sun, but generally lies along the local direction of the interplanetary magnetic field, which varies with latitude measured with respect to the magnetic poles, being vertical or nearly vertical at very high latitudes and horizontal or nearly horizontal at low latitudes. The flux becomes essentially isotropic (with no preferred direction) within tens of minutes to hours, depending on particle energy. Peak flux may occur minutes to days after onset, also generally depending on energy. The flux can be quite large throughout the event, although the flux at energies above several hundred MeV is generally not a significant contribution to the total fluence.

SPEs typically persist for hours to days, depending on energy. The time profiles and energies produced by the CME-driven shock are determined by both the evolving nature of the shock and the properties of the interplanetary medium through which the shock propagates. Many of the largest SPEs are part of multi-event episodes, produced as a single solar active region rotates across the face of the Sun. These episodes have the potential to produce elevated flux for many successive days. Although high-energy particles are generally produced when the CME-driven shock is still far from Earth, some SPEs have a substantial secondary peak when the CME-driven shock passes over the Earth (typically 18 to 30 hours after event onset). In most cases, these secondary increases are only at energies that do not pose a radiation hazard. But a few times per Solar Cycle, the shock's arrival at Earth also brings very large fluxes at very high energies, extending beyond ~100 MeV. These rare, powerful events are the most severe transient radiation environment to which suborbital flights may be exposed.

3.2.1 Energy Spectra

The energy distribution also varies substantially from event to event. In general the most significant energy range is from a few tens of MeV to a few hundred MeV. The drop in the energy spectrum is an important feature. "Soft" events have a larger proportion of particles with lower energy, "Hard" events have more than the average proportion of high energy particles.

3.2.2 Composition

On average, protons comprise more than 90% of the energetic ions produced in an SPE. For this and other reasons, protons are the primary concern when evaluating potential SPE radiation hazards. However, the processes that accelerate protons to high energies also accelerate heavier ions. Moreover, the relative abundances of the various heavy-ion species vary significantly from event to event, as well as with energy and with time during an event. In general, the heavy-ion species will not contribute substantially to the total dose.

3.2.3 Frequency of Events

The NOAA Space Weather Prediction Center declares that an SPE is underway when the number of protons with energy greater than 10 MeV exceeds 10 per cm^2 per sec per steradian (4π steradians is a full sphere). During most of the solar cycle there are roughly ten SPEs per year meeting this criterion. Each event will require the attention of those responsible for the safety of a suborbital space mission. Some will turn out to be too low in peak flux or total fluence to be of concern. Most will be large enough to have some impact on mission planning, possibly requiring a launch delay until the flux drops sufficiently near background levels. One to three times per solar cycle there will be an extremely large event (top five percent in peak flux or total fluence).

Catalogues of SPEs are tabulated on the basis of either peak flux or event-integrated fluence above some relevant energy thresholds. Both peak flux and fluence are needed to assess radiation hazards for launch systems. Figure 3.1 shows the frequency of events for recent solar cycles organized by the fluence of all particles with energy greater than 30 MeV.

3.3 Trapped Radiation

In addition to galactic cosmic rays and solar energetic particles, particles trapped in the Earth's magnetic field comprise the third major component of the near-Earth ionizing radiation environment. The trapped particles in these so-called "radiation belts" that surround the Earth include electrons, protons, and heavier ions. At Earth, the trapped electron spectra extend out to about 10 MeV, and trapped proton spectra extend to hundreds of MeV. The trapped proton intensities near Earth are among the highest proton intensities encountered anywhere in space. For this reason, trapped protons are an important design consideration for all spacecraft operating in near-Earth orbits. Measurements of the heavy ions trapped in Earth's magnetic field indicate that the energy spectra of the heavy ions are soft and that their intensities above a few tens of MeV/nucleon are too small to be of practical concern.

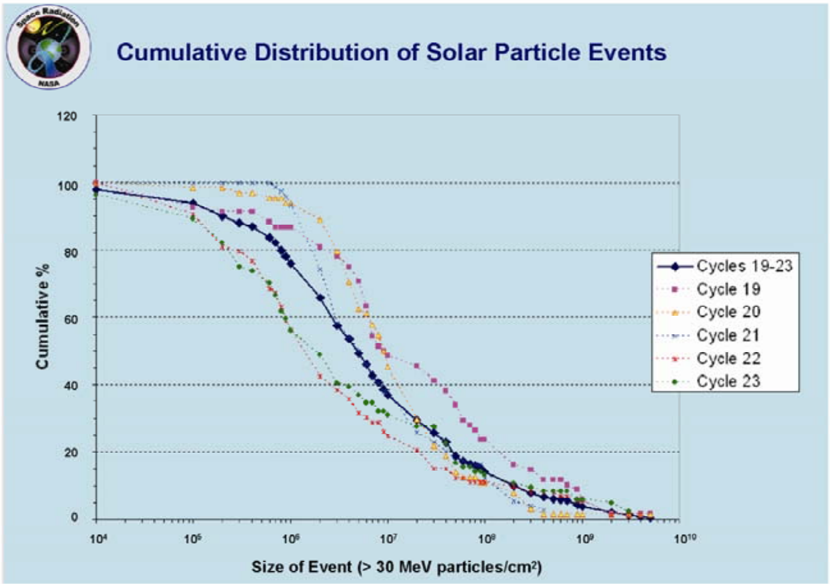


Figure 3.2. Cumulative Distribution of SPE. SOURCE: NRC 2008 and references therein.

3.4 Near Term Forecasts and Now-Casting

There are two classes of SPE forecast tools currently available to support human space flight: near-term, and "now-cast." Near-term forecast tools provide estimates of the probability of an event within the next few hours to days. Now-casts attempt to forecast the evolution of expected flux, fluence, and duration of on-going events. Of greatest importance for pending commercial missions are maximum flux (since for a short mission dose will be proportional to maximum flux), time to maximum flux, energy spectrum, and event duration. For mission planning, a low rate of false positives and the ability to predict when there will be no SPE within a given time frame are of greatest value.

The NOAA Space Weather Prediction Center (SWPC) and the United States Air Force Weather Agency (AFWA) are responsible for providing space weather forecasts. Each center has developed operational software to prepare SPE forecasts and alerts. The NOAA SWPC provides SPE forecasts to U.S. domestic civil users. The Air Force projections serve specialized DoD needs, but its forecasts are also available to commercial providers of space launch through the NOAA SWPC.

When no particle event is underway, and when there are no significant x-ray events, neither the SWPC nor USAF has a quantitative model or algorithm to produce multi-day forecast for SPEs. NOAA provides a one to three day probability estimate of energetic particle activity (along with estimates of the probability of significant x-ray flares and other geomagnetic activity). The particle event forecast is based on qualitative observations of on-going solar activity and solar active regions and their history. Long-lived active regions occasionally have a pattern of multiple eruptions. NOAA may upgrade the potential for a particle event when a region that produced one on a previous solar rotation (with a period of about 27 days) returns.

Even after an SPE has been observed to be underway, forecasts of peak flux are good only to within an order of magnitude or worse. The two operational models in use are the NOAA PROTONS model and the Air Force's Proton Prediction System (PPS). Both of these empirical models were developed before the central role of fast CMEs in producing large SPEs was widely recognized. These models predict and characterize SPEs starting from soft x-ray and microwave proxies, as well as optical information on the location of the active region. Utilization of these proxies contributes to the limited reliability of these models. Nevertheless, these models continue to be essential simply because real-time CME observations are not routinely available. NOAA PROTONS predicts the probability of occurrence for an SPE exceeding their threshold criterion (peak intensity >10 protons/cm^2-sr at >10 MeV), and occurrence time and value of the peak intensity. The USAF PPS predicts time, intensity, and spectra.

3.5 Secondary Radiation

Whenever the local space radiation environment in deep space impinges on the shell of the spacecraft, the solar and galactic cosmic rays penetrate the spacecraft structure and shielding and their physical characteristics are altered by atomic and nuclear collisions with the constituent atoms of the structural and shielding materials. The physical changes in these radiation fields as they pass through bulk material shielding (and through body tissues overlying critical organs) include energy losses, mainly due to atomic collisions and nuclear elastic and inelastic collisions, and changes in particle identities resulting from nuclear spallation or fragmentation reactions that produce secondary neutrons, protons, mesons, and heavier charged particles. Spallation and fragmentation occurs in both the projectile, which is usually moving at high speeds, and the target, which is usually stationary or nearly so. Hence, the more energetic secondary radiations are generally produced from the projectile nuclei. These alterations in the composition of the radiation fields as they pass through the spacecraft and crewmembers' bodies are described by radiation transport codes, which must include the effects of spacecraft and human geometries. Biological damage and the risk to crewmembers results from interactions of the altered, transported radiation environment at the local organ or tissue site. This local radiation environment will be some mixture of primary and secondary radiations, which vary depending upon the material composition and thickness of the target materials. As the thickness of the spacecraft walls increases, the differences between the internal and external environments increase as well. Because of self-shielding of internal body organs by overlying tissue, the local radiation fields at the internal organs are different than the internal environment within the spacecraft. Dosimetric quantities, such as dose, dose equivalent, and effective dose, which are related to biological risk, can be estimated from the calculated, local particle fluxes and energies, in the tissue or organ of interest. These radiation transport methods can also be used to assess damage to spacecraft electronics.

3.6 Radiation Shielding

As an example of the effects of particle transport through materials, in this section we consider the transmission of an intense SPE proton spectrum through relatively thick shielding (Figure 3.3). The calculation used a fit to the differential proton spectrum from the peak intensity during the October

20, 1989 SPE event (at 15:25Z) to specify the proton environment outside an infinite slab of 0.350 inches (350 mils) Aluminum followed by ~106 mils of Mallory 1000 (composition: 90% W, 5% Cu, and 5% Ni). This model thickness is much higher than typical aircraft structures, but nonetheless illustrates the difficulty of shielding high-energy primary protons and the generation of secondary particles.

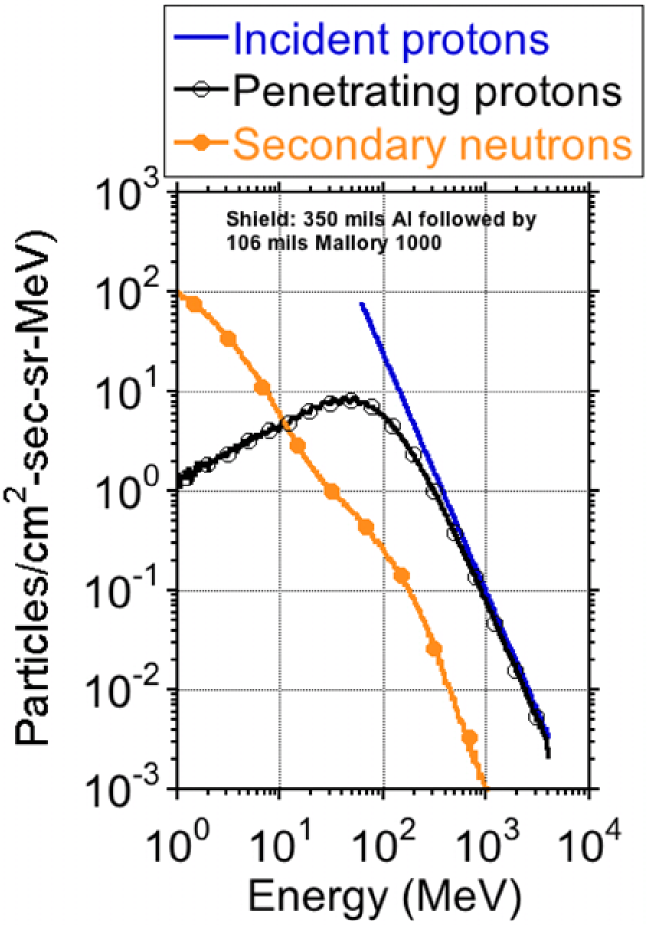


Figure 3.3 Calculated energy spectra of penetrating proton and secondary neutrons after traversing a thick Al + high-atomic number vehicle structure

The transport calculation followed >60 MeV incident protons, and the convergence of the penetrating and incident spectra shows that the bulk of the primaries have range greater than even this thick shielding. The generation of copious secondary neutrons is common to the problem of high-energy protons interacting with vehicle structures (e.g., Dyer & Lei, 2001 & references therein), hence the concern with neutron-induced upsets in avionics (see Section 5).

4. Biological Hazards of Radiation Exposure

We are all constantly exposed to radiation, in a variety of forms and to varying degrees. The crew and passengers of suborbital commercial space flight will experience enhanced exposure to cosmic radiation as they reach altitudes up to 100 km. However, because of the short duration of suborbital missions, they will likely get a lower dose than the crew and passengers of long duration commercial air flights. Nonetheless, it will be prudent to require that the providers of commercial suborbital missions to brief passengers the effects of radiation exposure the crew and passengers could experience from their mission(s). In addition, the providers should have the tools and expertise to monitor forecasts and measurements of the radiation environment.

4.1 Public Exposure to Radiation

Public exposure to radiation is described in a report by the National Council on Radiation Protection and Measurements [NCRP, 1987]. On average a person is exposed to less than 5 mSv per year, typically about 3.6 mSv. Of this, over eighty percent is from natural sources. About half (55 percent) of the total exposure is from radon, which is present to varying degrees in homes and in other buildings. About eight percent is from cosmic radiation reaching the Earth’s surface (about 0.26 mSv/year, doubling with each 2 km altitude above sea level). Another eight percent is from naturally occurring radionuclides in the soil and air. Eleven percent is from radionuclides in one’s body, both as a natural component of tissue and as natural components of the food one eats. See the Glossary for definitions of various measures of radiation exposure.

Another eighteen percent of the typical annual exposure is from man-made sources. Exposure from commercial air transportation is included within the estimate for man-made exposures. Typical cruising altitudes for commercial flights vary from 25,000 to 40,000 ft (8,000 to 12,000 meters). Dose equivalent rates at these altitudes vary from three to seven μSv per hour. For comparison, sea level exposure rate is only 0.03 μSv per hour. A five hour cross country commercial air trip would total on the order of 25 μSv or 0.025 mSv, well below the 0.26 mSv annual sea level cosmic ray exposure. [NCRP, 1995].

Some workers are exposed to higher levels of radiation than the general public. On average those workers with significant occupational exposure are exposed to about one to 3 mSv per year [NCRP, 1987].

4.2 Radiation Effects

When an ionizing particle goes through matter, it collides with the molecules in the target material. As it does so, it transfers its kinetic energy to the electrons of the molecules, breaking chemical bonds and changing the chemical composition of the target molecules. If the “target” happens to be within a living cell, the damage may affect the viability of the cell, the tissue it is part of, and ultimately impact the health of the individual. A damaged cell can repair itself, die early, or propagate a change to its genetic information. If it repairs itself, the system returns to normal. If it dies early, either because the damage is severe or because the cell enters “programmed death,” but not in concert with many neighbors, it may again have little impact on the health of the organism. If it and many of its neighbors die early, the tissue it is part of may lose function. If it cannot repair itself, or if it incompletely repairs itself, it may propagate genetic damage to later populations of cells. If this damage is significant, it may lead ultimately to serious consequences, including cancer.

Discussions of radiation-induced health risks are frequently divided into two categories: short term and long term. Short term consequences or “acute effects,” may include headaches, dizziness, nausea, and illness ranging from mild to fatal. The exposure needed to induce onset of even the mildest of these systems is on the order of 500 cGy which is well below the exposure that would be anticipated during a suborbital mission (less than 1 cGy, even during a solar storm, and more typically less than a few μGy).

However, the health risk incurred during a mission extends beyond its successful completion. Long term health risks due to exposure to the radiation environment—in particular, the increased risk of fatal cancer—last for the life of the passenger or crew member. Crew with repeated exposure to low doses during suborbital flight also face other dangers, including accelerated development of cataracts, skin damage, central nervous system damage, and impaired immune systems.

There is no doubt that exposure to substantial doses of radiation increases the risk of cancer sometime later in life. The hard part is quantifying "how much" the risk was increased over the risk the crew and passengers would face if they had not participated in one or more suborbital flights.

Most radiation health research to date has focused on the increased risk of cancer. Even in this field, there is substantial uncertainty. Sources of uncertainty include but are not limited to a lack of understanding of the causative chain of events from exposure to cancer; the difference between the exposure to the highly penetrating radiation unique to the space environment and the weakly ionizing radiation commonly experienced in terrestrial exposure; and a lack of directly relevant data (significantly fewer case histories of exposure to the highly destructive ionizing particles in the space environment). When detailed studies have been done, there is substantial uncertainty in translating results from impact on cells to impact on tissue, from impact on tissue to impact on body, and from animal populations to humans or even from "population average" to healthy adults.

Cancer is not the only end result. There is only now concerted effort to understand and quantify the effects of long term or repeated exposure to space radiation on the body's immune system, central nervous system, digestive system, etc.

Individual risks cannot be measured directly; they are calculated from measured radiation properties and computer model predictions. Due to all of the variables and unknowns discussed above, these risk calculations carry large uncertainties that make them difficult to quantify.

A rule of thumb, if used with caution, is that twenty cSv (effective dose) increases the probability of a fatal cancer by one percent [NCRP 1989, 1993a, 2000]. NASA has moved away from this paradigm to a confidence interval approach incorporating uncertainties [Cucinotta, et al. 2002].

According to the American Cancer Institute [*SEER Cancer Statistics Review*, 1975-2003, National Cancer Institute], the general population's lifetime risk of dying from cancer is 23 percent for males and 20 percent for females. Let's look in more detail at two candidate space tourists: a fifty year old white male ("Bob") and a thirty year old female, general population ("Alice"). Again referencing the National Cancer Institute [*DevCan: Probability of Developing or Dying of Cancer Software, Version 6.1.1*; Statistical Research and Applications Branch, National Cancer Institute], Bob has a 7.4 percent chance of developing some cancer and a 2.1 percent chance of dying of cancer before his 60th birthday, while Alice has a 1.5 percent chance of developing some cancer and a 0.2 percent chance of dying of cancer before her 40th birthday.

Figure 4.1 shows the historical radiation doses incurred by astronauts, compared to various exposure limits and typical doses related to some terrestrial activities. Figure 4.2 shows astronaut exposure rate by mission year and illustrates the variability of average daily dose rate experience through 2005.

These exposures can be assumed to be upper bounds on the exposure to be experienced in suborbital flight.

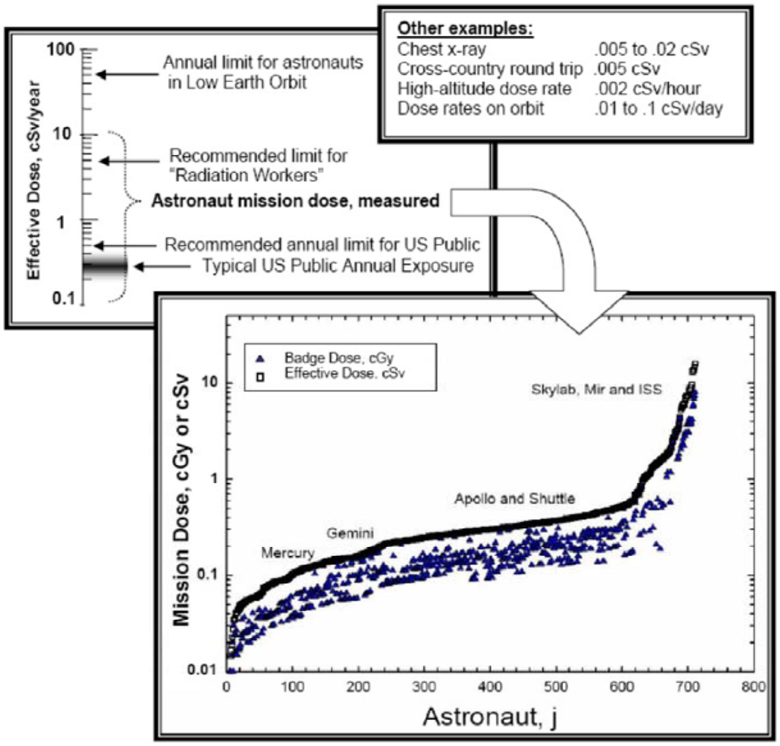


Figure 4.1 Radiation doses in context. Astronaut radiation exposure limits and history are compared in this figure with OSHA limits for US radiation workers, for the US public, and typical public annual exposure. Insert on lower left shows exposures from typical activities. Insert on lower right is a more detailed breakout of US astronaut mission doses through 2002. SOURCE: Cucinotta, et al., 2002.

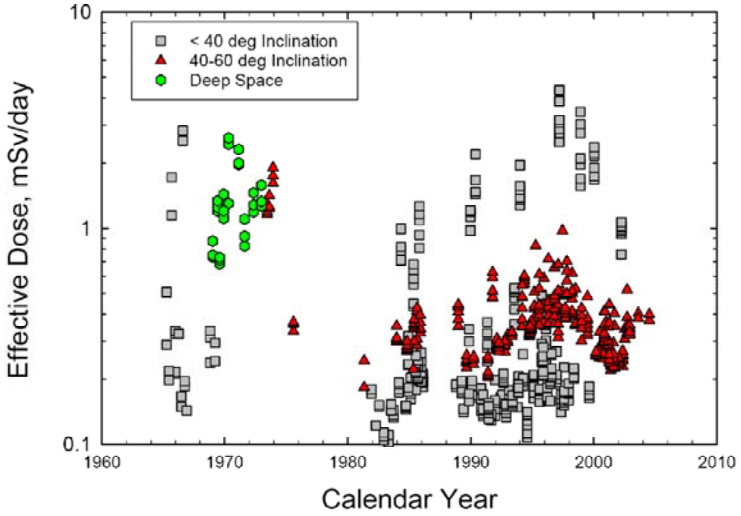
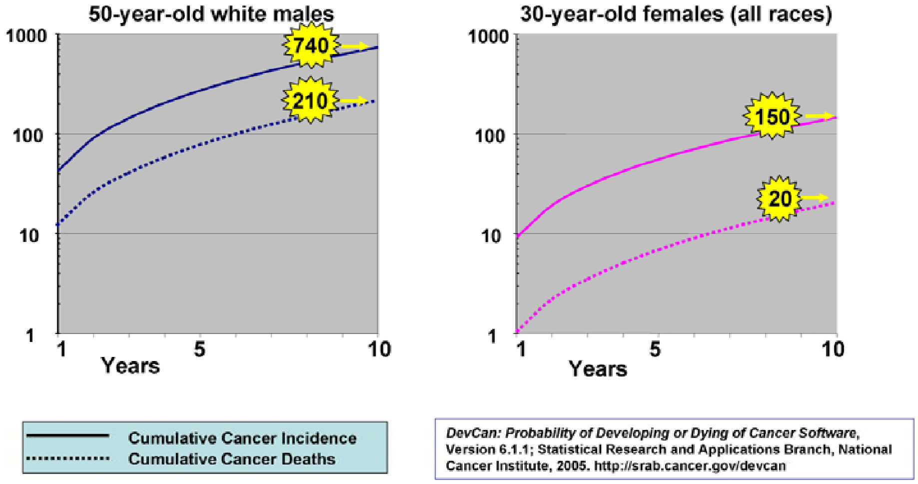


Figure 4.2 U.S. Astronaut exposure rate history through 2005. Exposure rate varies with altitude, orbit inclination, time in solar cycle, variations in solar activity, the vehicle shielding, orientation of the vehicle, and location within the vehicle. SOURCE: Cucinotta, 2007.

One can now make estimates of the suborbital-flight-related excess cancer fatalities per 10,000 tourists. Assuming a thirty minute sub-orbital flight, at exposure rates on the order of 10 µSv/hour, the equivalent dose would be on the order of 5 µSv or 0.0005 cSv, leading to 0.0025 lifetime fatal cancers among 10,000 tourists. Compare these numbers to 740 incidences of cancer (150 fatal), for Bob and 240 incidences (20 fatal) for Alice, within 10 years for a pool of 10,000 individuals (see Figure 4.3). A more detailed estimate of exposure using modeled dose rate versus altitude, representative suborbital trajectories, and various launch sites follows in the next section.



DevCan: Probability of Developing or Dying of Cancer Software, Version 6.1.1; Statistical Research and Applications Branch, National Cancer Institute, 2005. http://srab.cancer.gov/devcan

Figure 4.3 Cumulative Cancer Incidence and Deaths for two representative potential commercial space tourists. (US – 10,000 Starting Population). Graph shows cumulative number of new cancers and cumulative number of cancer deaths. [Turner, 2006]

4.3 Estimates of Suborbital Exposure

The following methodology was used to quantify the effect of the space weather environment on suborbital flights:

A model of the radiation environment from the surface to 100 km was used to estimate the radiation exposure at representative latitudes and longitudes

- Alaska (65N 150W)
- Intermediate (50N 128W)
- New Mexico (35N 105W)

Suborbital flight trajectories were generated to represent nominal profiles (altitude vs. time)

- Airlaunch, New Mexico Spiral
- All Rocket, New Mexico Spiral
- Horizontal TakeOff/Horizontal Landing Combined Jet and Rocket
- Vertical TakeOff/Vertical Landing New Mexico to the Eas

Dose Equivalent was generated for each trajectory at each location under the following conditions

- Quiet solar conditions at solar minimum (maximum GCR contribution)
- Two solar storm conditions
  - 29 September 1989
  - 24 October 1989

The radiation model used was the QinetiQ Atmospheric Radiation Model (QARM). It is a comprehensive atmospheric radiation model constructed using Monte Carlo simulations of particle transport through the atmosphere. It uses atmospheric response matrices containing the response of the atmosphere to incident particles on the upper atmosphere. It was run online at http://geoshaft.space.qinetiq.com/qarm/index.jsp?URL=start.jsp. This model is optimized for calculation of the radiation environment at aircraft altitudes, and has been validated up to 40 km. An alternative model considered was the CREME96 model, but it provides orbit-average doses, not point doses, and it is optimized for orbital altitudes. Since less than five minutes on each trajectory is above 40 km, QARM should provide a good initial representation of the exposure. The dose equivalent was calculated under quiet solar conditions versus altitude at three locations, chosen to represent a mid-latitude, high-latitude, and intermediate launch site (see Table 4.1). It is important to note that QARM does not include vehicle shielding in its calculations.

	Cumulative Dose Equivalent (microSievert)		
	65N 150W	**50N 128W**	**35N 105W**
Airlaunch, NM Spiral	2.35	1.86	0.98
All Rocket, NM Spiral	1.95	1.56	0.84
HTHL Jet and Rocket	2.64	2.15	1.15
VTVL Jet and Rocket	1.03	0.71	0.34

Table 4.1 Cumulative Dose Equivalent for suborbital trajectories for quiet solar conditions, solar minimum, GCR maximum from the QARM model

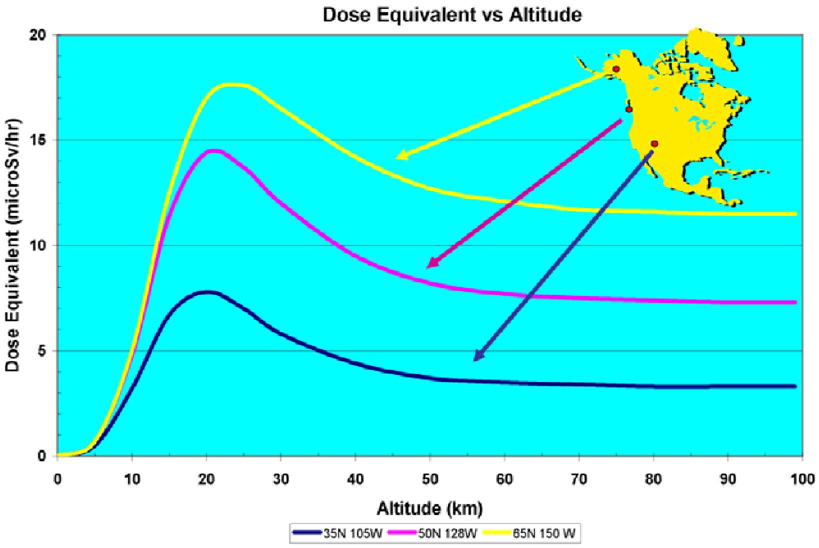


Figure 4.4 QARM Dose Equivalent (in tissue, no additional shielding) vs Altitude for solar minimum (maximum GCR) under geomagnetically quiet conditions (Kp ~ 2). More active solar conditions (Kp >5) could increase the dose by fifty percent or more.

The four flight profiles used for analysis are shown in Figure 4.5. They provide a good range of representative trajectories. All four have a peak altitude just over 100 km. Three of the four trajectories last only 15 minutes. The longest flight, representing a horizontal take-off and horizontal landing, spends much of its time below 20 km and its time profile above 20 km is similar to the other three profiles.

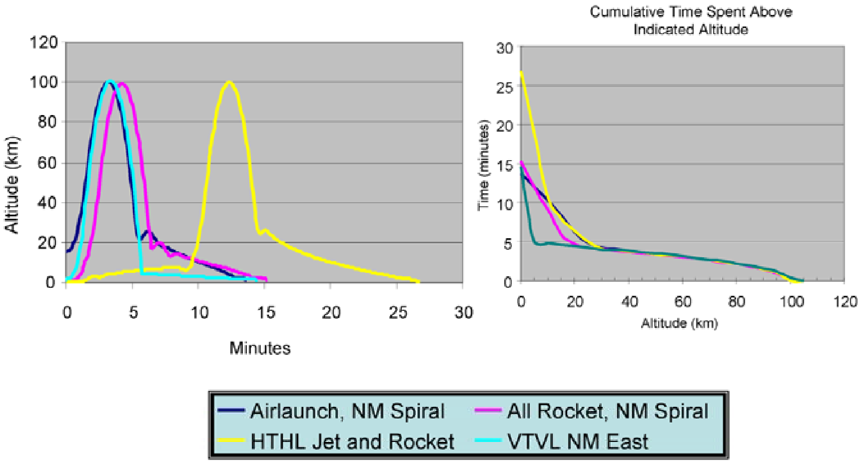


Figure 4.5 Flight trajectories. The panel on the left shows altitude versus time, while the panel on the right shows cumulative time above the indicated altitude.

Table 4.1 shows the dose equivalent under no additional shielding for the four trajectories and three launch locations for quiet solar conditions, solar minimum, GCR maximum. Note the range is roughly from 0.3 μSv to about 3 μSv.

Figure 4.6 provides more detail, showing how the dose equivalent accumulates through the flight. Note that the HTHL flight is much higher and the VTVL flight is much lower than the other types. This is because the HTHL flight spent the longest time in flight and spent as much time as the others at altitudes greater that 10 km, while VTVL flight spent the least time above 5 km.

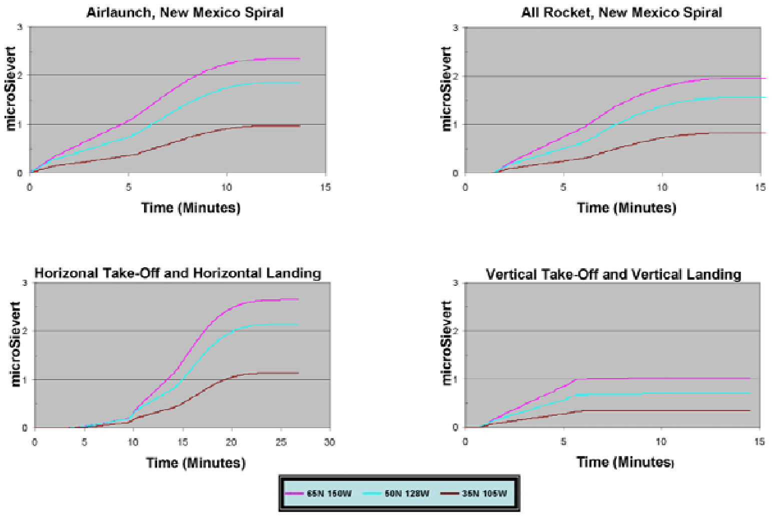


Figure 4.6 Cumulative dose equivalent for various suborbital trajectories and launch sites for quiet solar conditions, solar minimum, GCR maximum.

Figure 4.7 shows the dose equivalent rate for the various trajectories and locations.

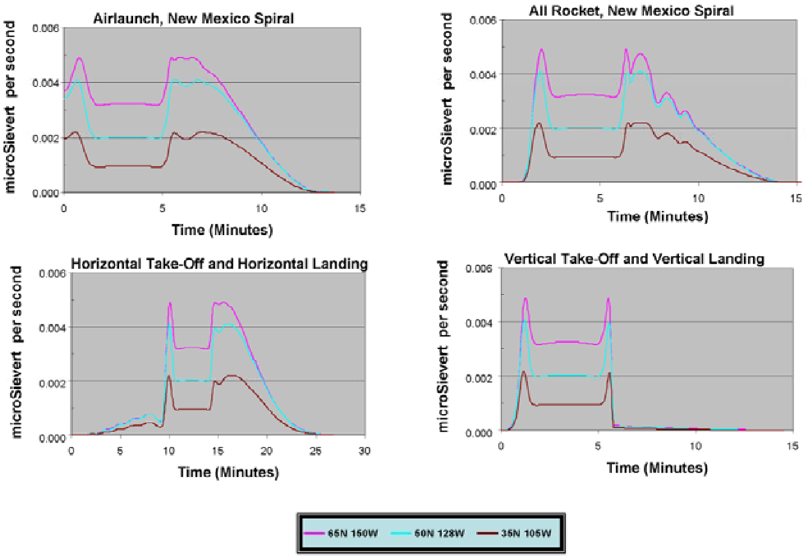


Figure 4.7 Dose equivalent rate for various suborbital trajectories and launch sites for quiet solar conditions, solar minimum, GCR maximum

In general, the Earth's magnetosphere provides shielding everywhere, but it is more effective at low latitudes than higher latitudes. Additional observations, working down from orbital altitudes to the surface:

- Near 400 km the dose or dose equivalent is divided between contributions from trapped radiation (largely high energy protons) and incident Galactic Cosmic Radiation (GCR) and, at mid to high latitudes, periodic SPEs.
- 200 to 100 km the main contributions are a (presumed) minor contribution from residual trapped radiation with (presumed) significant contribution from incident GCR, and, at the highest latitudes, periodic SPEs.
- From 100 to 40 km the unscattered GCR are the primary influence. The dose increases with increasing latitude
- From 40 km to the surface, secondary particles from scattering the GCR become dominant, peaking near 20 km at a dose that increases with increasing latitude.
- The exact transition of dose from 40 to 100 km is not well characterized, particularly as point dose measurements vs. latitude.

Solar storm exposure can be orders of magnitude greater than experienced during quiet geomagnetic and solar conditions. QARM was used to estimate the impact of a solar storm on suborbital missions at high latitude. To do this, the dose equivalent versus altitude was generated for two representative storms, one from 29 September 1989 and one from 24 October 1989. The September storm represents a severe storm. The October 89 storm was also large, but did not have the impact of the September 89 storm. It is important to note that these cases were used because they were readily available with the internet-accessible interface to QARM. It would be highly advisable to do similar analysis for other storms, particularly the August 1972 storm and the January 2007 storm, which had a very rapid increase in flux from event onset. It would also be important to model the impact with other radiation transport codes and with vehicle shielding.

Figure 4.8 shows the dose equivalent versus altitude from QARM at 65 N 150 W for 29 Sept 89, 24 Oct 89, and for comparison, the quiet GCR used earlier. There is a rapid drop in exposure as latitude decreases from 65 N to 50 N and below, as shown in Figure 4.9, dropping below GCR exposures below 45 degree N latitude. In general, the exposure to crew and passengers during a solar storm would be very sensitive to:

- Total exposure duration
- Timing relative to event onset and peak
- Geomagnetic conditions
- Flight profile
- Shielding provided by vehicle

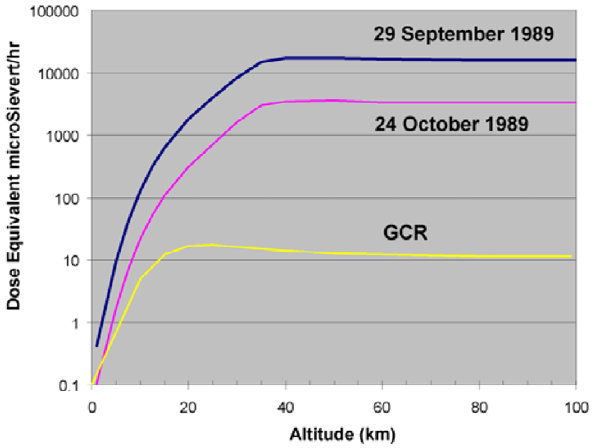


Figure 4.8. Dose equivalent versus altitude from QARM at 65 N 150 W for 29 Sept 89, 24 Oct 1989, and for comparison, the quiet GCR used earlier.

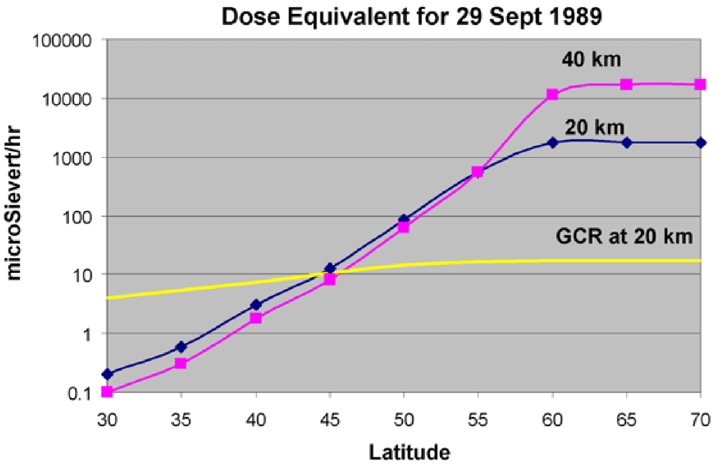


Figure 4.9 Variation of dose equivalent versus latitude from QARM along the 150 W longitude line at 20 and 40 km for 29 Sept 89 and for comparison, the 20 km quiet GCR used earlier. Note the dose equivalent from solar storms increases exponentially with latitude, up to a peak above 60 degrees.

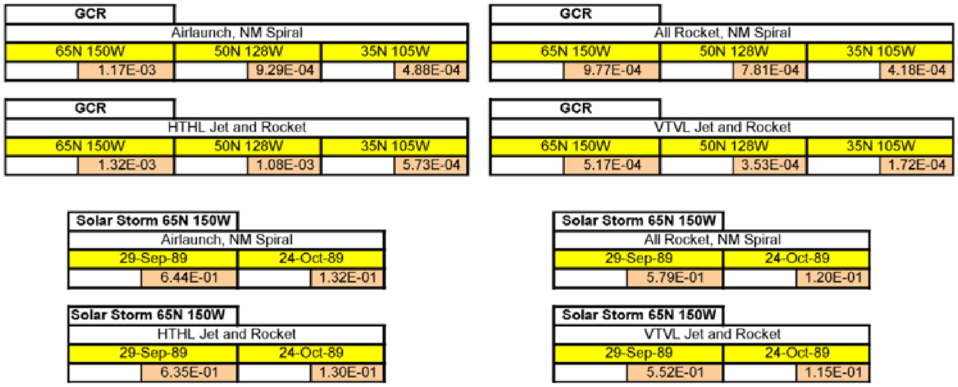
Table 4.2 shows the dose equivalent under no additional shielding for the four trajectories at 65 N 150 W for the solar storms and for comparison, quiet solar conditions. Note the 29 September dose equivalent is over 1 mSv, three orders of magnitude more than the microSievert range for GCR exposure. This exposure would drop significantly at lower latitudes. It is also likely that the exposure would drop significantly with even modest vehicle shielding.

	Cumulative Dose Equivalent (microSievert)		
	Quiet GCR	29 Sep 89	24 Oct 89
Airlaunch, NM Spiral	2.35	1287	263
All Rocket, NM Spiral	1.95	1157	239
HTHL Jet and Rocket	2.64	1269	259
VTVL Jet and Rocket	1.03	1103	230

Table 4.2 Cumulative Dose Equivalent for suborbital trajectories for two solar storms and quiet solar conditions, from the QARM model.

A few conclusions can be drawn from the QARM calculations. If a suborbital mission were to launch at high latitude during the peak of a solar storm, the exposure could be as much as two to three orders of magnitude greater than the same mission launched during quiet solar conditions at peak GCR. However, the exposure drops exponentially with decreasing latitude at latitudes less than about 60 degrees, dropping below GCR exposures below 45 degree N latitude. It is significant to note that while solar storms cannot be forecast days or even hours in advance, they can be reliably detected minutes to tens of minutes in advance. Even this short notice should be adequate to cancel or delay suborbital missions, which have durations on the order of 15 to 30 minutes.

With some caution, the rule of thumb that 20 mSv effective dose causes a one percent increase in lifetime fatal cancers can be applied to the calculated dose equivalents in Tables 4.1 and 4.2 noting that it is very questionable that it can be used at the very low exposure rates to be experienced in suborbital flights [NCRP, 1993b]. Given that caveat, the results are shown in Table 4.3. The table assumes in a population of 10,000 exposed individuals one microSievert leads to 0.0005 excess lifetime fatal cancers. However, this "rule of thumb" may not apply at low dose rates. If it does, or if it is close, then quiet GCR lifetime fatal cancer rates will be less than .001 per 10,000 exposures but during a severe solar storm there may be one excess fatal cancer per 10,000 exposures. Note even the larger number is small compared to the expected natural rates of 740 cancer incidence and 210 fatal cancers within 10 years for 10,000 50-year old white males and 150 cancer incidence and 20 fatal cancers within 10 years for 10,000 30-year old race-averaged females. We emphasize that at this point exposures do not take shielding into account.



GCR		
Airlaunch, NM Spiral		
65N 150W	50N 128W	35N 105W
1.17E-03	9.29E-04	4.88E-04

GCR		
All Rocket, NM Spiral		
65N 150W	50N 128W	35N 105W
9.77E-04	7.81E-04	4.18E-04

GCR		
HTHL Jet and Rocket		
65N 150W	50N 128W	35N 105W
1.32E-03	1.08E-03	5.73E-04

GCR		
VTVL Jet and Rocket		
65N 150W	50N 128W	35N 105W
5.17E-04	3.53E-04	1.72E-04

Solar Storm 65N 150W	
Airlaunch, NM Spiral	
29-Sep-89	24-Oct-89
6.44E-01	1.32E-01

Solar Storm 65N 150W	
All Rocket, NM Spiral	
29-Sep-89	24-Oct-89
5.79E-01	1.20E-01

Solar Storm 65N 150W	
HTHL Jet and Rocket	
29-Sep-89	24-Oct-89
6.35E-01	1.30E-01

Solar Storm 65N 150W	
VTVL Jet and Rocket	
29-Sep-89	24-Oct-89
5.52E-01	1.15E-01

Table 4.3 Excess fatal cancers per 10,000 passengers. The table assumes in a population of 10,000 exposed individuals one microSievert leads to 0.0005 excess lifetime fatal cancers. However, this "rule of thumb" may not apply at low dose rates.

4.4 Summary Observations

Exposure during suborbital missions under quiet solar conditions is not likely to be significant---somewhat less than a cross country commercial air flight. Exposure during a severe solar storm at high latitude would be modest, but it potentially could be large enough to have a detectable impact on long-term cancer rates. Suborbital missions should be avoided during solar storms, particularly if the launch site is at high latitudes.

Since these conclusions are drawn from a single transport code designed for aircraft calculations, more measurements and better models of the radiation environment are needed in the range from 40 to 100 km at all latitudes under varying solar conditions, with independent transport codes that include vehicle shielding.

Effective implementation of a policy of "informed consent" will require the providers have as part of their support staff a team of experts familiar with or active in current research in

- The space environment ("space weather")
- Techniques to monitor measurements and forecasts the radiation environment
- Techniques and models to estimate the doses within the body under realistic shielding
- Biological effects of radiation

In addition, the providers should include instrumentation in the vehicle to directly measure the radiation environment inside the vehicle throughout the mission. Providers should maintain the models and expertise needed to translate the measured environment into estimates of the dose for the crew and passengers at a variety of locations, and they should be prepared to continuously compare predicted dose with observed dose.

One final note of a practical nature: radiation exposure is a sensitive issue. The perception that ANY exposure to radiation is bad is widespread, in spite of the fact that a low level of exposure is always present. The risks of radiation exposure to astronauts spending weeks to months in orbit and in deep space are well known to the public, and the perception that the risk will be significant to any type of space travel, even suborbital travel, will always exist. Compound that with the fact that some space tourists will inevitably, within a few years of the experience, die of some form of cancer. It therefore seems incumbent on the launch operators to meet or exceed any regulatory requirement of monitoring imposed by quantifiable risk estimates.

5. System Effects

In this section we discuss possible effects of the natural space environment on the suborbital vehicle's electronics. These effects are of interest because the vehicle will include typical aircraft altitudes, where there is a large body of research on hazards to avionics (e.g., Normand 1996), and could briefly reach the top of the atmosphere (Figure 4.5) where the primary particle environment can be similar to low-Earth orbits for satellites.

5.1 Total Radiation Dose

We assume that the total radiation dose due to the GCR and SPE environments is not relevant for the suborbital vehicle systems because of the relatively low doses involved compared to orbital vehicles. For example, assuming a quality factor of 10 appropriate for high-energy protons and the entire neutron environment (NRCP, 2000), the cumulative dose for the 29 September 1989 SPE in Table 4.3 corresponds to a dose on the order of 10 cGy, whereas commercially-available off the shelf electronics may fail at doses on the order of a few krads (e.g., Winokur et al. 1999). A complete assessment of the total dose on the actual suborbital vehicle electronics is outside the scope of this report.

5.2 Ionospheric Effects

Flights up to ~100 km will traverse the D region of the ionosphere (50-90 km) where electrons in the high-energy tail (>10's keV) of the auroral distribution create the ionization (e.g., Whalen 1985). Being much below the altitudes at which spacecraft need to consider effects of charging in auroal arcs, such charging effects are probably not relevant for suborbital flights. However, the D region of the ionosphere absorbs high-frequency radio signals (3-30 MHz), so the short duration (15 min) increases of D-region absorption that occur during geomagnetic activity at high latitudes (>60 deg) could be relevant if the suborbital system uses such frequencies. Another hazard to HF communication through the D-region is increased absorption during solar flares, where the peak absorption occurs at the sub-solar point (e.g., http://www.swpc.noaa.gov/dregion/dregionDoc.html).

5.3 Single-Event Effects

The actual charged and neutral particle environment up to 100 km is a complex superposition of primaries (GCR & SPE) and secondaries formed from interactions with the atmosphere. The detailed analysis of the susceptibility of a particular part or of an entire subsystem (e.g., communications; avionics; life support) will be complicated in part because of the relatively poorly-explored nature of the environment above typical aircraft altitude and well-below typical low-Earth satellites. The QARM model used in Section 4.3 includes recent measurements of the relevant particle populations (Lei et al. 2006).

The remaining space and atmospheric effects that we consider are those due to single-event effects in microelectronics. In this scenario, a charged primary or charged secondary particle deposits enough energy within a device such as a random-access memory to effect the state of a memory location, or an atmospheric neutron (formed as a result of interactions of primary GCR and SPEs with the atmosphere) collides with material to create energetic and ionizing particles which then interact with electronics.

Normand [1999] reviewed the environment data at altitudes up to 65,000 feet (~20 km), showing examples of correlations of upset rates if avionics parts with predictions and concluding that the largest contribution to memory upset rates was from the neutron environment. In the years since the

Normand [1999] analysis there have been other studies of the neutron susceptibility of candidate avionics (e.g., Belcastro et al. 2007) and studies of other suborbital scenarios (e.g., Solin et al. 2005). The current focus in avionics is on techniques of error handling because shielding is not feasible and using space-qualified parts is expensive.

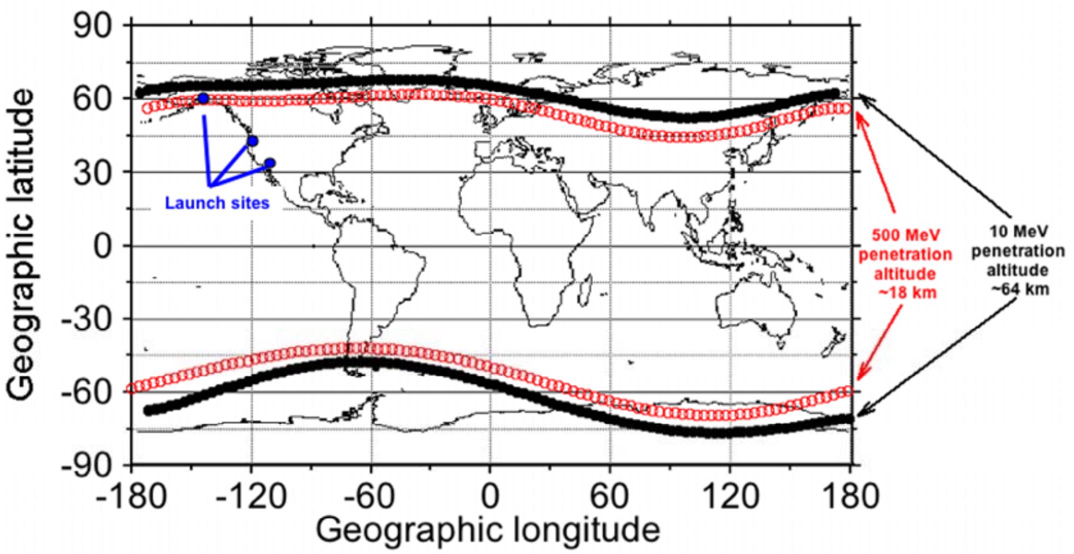


Figure 5.1. Geographic coordinates of the geomagnetic cutoffs for 10 and 500 MeV primary protons.

As suggested by the total dose calculations with the QARM model in section 4, the hazards for vehicle avionics will depend on solar and geomagnetic activity and launch location. Figure 5.1 plots the geomagnetic cutoff for two primary proton energies in terms of geographic latitude and longitude. The curves vary with location because of the offset and tilt of the geomagnetic field relative to the Earth's surface. Because of the offset and tilt, there is no single latitude for a given longitude that characterizes the radiation environment. On the scale of the plot, there is no significant change in the locus of points with altitudes considered in this study.

Primary protons with higher energies (500 MeV in Figure 5.1) have access to lower latitudes and the access can be as much as 10 degrees lower during geomagnetic storms. The details of the primary solar and galactic access to a given point in the atmosphere are complex (e.g., Dyer et al. 2007 & references therein). However, the two launch sites of this study in CONUS are well below the typical cutoffs for the bulk of the primary SPE energy spectrum and thus characterizing the expected particle environments from these launch sites, using models such as QARM, will be more reliable than for the site representing Alaska.

5.4 Mitigation Techniques

Some techniques that are used in the satellite and aircraft avionics industries might also be applied to suborbital missions such as predicting upset rates given ground-based measurements of single-event effect cross sections and the flight environment, then determining if additional error handling logic is required. This addresses the hazard before flight, while the vehicle engineering is still occurring. The suborbital missions benefit from a much-decreased time at altitude compared to traditional aircraft avionics, so all else being equal, these missions should have a much lower failure rate.

However, details depend on the actual parts in question and the quality of the prediction depends on testing in the relevant environment. For example, Normand [1999] suggests that the charged pion environment (a secondary particle created from interactions of GCR and SPE with the atmosphere) may become relevant with small feature sizes (< 0.1 micrometer).

Delay of launch is another mitigation technique that is possible for the missions of interest. Some launch vehicles use launch delay to minimize the space environment hazards at launch and early orbit, but the space vehicle must eventually operate through whatever the environment provides on orbit. In the case of non-time critical suborbital missions, a launch delay until the SPE environment is below some threshold would provide additional margin if some vehicle part has too high an upset probability. Again, the only way to determine if delay would be necessary is through analysis of the part and the systems it supports.

It is most likely that the lower intensity primary and secondary environments below some latitudes (such as ~50 degrees latitude in the 150 deg West longitude case in Figure 4.9) are benign enough that launch can occur at any time, including the ~5% of the time when SPEs occur. Thus, in the remaining case of the northernmost launch site, a possible launch commit criterion could be based on the event probability distributions in Figure 5.2.

Here we show historical data on geomagnetic storm intensity (measured with the Kp index), which would correspond to increased probability of intense auroras and access of SPE to lower latitudes. Figure 5.2 also shows the probability of occurrence of SPE with protons above 30 MeV, corresponding to an increased hazard of single-event effects. In lieu of detailed parts analysis, one could place a threshold at the 99% worst-observed Kp (a planetary index of magnetic field perturbation) and SPE environments and delay launch until these environments fall below threshold. Figure 5.3 shows the resulting delay times (including the delay for high-energy electrons at geostationary orbit that are not relevant for this study). For the SPE hazard, the resulting delay could be a day or more.

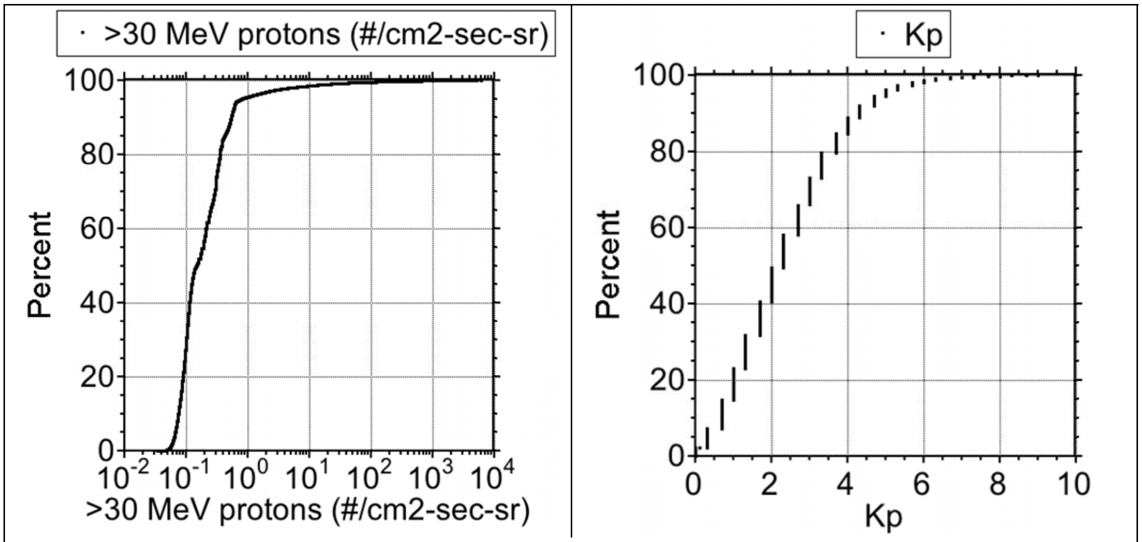


Figure 5.2 Probability distributions of SPE >30 MeV protons (left) and geomagnetic storms measured with the 3-hr Kp index (right). The datasets used to generate these distributions included data from 1980 to 2007.

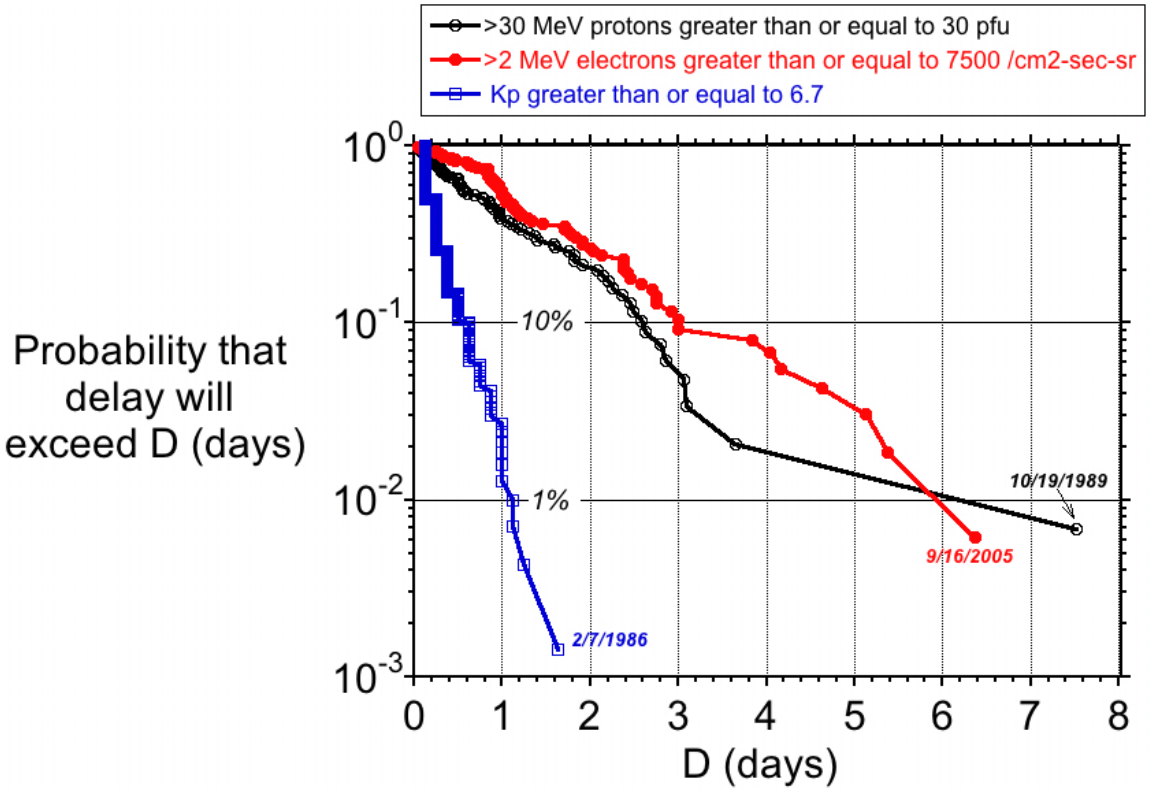


Figure 5.3 Probability that launch would be delayed D days if thresholds on the SPE (black) and geomagnetic activity (blue) were at the 99th percentile.

6. Potential Need for Space Weather Safety Regulations

6.1 Introduction

In this section we examine issues relating to informed consent and the mitigation of risk to crew and passengers (also denoted "participants" with the meaning of the Space Law Amendments Act of 2004 [www.faa.gov/about/office_org/headquarters_offices/ast/media/PL108-492.pdf]. Regarding the safety of "space flight participants," the intent of Congress appears to be to promote "space tourism" as an industry and to ensure that participants in tourist-oriented sub-orbital and orbital flights are put on notice as to the hazards associated with such operations. This report builds upon this presumed intent, since space weather *per se* is not a hazard associated with "launch or re-entry," which are the only phases of flight explicitly addressed in the applicable legislation.

From the outset, it must be acknowledged that the physiological effects of single and multiple exposures to space weather phenomena are neither well understood nor satisfactorily documented in the sub-orbital operational environment. To date, the region between the beginning of "space" (sixty-two miles / one hundred kilometers) and the altitudes where low earth orbit (LEO) vehicles spend the majority of their time has been commonly experienced by manned spacecraft and their crews only for relatively brief periods during ascent and descent.

Notwithstanding the above, there is a sizeable body of knowledge regarding the general health hazards associated with radiation exposures associated with specific jobs in a number of industries. The source of the radiation presenting the hazard is not relevant to recognizing the threat and quantifying the risk (although it definitely is germane to determining appropriate countermeasures. Therefore, some initial judgments can be made regarding the hazards most likely to be encountered as a result of deliberate one-time and cumulative exposure to space weather phenomena, as well as the types of briefings, monitoring, and protections that may be appropriate for sub-orbital spacecraft occupants – crewmembers and participants alike.

The brief discussion which follows is intended only as a general outline to suggest subsequent research into, and regulatory action associated with the impact of the space environment on suborbital commercial space flight. The observations presented here must be considered preliminary in nature; significantly expanded analysis will be essential in assembling a defensible foundation upon which future rulemaking can be based. However, it seems evident that three sets of regulatory guidance will be required to properly protect both crewmembers and tourists:

- A standard "hazard communication" briefing, incorporated into regulations in a format similar to that provided in 14 CFR §121.571 for airline passenger pre-flight briefings.[1]
- A set of requirements for space operators governing ionizing radiation monitoring of crewmembers, as well as mission scheduling and flight planning standards to limit cumulative exposures.

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[1] The working procedural assumption is that space flight participants will be required to receive training, rather than just a pre-flight presentation once aboard their spacecraft. The recommended briefing should be a part of that syllabus. The term "hazard communication" is used in other disciplines, but may be appropriate to adopt for use in the context of Congressionally mandated participant awareness measures as well; see "Defining "Space Weather" for Regulatory, Safety Assessment and Hazard Communication Purposes."

- Spacecraft design criteria providing for, as a minimum, crew compartment shielding sufficient to give passenger and crew the same accumulated exposure accounting for the longer exposure times of the former.[2]

6.2 Ensuring the Safety of Passengers

For passengers aboard revenue spaceflights, Congress has created a framework within which the government's regulatory discretion from the outset is somewhat limited. The relevant legislation, incorporated into 49 U.S.C. §70102, *et seq.*, explicitly creates the construct of "space flight participants" – individuals who are not crewmembers, but are carried within a launch vehicle or re-entry vehicle. These individuals constitute the "passenger" population that must be advised of hazards and protected from gross harm, but for whom it is clear that Congress does not wish to regulate exceptional protections.

6.3 Operational Risks

The minimization of operational risk will be central to all aspects of commercial space operations involving manned spacecraft. NASA evolved its notion of "man-rated" systems during Project Mercury in the early 1960s by classifying different components of the overall system by the criticality of their reliability [see reference in footnote 3 at the end of the list]:

- Class 1 (95-100% reliable):
  - Capsule structure and reentry properties
  - Separation mechanism and posigrade rocket
  - Tower and abort rockets
  - Voice communications
  - Abort sensing instrumentation system
  - Manual control system
  - Retrorocket system
  - Parachute landing system
  - Ground environment system
  - Recovery operation
  - Pilot training

- Class 2 (85-95% reliable):
  - Landing bag
  - Environmental control system
  - Automatic stabilization and control system

- Class 3 (75-85% reliable)
  - Booster
  - Telemetry[3]

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[2] This recommendation is based on the expectation that passenger-oriented space operators will seek to build their spacecraft to be as light as possible (for economic reasons) and to have as many windows as possible available to participants (for tourism and promotional reasons).

[3] See Donald F. Hornig, et al, *Report of the Ad Hoc Mercury Panel*, April 12, 1961, p. 18; cited at http://history.nasa.gov/SP-4201/ch10-7.htm. The two items in the Class 3 category were characterized as "not per se a cause for alarm" with respect to the safety of the astronauts, but were seen as having a bearing on mission success.

The basic logic of *the relative importance* of the components within these three classes holds up surprisingly well over time. Any launch vehicle certification process developed to support the manned commercial space market undoubtedly will use some variation on current FAA and NASA criteria. This should be more than adequate to protect all occupants – crew and participants alike – against system-related catastrophic hazards encountered during launch, mid-flight and recovery. This leaves environmental conditions (i.e., space weather) as the principal hazard requiring consideration for abatement.

Except in the highly unlikely event of a sudden change in solar activity after launch, a single sub-orbital flight will not expose space flight participants to unsafe doses of ionizing radiation, as discussed in Section 3.[4] Part of the overall hazard communication process should be to inform space flight participants of the exact exposure they received during their flight at mission's end. A formal requirement to this effect would be fully consistent with the intent of Congress. It also would support not only informed acceptance of risk but an understanding of actual exposure upon which post-flight decisions regarding subsequent medically required or employment-related exposures could be based.

6.4 Ensuring the Safety of Crew Members

Notwithstanding the above discussion of space flight participants' safety, nothing in AST's enabling legislation gives launch operators any relief from their obligations to properly protect spacecraft crew members, who will be repeatedly exposed to all of the hazards associated with space weather. Therefore, from a regulatory perspective, it is important to bear in mind two aspects of crew safety and health which also could draw Occupational Safety and Health Administration (OSHA) interest in space operations and operators if left unaddressed:

- OSHA's "General Duty Clause" may be expected to figure prominently in all discussions regarding crew protection.[5]
- The "grandfathering" that limits OSHA's ability to regulate exposures of aircrew members (specifically, pilots and flight attendants), may not be applicable in the space domain, since it may be argued that pre-existing regulatory standards are not in place.

The General Duty Clause typically requires four tests to be applied to each hazardous condition:

- There must be a hazard.
- The hazard must be recognized.
- The hazard causes or is likely to cause serious harm or death.
- The hazard must be correctable.

In the context of space weather-related hazards to space crewmembers (since the passengers/participants would not be subject to "workplace" protection of any type), the General Duty Clause criteria may be relevant to safety and occupational health risks arising from radiation exposures:

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[4] Safe and unsafe radiation exposures will be quantified in the next section.

[5] Section 5(a)(1) of the Occupational Safety and Health Act (29 U.S.C. §654): "Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees."

- Space weather phenomena are potentially a hazard, being encountered in a "workplace" involving prolonged, relatively low-dose cumulative radiation exposure or, alternately, having the potential for leading to unpredictable but dangerous single exposures.
- The health hazards associated with cosmic radiation are broadly understood, and exposures can be equated with existing radiological health limits established for currently defined "radiation workers."
- Cumulative doses of ionizing radiation beyond established limits are known to be harmful.
- Controls such as crew scheduling, suborbital flight profiles taking maximum advantage of terrestrial protections from space weather, cancellation of operations during periods of enhanced solar activity, vehicle shielding, and post-flight alerting of greater than normal exposures all are available as means of mitigating the risk associated with the space weather hazard.

Following logic similar to that presented above, in 1990 the International Commission on Radiobiological Protection (ICRP) recommended that conventional aircraft flight crew members be treated as radiation workers and regularly counseled on their respective exposures.

As discussed in Section 3, it is not clear what the actual radiation dose could be experienced on single or multiple sub-orbital flights. Atmospheric and magnetospheric protection and shielding will provide some moderation and protection, but the extent and variability of such protection is not fully quantifiable.

6.5 Defining Space Weather for Regulatory, Safety Assessment and Hazard Communication Purposes

In the spirit of hazard communication the question then becomes, "What should crewmembers and spaceflight participants be warned of, and to what extent can any such a warning facilitate a truly informed acceptance of risk?"

From a safety perspective, space weather is a blanket term used to refer to the potentially hazardous effects of natural phenomena encountered in the space environment. In particular, it refers to ionizing radiation coming from deep space (galactic cosmic radiation), the Sun (solar cosmic radiation), and trapped radiation as discussed in Section 3. Cosmic radiation effective dose rates vary with both altitude and latitude.

The hazards associated with prolonged or intense exposure to ionizing radiation are generally well understood, and there already are some noteworthy guidelines in place that may be applied to this issue. For example, Article 42 of the European Union's "Basic Safety Standards Directive" prescribes requirements for assessing aircrew exposures, scheduling crews with those assessments in mind, communicating the hazard to exposed workers, and paying particular attention to minimizing the exposure of female crewmembers.[6]

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[6] *See* Journal of Radiological Protection, 19: 70-73 (1999). This article makes the points that aircrews are exposed to a greater range of radiation types and energies than is typically encountered in occupational exposures to ionizing radiation, and that "half of aircrews' doses are due to neutrons." (Some studies suggest that the structure of the aircraft may play a part in this, whereby high-energy neutrons are amplified by aluminum in the fuselage, raising interior doses to levels greater than would be encountered if an individual was simply exposed to the ambient radiation present at the same altitude and latitude. *See* NASA TN D-7715, "Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes – Relevance to SST Operations and Space Research," 1974; *see also* NASA RP-1257, "Transport Methods and Interactions for

Doses for use in crew scheduling should be calculated by taking into consideration the planned date and location of departure, the time spent in the ascent, cruise, and descent phases of flight, the destination, and the current status of the solar cycle (an 11-year waxing and waning of solar activity). This knowledge, in combination with actual exposure data, will be essential to require operators to track, since reducing flight hours has been and remains the only proven solution for reducing ionizing radiation exposure.[7] Publicly available software such as QARM used in Section 4 and CARI-6, developed by the Civil Aerospace Medical Institute, can estimate these doses.

6.6 Mitigation of the Space Weather Hazard to Spacecraft Occupants

Space weather phenomena are virtually impossible to predict with any degree of accuracy. The generally cyclic nature of galactic cosmic radiation activity is reasonably well understood, but current technology is limited to identifying solar storm events in general as they occur, i.e., with limited warning time (minutes to tens of minutes) that can be used to delay a vehicle's launch. This limits mitigation options to three basic strategies:

- Crew scheduling to minimize individual annual exposures
- Crew compartment shielding to protect the most frequently exposed occupants to levels comparable with infrequent passengers
- Sufficient operational flexibility and timely enough event warning to make last minute launch abort or early flight termination a viable means of avoiding excessive exposures

For the purposes of crafting suitable regulations regarding exposures, it is essential to remember that the FAA will need to explicitly distinguish between <u>predicted</u> exposures (which should be used for advance scheduling) and <u>actual</u> exposures (which only can be determined after the fact, and may vary significantly from predictions in the presence of solar particle events and other highly unpredictable conditions). The former may be used to build crew rosters, while the latter should form the basis for modifying them based on the actual cumulative doses experienced by each individual.

It also will be necessary to provide for mandatory monitoring of exposure levels separately in the crew compartment and the passenger compartment of each sub-orbital spacecraft. Shielding that can and should be used to reduce pilot and co-pilot exposures may be somewhat less practical where paying "space flight participants" are located; the latter will want as much opportunity as possible to enjoy the view, meaning that transparencies and other minimally protected structural elements necessary for their convenience may not provide the same protection for back-end crewmembers ("space flight attendants") as enjoyed by the flight crew.[8]

Space Radiations," 1991.) The article also notes that aircrew flying typical schedules have been shown to receive roughly double the annual exposure (2 millisieverts, or 2mSv, per year) received by workers in the nuclear industry, although that fact should be balanced with the understanding that people living in high radon areas may receive four times the aircrew dose in their daily lives.

[7] Per NASA/TM-1999-209131, Aircraft Radiation Shield Experiments – Preflight Laboratory Testing (1999), "Theoretical analyses suggest that high-altitude ionizing radiation shielding characteristics are a function of atomic number. The smaller an atomic number is, the better the overall shielding characteristics will be. This finding may make it possible to find a reasonable shielding material that can be incorporated in the acoustical linings and décor of the cabin, or more practically, integrated with the structural material itself." Thus, future vehicle certification standards should specifically address the need to provide cosmic radiation protection to occupants – especially spacecraft crew members – by different structural materials.

[8] Space flight attendants undoubtedly will require special training for their flight-specific duties. They also may require health monitoring and operational limitations similar to those imposed upon "physiological training"

6.7 Next Steps

From an institutional perspective, the task of enshrining the above considerations into suitable regulations would seem relatively straightforward. However, there will be significant political resistance to some aspects of any FAA effort to protect space crew members from hazards extrapolated from a body of knowledge that already addresses these hazards in the context of commercial airline operations. There also is an FAA/OSHA partnership in place regarding aircraft "workplace" hazards that can and should be engaged to ensure each agency is comfortable with whatever course of action would seem most appropriate based on the space weather hazards described in this paper.

Safety-specific regulatory action associated with space weather hazard mitigation seem to be warranted in three areas:

- Development of a standard "hazard communication" briefing, incorporated into regulations in a format similar to that provided in 14 CFR §121.571 for airline passenger pre-flight briefings. In addition to offering detailed space weather risk and dosage information as outlined above, this briefing also could incorporate information regarding the overall reliability of the spacecraft and supporting infrastructure, as well as the extremely low likelihood of any kind of mid-flight collision during a single suborbital flight.[9]
- Establishment of formal requirements for launch operators governing ionizing radiation monitoring of crewmembers, as well as mission scheduling and flight planning standards to limit cumulative exposures. All of the above should be based on existing knowledge, but also be subject to updating as operational knowledge of the suborbital environment grows.
- Development of explicit spacecraft design and certification criteria providing for, as a minimum, crew compartment shielding greater than that required for the spaceflight participants' compartment to balance participant interest in maximizing their tourist experience and the need to properly protect those launch operator employees who will be subject to repeated exposures to the hazards of space weather phenomena.

Additional research in all three of these areas would be appropriate, as would more closely aligning their final form based on analogous regulations issued by the Associate Administrator for Aviation Safety (AVS). In addition, research and development projects aimed at creating new means of gathering advance information regarding solar activity, effective means to model and monitor the actual environment inside the vehicle and better means of processing and disseminating actionable knowledge related to such activity in near-real time should be explored as well.

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specialists who regularly accompany pilots on recurrent hypobaric ("altitude chamber") training missions. It is possible that those individuals may not be allowed to fly as often as flight crew members if their cumulative radiation exposure is significantly greater.

[9] Some mathematical models have been constructed to quantify on-orbit collision risk that may be adaptable to this purpose, taking into consideration spatial density (the number of objects that reside in a given volume of space), time at risk, the projected cross-sectional area of a given spacecraft along a specific trajectory, and relative velocity (as a function of the relative angle of encounter of the object with another object and the velocity of the colliding objects). See Kaman Sciences Corporation, *On-Orbit Collision Hazard Analysis in Low Earth Orbit Using the Poisson Probability Distribution*, August 26, 1992.

7. Summary and Conclusions

Owing to the short duration of flights (~30 minutes, or less) and the even shorter exposure at altitudes where all but the most energetic particles may penetrate with significant fluxes (~ 5 minutes), the exposure of crew and passengers is minimal, except under Solar Particle Events occurring less than about 5% of the time. Under typical conditions the radiation exposure to crew and passengers on a suborbital flight is less than that for long-duration commercial air flights.

Primary protons with higher energies (500 MeV) have access to lower latitudes, and the access can be as much as 10 degrees lower during geomagnetic storms. The details of the primary solar and galactic access to a given point in the atmosphere are complex (e.g., Dyer et al. 2007 & references therein). However, the two CONUS launch sites of this study are well below the typical cutoffs for the bulk of the primary SPE energy spectrum. It is most likely that the lower intensity primary and secondary environments below some latitudes (such as ~50 degrees latitude in the 150 deg West longitude case in Figure 4.9) are benign enough that launch can occur at any time, including the ~5% of the time when SPEs occur.

Delay of launch is another possible mitigation technique. Some launch vehicles use launch delay to minimize the space environment hazards at launch and early orbit, but the launch vehicle must eventually operate through whatever the environment provides on orbit. In the case of non-time critical suborbital missions, a launch delay until the SPE environment is below some threshold would provide additional margin for space flight participants and sensitive electronics. Thus, in the case of a high-latitude site, such as a hypothetical Alaska launch site, a possible launch commit criterion could be based on the event probability distributions. Forecasts and monitoring (now-casting) support is available from NOAA's Space Weather Prediction Center

Although the radiation risk for crew and passengers is minimal, except at high latitudes and during solar and geomagnetic disturbances, including SPEs, crew and passengers should be monitored for radiation exposure. This is because of the potential for litigation should passengers or crew develop illnesses of a type that have been linked to radiation exposure, and because of the possibility, however remote, that the onset of an event such as an unanticipated SPE could occur during flight.

This report has identified uncertainties in the biological and electronic system susceptibility to radiation, as well as uncertainties in what the radiation environment might be during flight. Biological effects is a broad and active area of research and little can be done in the way of follow-up work other than updates based on new findings. The radiation field at suborbital altitudes has not been extensively studied, and this is an area where follow-on work would be fruitful.

System effects, such as single event upsets may employ some techniques that are used in the satellite and aircraft avionics industries and apply them to suborbital missions. An example is predicting upset rates given ground-based measurements of single-event effect cross sections and the flight environment, then determining if additional error handling logic is required. Details depend on the actual parts in question and the quality of the prediction depends on testing in the relevant environment.

8. Abbreviations

AST	Office of Commercial Space Transportation, FAA
COTR	Contracting Officer's Technical Representative
FAA	Federal Aviation Administration
LV	launch vehicle
RLV	reusable launch vehicle
NOAA	National Oceanic and Atmospheric Administration

9. Glossary

A – atomic mass, the number of protons and neutrons in the nucleus of an atom.

Absorbed dose (D): the average energy absorbed in tissue per unit mass, in units of Gray (Gy) A centiGray is equal to a term in earlier use, now not as common, the "rad." Same dose has difference consequences for different radiation. Units: Gray (Gy) = 1 J/kg. 1 cGy is equal to 1 rad . Since the stopping power of a target material varies with its atomic number and atomic mass, the material within which the dose is measured should be noted (dose in tissue or dose in aluminum, for example).

Acute effects – short-term biological effects of radiation, including headaches, dizziness, nausea, and illness that can range from mild to fatal.

ALARA (As Low as Reasonable Achievable) – a legal requirement to strive that a radiation worker does not approach dose limits and that such limits are not considered as "tolerance values."

Biological endpoint: the effect or response being assessed, e.g., cancer, cateracts.

Chronic effects – effects of radiation that do not appear until long after the dose was received. Includes cancer, cataracts, and nervous system damage.

Computerized Anatomical Man/Female – a model of human geometry used to evaluate radiation doses at various points inside the body.

Coronal Mass Ejections (CMEs) – an explosion of plasma released from the atmosphere (or corona) of the Sun.

Deterministic Process – an event that will occur whenever its dose threshold is exceeded.

Dose – See "Absorbed Dose"

Dose equivalent (H) – An estimate of radiation risk. The product of dose times a weighting factor, which accounts for differences in the biological effectiveness of different charged particles that produce the absorbed dose. $H = Q \times D$, where Q is a quality factor based on the type of radiation (Q=1 for x-rays) and D is absorbed dose. The same dose equivalent has same consequences for different radiation Units: Sievert (Sv) = 1 J/kg. 1 cSv is equal to 1 rem .

Effective dose (E): estimate of radiation risk. It is a weighted sum of the individual effects of all types of radiation present over all of the individual types of tissue in the body. It has units of Sv (Sievert).

$$E = \sum_R \sum_T w_R w_T D_{R,T}$$, where

w_R : a weighting factor for the type of radiation

w_T : a weighting factor for the type of tissue

$D_{R,T}$: average dose from radiation R in tissue T

Electron-volt (eV) – a unit of energy equivalent to approximately 1.6 x 10^{-19} Joules.

Equivalent dose (HT) – estimate of radiation risk. It is the product of the mean absorbed dose in a tissue or organ and the radiation weighting factor. It has units of Sv.

Excess risk -- The probability of a certain effect on an individual who has been exposed to a given dose of radiation compared to the baseline probability of that effect.

Fluence, or particle fluence (F) - the number of particles incident on a small sphere centered at a given point in space, divided by the cross-sectional area of that sphere. Mathematically, it is given as dN/da, where N is the number of particles, and a is the cross-sectional area. It has units of m^{-2}

Fluence rate (dF/dt) - the change in fluence over a given small time interval, or the time derivative of the fluence. It has units of $m^{-2}s^{-1}$.

Flux (Φ)- see fluence rate. "Flux" is a term historically used by the nuclear community for the fluence rate. It is also referred to as the "particle flux density." The term flux is a deprecated usage by the ICRU convention in order to eliminate confusion between the "particle flux density" and the "radiant flux".

Galactic cosmic radiation (GCR) -- essentially isotropic distribution of highly energetic particles from within and beyond our galaxy. It is primarily made of hydrogen and helium, but contains traces of all the elements.

Gray (Gy) – SI unit of absorbed dose. (J/kg)

Gray-equivalent – The product of mean absorbed dose (DT) and Relative Biological Effectiveness, which depends on particle type and energy

HZETRN – a transport code developed specifically for high-charge high-energy particles that is widely used for space radiation shielding and design calculations.

Kp – An index of geomagnetic activity. It is derived by calculating a weighted average of K-indices from a network of geomagnetic observatories. The K-index is quasi-logarithmic local index of the 3-hourly range in magnetic activity relative to an assumed quiet-day curve for a single geomagnetic observatory site.

LEO (Low Earth Orbit) – the environment in which the majority of recent Space missions have been concentrated, where the magnetic field of the Earth provides protection against much of the radiation that would be encountered on more distant exploration missions.

LET (Linear Energy Transfer) – the rate of energy loss in matter per unit of ionizing particle track length. It is measured in keV/μm.

Mean Absorbed Dose (DT) – Average absorbed dose in a tissue.

Permissible Exposure Limit (PEL): the maximum amount of radiation an astronaut may be exposed to. For terrestrial workers, PELs are legal limits, defined by OSHA. NASA PELs are set by the Chief Health and Medical Officer.

Quality Factor – The LET-dependent factor by which absorbed dose is multiplied to obtain the dose equivalent. Quality factors are used so that absorbed doses for all kinds of ionizing radiation can be compared on a single scale when evaluating risk of cancer incidence.

RAD – an archaic unit of absorbed radiation dose, equal to 1 cGy (see Gray).

Relative Biological Effectiveness (RBE) -- a measure of the effectiveness of a specific radiation or particle in producing a specific biological outcome relative to the same dose of gamma-rays:
$RBE = D_{\gamma} \Big/ D_{rad\ of\ \text{interest}}$

Risk of Exposure Induced Death - (REID) the measure of risk used by NASA as a standard for radiation protection. It represents a calculation of the probability of fatal cancer due to exposure to radiation in Space.

Secondary radiation – radiation that has been generated by passage of a primary particle through a material.

SEE – single event effect. This refers to a class of effects in which the damage results from a *single* ionizing particle traversing a microelectronic device, rather than the accumulated impact of a large number of particles

SEU – single event upset. This is a type of SEE where a bit is flipped.

Sievert (Sv) – the SI unit of effective dose and dose equivalent (1 SV = 1 J/kg). It is a function of the absorbed dose and biological weighting factors.

Solar cycle – the 11-year cycle of solar wind intensity, ranging from solar minimum to solar maximum back to solar minimum. It is caused by the reversal of the Solar dipole field roughly every eleven years. Since it takes two polarity reversals to duplicate the original state, some say the cycle duration is close to 22 years.

Solar flare – a burst of energy released from the atmosphere (or corona) of the Sun.

Solar particle event (SPE) – large fluxes of energetic particles produced between the Earth and the Sun that can last from a few hours to a few days. Signatures of solar energetic particle events include significant increases in electromagnetic radiations such as radio waves, x-rays, and gamma rays.

South Atlantic Anomaly – A region above the South Atlantic Ocean where the radiation intensity is significantly higher than other locations around the Earth at similar altitudes. It is caused by the offset of the Earth’s magnetic field relative to the Earth’s rotation axis.

Spallation – A high energy nuclear reaction in which a high atomic number target nucleus is struck by a high energy, light particle (typically a proton); this causes the target nucleus to break up into many secondary particles.

SRAG (Space Radiation Analysis Group) -- the radiation protection body of NASA responsible for radiation monitoring, projecting exposures, and ensuring adherence to principles of ALARA.

Stochastic process – the likelihood of an event occurring can be described by a probability distribution.

Stopping Power – the average energy loss of the particle per unit path length, measured for example in MeV/cm.

Tissue Weighting Factor (wT) HT – A factor representing the ratio of the risk of stochastic effects attributable to irradiation of a given organ or tissue to the total risk when the whole body is uniformly irradiated. The tissue weighting factor is independent of the radiation type or energy.

Trapped radiation – ionized particles held in place by Earth's magnetic fields. Also known as the Van Allen belt.

Z – Atomic number, the number of protons in the nucleus of an ion.

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