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Radiological Assessment for Space Station *Freedom*

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Abstract

Circumstances have made it necessary to reassess the risk to Space Station Freedom crew members that arises from exposure to the space radiation environment. An option is being considered to place it in an orbit similar to that of the Russian Mir space station. This means it would be in a 51.6° inclination orbit instead of the previously planned orbit with a 28.5° inclination. A broad range of altitudes is still being considered, although the baseline is a 407 km orbit. Recent data from the Japanese A-bomb survivors have made it necessary for NASA to review current exposure limits. Preliminary findings of the National Council on Radiation Protection and Measurements indicate that the limits must be significantly reduced. Finally, the Space Station will be a laboratory where effects of long-term zero gravity on human physiology will be studied in detail. It is possible that a few crew members will be assigned to as many as three 1-year missions. Thus, their accumulated exposure will exceed 1,000 days.

Results of this radiation risk assessment for Space Station Freedom crew members finds that females less than 35 years old will be confined to mission assignments where the altitude is less than about 400 km. Slight restrictions may also need to be made for male crew members less than 35 years old.

Introduction

The baseline orbit for Space Station Freedom (SSF) has a 28.45° inclination and an initial altitude of 407 km (220 nm). This orbit will decay at a rate which is controlled by solar activity. After a decay of approximately 9 km, the plan is to boost the space station back to 407 km. Other orbits with different altitudes and/or inclinations are also being considered. One consideration is to place the space station in an orbit that allows the Space Shuttle to dock with the Russian *Mir* space station, which is in an elliptical orbit with a 51.6° inclination° and at an altitude ranging from 380 to 420 km,

This paper reports an assessment of risks to crewmembers arising from exposure to the space radiation environment. Several factors have led to the need for such an assessment. First, there is a real possibility that SSF will have a significantly different orbit from the current baseline one. In addition, preliminary findings of the National Council on Radiation Protection and Measurements (NCRP), Scientific Committee 75, indicate that current NASA exposure limits for low-Earth orbit (LEO) flights must be reduced. Recent data from Japanese A-bomb survivors indicate that the risks of radiation-induced hard tumors are significantly greater than shown in earlier data. Then, there is a possibility that flight assignments of up to a year in duration will be made so that SSF crew members can serve as subjects for research on physiological effects of long-duration exposure to microgravity. Some crew members could be given up to three 1-year assignments which significantly increases the effects of exposure to space radiation.

Assumptions, Inputs, and Data Pedigree

To assess the radiation risks of SSF crew members, mass distributions are required for the four SSF modules: the U.S. habitation and laboratory modules, the Japanese module, and the European Space Agency (ESA) module including the spacecraft hull, micrometeoroid shield, and rack housings for the electronics and other equipment. In addition, mass distributions of the four nodes which interconnect the modules are needed. Because the equipment to be mounted in the racks cannot be specified at this time, it is not included. Body self-shielding is computed using anatomical models of crew members and is included in the mass shielding distribution. Spatial distributions of the mass were obtained using a ray-tracing technique that determines the material thickness in 512 evenly spaced solid angles at selected "dose-points."

Circular orbits of SSF are considered with altitudes between 175 nm (324 km) and 275 nm (509 km) and with inclinations of 28.45° and 51.6°. [Actually, data from 57° inclination flights of the Space Shuttle are used to estimate radiation exposures in a 51.6° orbit because the measurements made provide the best estimate of the expected SSF environment.]

The AP8 proton model (Sawyer and Vette, 1976) was used to describe the trapped-belt environment at solar minimum and solar maximum. The AE8 electron model (Teague and Vette, 1974) was used to estimate trapped electron exposures at solar minimum. Neither the proton nor the electron model allows for intermediate levels of solar activity, nor do they describe the anisotropic, pitch-angle distributions of trapped particles. They provide only omindirectional particle intensities. The temporal behavior of the Earth's geomagnetic field was described by two different models: the 1965 International Geomagnetic Reference Field, epoch 1964, (IAGA, 1969) for solar minimum conditions and the 1970 U.S. Coastal and Geodesic Survey (USCGS70), epoch 1970, geomagnetic field model for solar maximum conditions (ref 1). Magnetospheric conditions were assumed to be "quiet."

Galactic cosmic ray (GCR) intensities were computed using the Naval Research Laboratory Cosmic Ray Effects on Microelectronics (CREME) model (Adams et al., 1986). The 1985 International Geomagnetic Reference Field, epoch 1990 (IAGA, 1985), was used as input to the CREME routine, "Geomag," to compute particle transmissions to locations within the geomagnetic field. The calculated values were normalized to measured values in the Space Shuttle using Mt. Climax neutron monitor data.

The biologically significant dose equivalents were computed at various locations in the SSF using the program PDOSE that was developed by the NASA Johnson Space Center (JSC) (ref 3). The program is based on proton range-energy and linear energy transfer (LET) tables of Janni (1982). Trapped electron exposures were computed using the program EDOSE which was also developed by NASA JSC. EDOSE uses data from look-up tables compiled by Berger and Seltzer (ref 2) using a Monte Carlo electron-photon transport code SHIELDOSE. GCR exposures were computed using the program, HZETRN, developed by the NASA Langley Research Center (Wilson et al., 1991). Calculations of the dose equivalent are based on the quality factor versus LET relationship from International Commission on Radiological Production (ICRP) (1977) instead of ICRP (1960). Differences will be discussed.

It is assumed that crew members who are selected for long-duration missions will not perform extravehicular activity (EVA) so that their exposures can be minimized. This means that only those crew members who receive 180-day flight assignments will perform the necessary EVA on SSF. Further, it is assumed that those crew members selected to participate in long-duration missions will spend 90 percent of the time in the laboratory module and 10 percent of the time in an end-node.

Radiation Limits

Table I lists current NASA radiation exposure limits in units of sievert (Sv), where 1 Sv = 100 rem., for the blood-forming organs (BFOs) and skin for LEO missions (NCRP, 1989). A comparison between the current career BFO limits and those proposed by the NCRP Scientific Committee 75 are given in **Table II** as a function of age and sex. The proposed BFO limits are more than a factor of two less than current limits. Larger risks are indicated for females, especially those at younger ages. For example, proposed career exposure limits for 25-year-old female crew members are about 3.7 times greater than for 55-year-old female crew members. By comparison, the proposed career limits for 25-year-old male crew members is 2.38 times greater than for 55-year-old male crew members. *Note that the limits for skin will always be three times or more greater than for BFOs.* **This means that in cases where the ratio of skin to BFO exposures is less than 3, BFOs will be the critical organ which limits exposure. Table III** (Charles Land, private communication) gives National Cancer Institute data on the excess lifetime risk of cancer mortality as a function of age and sex.

Table I. Current NASA Exposure Limits (in Sv) for LEO Missions (NCRP, 1989).

	BFO	SKIN
30-days	0.25	1.5
Annual	0.50	3.0
Career:		
Males	2.0+0.075 (Age-30 yr)	6.0
Females	2.0+0.07.5 (Age-38 yr)	6.0

Table II. Current and Proposed Career BFO Exposure Limits in Sv.

Age	Females		Males	
(years)	Current	Proposed	Current	Proposed
25	1.0	0.4	1.5	0.7
35	1.75	0.9	2.5	1.1
45	2.5	1.1	3.25	1.5
55	3.0	1.5	4.0	1.9

Table III. Excess Lifetime Risk of Cancer Mortality (percent/Sv) from Radiation Exposure.

Age (yr)	Females	Males
25	8.2	6.1
35	4.0	3.1
45	2.8	2.2
55	2.4	1.9

Assessment Results

Figure 1 shows skin dose equivalent rates measured at the least shielded location inside the Space Shuttle for flights with a 28.5° inclination as a function of altitude and solar activity. [The F10.7 cm solar radio frequency intensity is taken as the measure of solar activity.] Computed exposures using the AP8 trapped proton model for solar minimum and solar maximum are shown for comparison. As a rule, the measurements are bounded by the calculations. Fits to the measurements are shown for three ranges of solar activity. For example, dose equivalent rates at 220 nm (407 km) are between 0.6 and 1.0 mSv/day, depending on solar activity.

Figure 2 shows skin dose rates (in gray, Gy, where 1 Gy = 100 rads) measured at two locations (DLOC2 is the least shielded area, and DLOC1 is more heavily shielded) inside the Space Shuttle for flights with inclinations greater than 49.5° as a function of altitude. The measurements are again bounded by calculations which used the AP8 trapped proton model for solar minimum and solar maximum. Also shown are measurements made on selected Soviet spaceflights which are in good agreement with the measurements made on Space Shuttle flights. The range of values at a single altitude is principally due to differences in solar activity at the times of flights. Dose rates at 220 nm (407 km) range between about 0.2 and 0.5 mGy/day. The dose rates in mGy/day must be multiplied by an effective quality factor to convert to dose equivalent rates. The effective quality factor for the Space Shuttle is about 2.4 at about 150 nm (278 km) and about 1.7 to 1.8 at about 220 nm (407 km), depending on solar activity and inclination. Thus, at 220 nm the dose equivalent rates range between 0.3 and 0.75 mSv/day.

Figure 3 shows the fractions of the total BFO dose equivalent exposures contributed by GCR as a function of altitude for both 28.5° and 57° inclinations. [Exposures will be similar at 51.6°.] In general, GCR contributes almost all the radiation exposure at and below about 280 km. The contribution of trapped belt protons increases rapidly with altitude so that they account for more than 90 percent of the total dose equivalent exposure above about 450 km in a 28.5° inclination orbit and above about 550 km in a 51.6° orbit. At 220 nm (407 km) GCR accounts for about 20 percent in a 28.5° inclination orbit and about 30 percent in the high inclination orbit.

Calculated ionizing radiation exposures to crew members in the SSF end-nodes and in the SSF laboratory module are given in **Table IV** for orbits with a 28.5° inclination. In the space environment, the ratio, skin/BFO, of dose equivalents ranges between about 1.2 and 2.5 and is always less than 3. Thus, **exposures to the BFO will always be the limiting critical condition in an orbit with an inclination of 28.5°**.

If the new ICRP (1991) quality factor versus LET relationship had been used instead of the ICRP (1977) relationship, daily BFO dose equivalent exposures would be about 2.5 percent greater. If 90 percent of the time is spent in the module and 10 percent is spent in the end-node, the maximum exposure will be 0.30 mSv/day for an altitude of 400 km.

Calculations using the PDOSE program obtain effective quality factors which are less than those obtained by measurements made on Shuttle flights using the NASA JSC Tissue Equivalent Proportional Counter. More complete calculations using the BRYNTRN radiation transport code developed at the NASA Langley Research Center (Wilson et al., 1989) include contributions from nuclear reactions which fragment the atoms of the shielding materials yielding fragment particles and neutrons. Use of the ICRP (1991) definition of the quality factor increases estimates of the dose equivalent by about 20 percent. Thus, the maximum estimated exposures which occur at solar minimum are 0.36 mSv/day for a 400 km altitude.

Table V gives calculated exposures for SSF crewmembers as a function of altitude in an orbit with a 51.6° inclination. These results show that at low altitudes (below about 250 nm), the radiation exposure is higher than in a 28.5° inclination orbit. The dominant source of this increase is the GCR component. At higher altitudes, exposures at 28.5° are higher than for higher inclination orbits. The ratio of skin to BFO dose equivalent rates ranges between 1.1 and 1.8, and therefore less than the ratio of exposure limits. **Thus,**

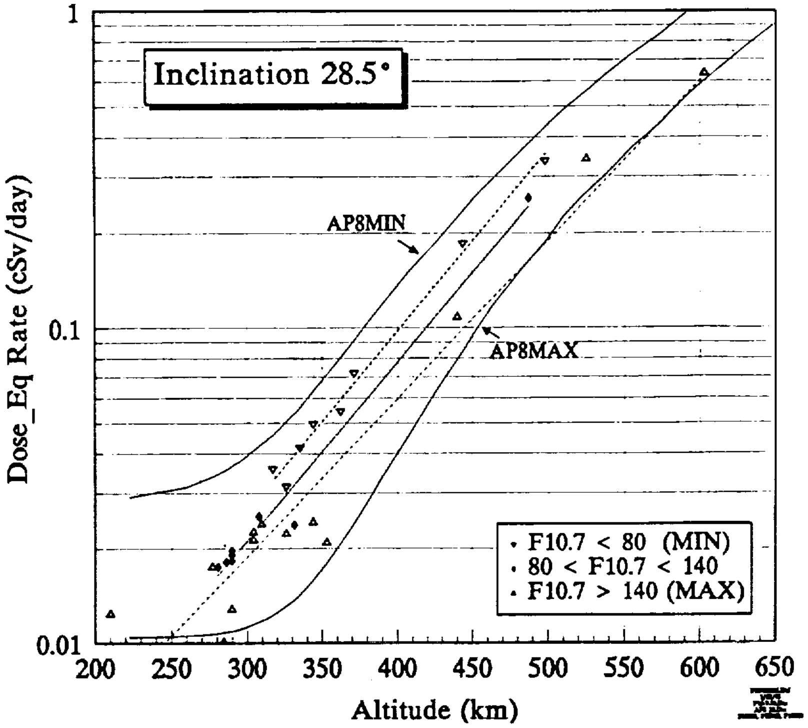

Figure 1. Dose equivalent rates measured on Space Shuttle flights with 28.5° inclination orbits. The solid lines are calculated values of the dose equivalent rates at solar minimum and solar maximum. The dashed lines are least-squares fits to the measurements for different solar cycle conditions.

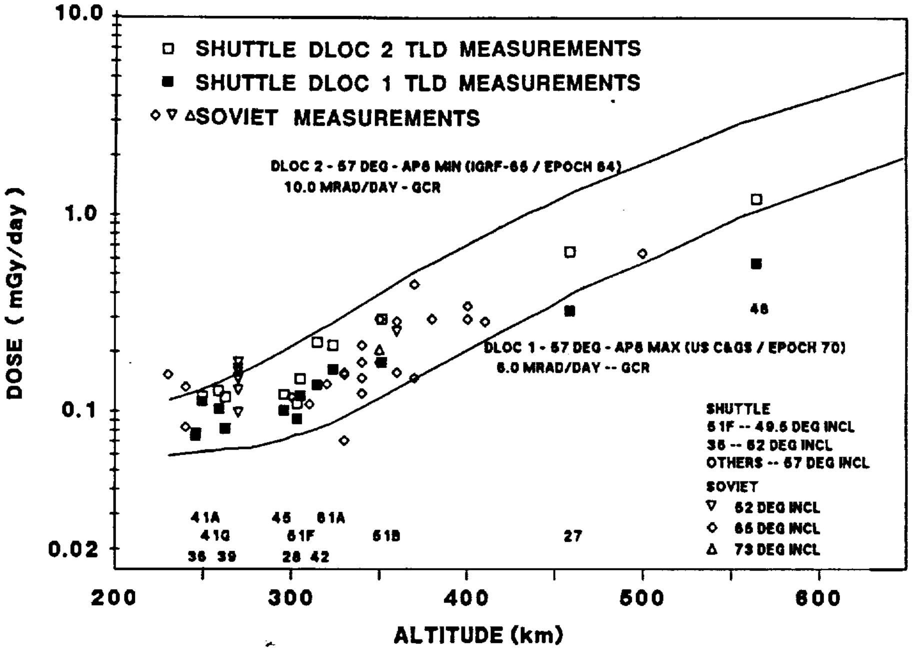

Figure 2. Dose rates measured on Space Shuttle and selected Soviet spaceflights for high inclination orbits (> 48°). The solid lines are calculated dose rates for solar minimum and solar maximum conditions.

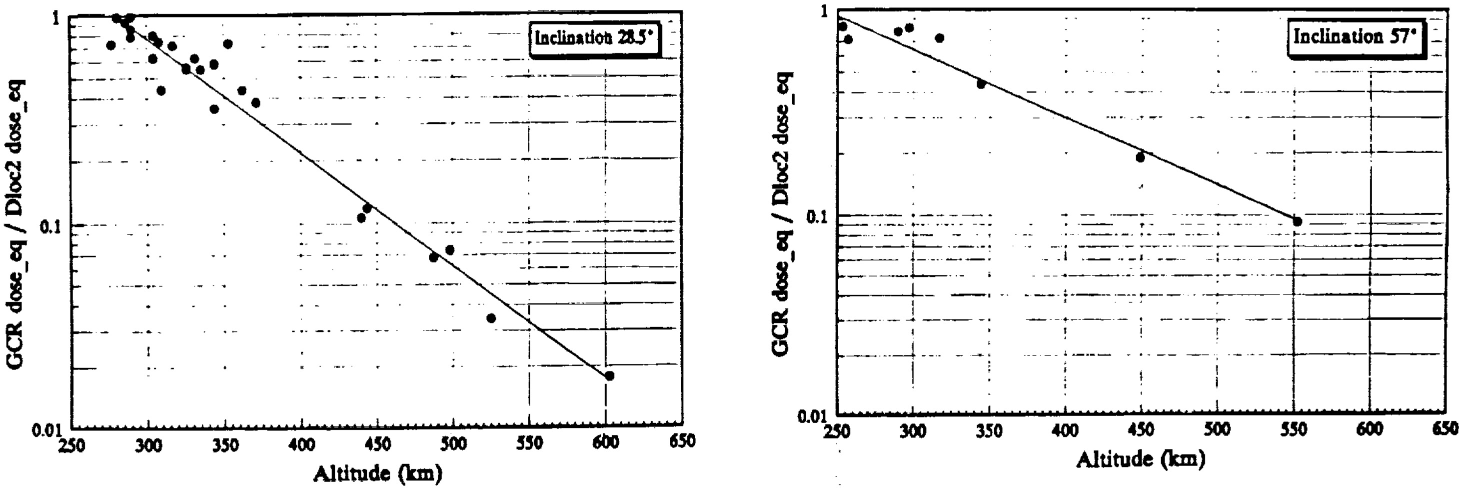

Figure 3. Fractions of the total BFO dose equivalent rates contributed by GCR. The left figure applies to orbits with a 28.5° inclination and the right applies to those with a 57° inclination.

Table IV. Calculated dose equivalent rates for SSF in a 28.5° inclination orbit for solar minimum conditions.

	Dose Equivalent Rate (mSv/day)					
	325 km		400 km		510 km	
	Skin	BFO	Skin	BFO	Skin	BFO
End-Nodes	0.31	0.21	0.66	0.42	2.68	1.55
Lab Module	0.20	0.16	0.40	0.29	1.50	1.01

Table V. Calculated dose equivalent rates for SSF in a 51.6° inclination orbit for solar minimum conditions.

	Dose Equivalent Rate (mSv/day)					
	325 km		400 km		510 km	
	Skin	BFO	Skin	BFO	Skin	BFO
End-Node	0.47	0.37	0.96	0.61	2.21	1.25
Lab Module	0.36	0.33	0.61	0.48	1.22	0.86

exposures to the BFO are also the limiting critical condition in a 51.6° orbit. The BFO dose equivalent in a 400 km, 51.6° orbit is 0.49 mSv/day if crew members spend 10 percent of the time in the end-node and 90 percent of the time in the SSF laboratory. The probability of a solar particle event contributing a significant radiation exposure to crew members in a 28.5° inclination orbit is negligible. Crew members inside spacecraft in such low inclination orbits are highly protected by the Earth's magnetic field. However, this would not be the case for EVA in high inclination orbits.

A very large solar particle event occurred on September 29, 1989, that was responsible for increasing the mean daily radiation level inside the *Mir* space station by a factor of 10 above the nominal background (Lobakov et al., 1992). The total dose from the group of three large solar particle events which occurred during September-October 1989, was among the highest ever recorded for a similar period of time. During this event, the *Mir* space station was in an elliptical orbit at altitudes between 380 and 420 km and an inclination of 51.6°. Therefore, the measurements may be considered a reasonable limit for a 51.6° orbit. The cumulative dose measured by the Russians from the group was about 0.036 Gy (Benghin et al., 1992).

Radiation Risk for Long-Duration SSF Mission Assignments

Risk to crew members from LEO exposures to space radiation strongly depend on altitude and inclination as well as duration of exposure. *Figures 4 and 5* show the computed risk for males and females, respectively, as a function of altitude for 1,000-day assignments in 28.5° and 51.6° inclination orbits assuming that crew members spend 90 percent of the time in the laboratory module and 10 percent of the time in an end-node. The level of risk considered to be acceptable (NCRP, 1989), 3 percent, is indicated. Risk exceeds 3 percent for 25-year-old male crew members only above 400 km in the 51.6° orbit and above 450 km in the 28.5° orbit. Risk exceeds 3 percent for 25-year-old female crew members above 350 km in a 51.6° orbit and above 420 km in a 28.5° orbit. In addition, the risk to 35-year-old female crew members exceeds 3 percent for either inclination above about 480 km. [Risk for ages between those given must be obtained by extrapolation from these data. For example, the risk for a 30-year-old female will exceed 3 percent for altitudes above about 400 km.]

Constraints for SSF crew member assignments were determined using data based on continuous exposure. Since the actual assignments will be for multiple mission assignments, exposures will be fractionated rather than continuous. Thus, a period of healing between intermittent exposures is possible. However, studies on fractionated exposures using animals indicate that, for some high-LET radiation, the radiation risks are increased if the dose is delivered in separate intervals. Thus, it is possible that career exposure limits might need to be reduced even further in such exposure scenarios. Finally, other long-term effects, such as effects on the central nervous system, which have not yet been adequately examined are not considered in this assessment.

Conclusions

A detailed study has been performed on the risk from radiation exposures of crew members on SSF assignments up to approximately 3 years. Orbits ranging from 325 km to 510 km and inclinations of 28.5° and 51.6° were considered. Constraints were identified for crew members as a function of altitude, age, and sex when the risk is greater than the 3 percent acceptable level. The principal constraint is governed by the age of the crew member. Twenty-five year-olds of either sex are constrained in the altitude range of SSF to which they can be assigned a mission. However, males above 35 years old will not be constrained. Thirty-five-year-old females are only constrained to orbits with altitudes less than about 480 km.

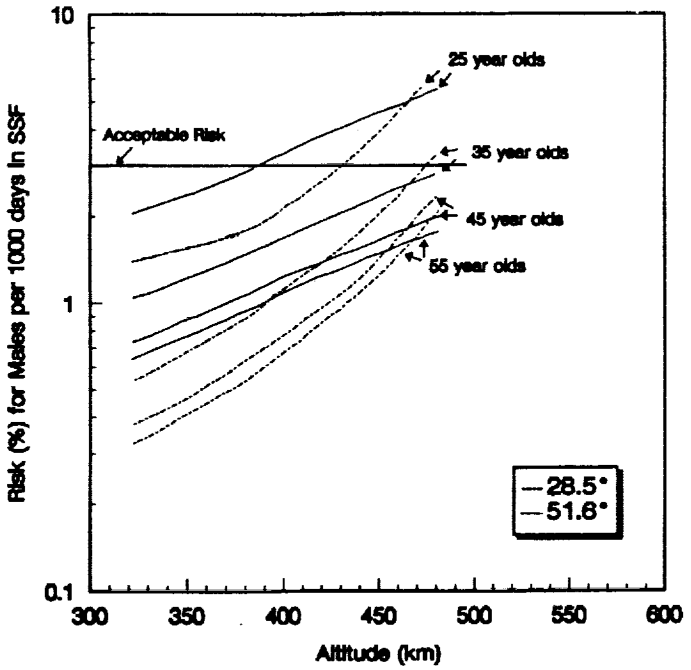

Figure 4. Radiation exposure risk to male SSF crew members assuming that 90 percent of the time is spent in the laboratory module and 10 percent is spent in an end-node.

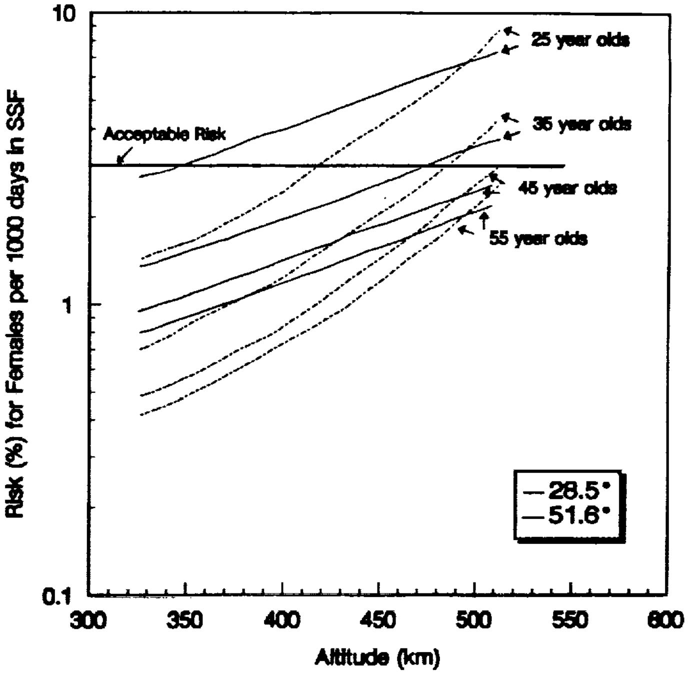

Figure 5. Radiation exposure risk to female SSF crew members assuming that 90 percent of the time is spent in the laboratory module and 10 percent is spent in an end-node.

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13. ABSTRACT *(Maximum 200 words)*

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