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# ACCEPTABILITY OF RISK FROM RADIATION – APPLICATION TO HUMAN SPACE FLIGHT

Symposium Proceedings No. 3

Held May 29, 1996
Arlington, Virginia

*National Council on Radiation Protection and Measurements*

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# *Acceptability of Risk from Radiation—Application to Human Space Flight*

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Issued April 30, 1997



National Council on Radiation Protection
and Measurements
7910 Woodmont Avenue
Bethesda, Maryland 20814-3095

NCRP

# Preface

The National Council on Radiation Protection and Measurements (NCRP) was asked by the National Aeronautics and Space Administration to conduct a symposium on acceptable risk for humans involved in space activities. This Symposium was organized by a Program Committee consisting of

**Paul Slovic**, *Chairman*
Decision Research
Eugene, Oregon

*Members*

**R.J. Michael Fry**
Oak Ridge National Laboratory
Oak Ridge, Tennessee

**Eric J. Hall**
Radiological Research Laboratory
Columbia University
New York, New York

**Dade W. Moeller**
Dade Moeller & Associates, Inc.
New Bern, North Carolina

**Chris G. Whipple**
ICF Kaiser
Oakland, California

In addition to serving on the Program Committee, Dade Moeller, participating as a Consultant to the NCRP, played a major staff role in connection with the work of organizing and promoting the Symposium and, subsequently, served as rapporteur for the meeting, and editor of these Proceedings.

Participating from the NCRP Secretariat were:

**William M. Beckner**, *Senior Staff Scientist*
**Cindy L. O'Brien**, *Editorial Assistant*
**Laura J. Atwell**, *Staff*
**Tabitha M. Buck**, *Staff*

The Council wishes to express its appreciation to all of these individuals for the time and effort devoted to conducting the Symposium and the preparation of these Proceedings.

Charles B. Meinhold
*President*, NCRP

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# Contents

# Opening Remarks

Charles B. Meinhold
President, NCRP

Good morning, I am delighted to welcome all of you to the National Council on Radiation Protection and Measurements' (NCRP) symposium on "Acceptability of Risk from Radiation—Application to Human Space Flight."

This is just one of a number of National Aeronautics and Space Administration (NASA) sponsored activities of the NCRP. This symposium is particularly interesting since it highlights not only NCRP's strong interaction with the manned space program but also our continuing attention to the risk associated with exposure to ionizing radiation.

Here on earth we can use the experience of workers in a variety of industries to give us a framework for developing radiation limits. For our astronauts this is not nearly so obvious. Hopefully today we will all learn more about the acceptability of risk in manned space flight.

Your Program Chairman for this Symposium is Dr. Paul Slovic, President of Decision Research and NCRP Vice President for Policy Analysis and Decision Making.

# Objectives of the Symposium

Paul Slovic
Symposium Chairman

Thank you very much, Charlie. As many of you are aware, the NCRP has been quite active over the years in developing radiation exposure guidelines for space activities. In 1983, NASA asked the NCRP to examine radiation risks in space and to make recommendations about career radiation limits for astronauts. Cancer was considered the principal risk and the recommendations were set on this basis. In making the recommendations provided in NCRP Report No. 98, published in 1989, a three percent excess lifetime cancer mortality was selected as a guideline for establishing the limits. This is less than the lifetime risk of a fatal accident in most hazardous occupations. In light of new data about the risks of the stochastic effects of radiation, Scientific Committee 75 of the NCRP has been reevaluating the recommendations made in 1989 and before. They are also taking into consideration new information about the radiation environment in space, especially within the space station and vehicles in orbit. In conjunction with that effort, NASA has asked the NCRP to convene today's symposium, and to take a closer look at the philosophy of radiation protection and acceptable risk as it pertains to the three percent excess risk guideline. Our objective today is to examine the technical, strategic, and philosophical issues pertaining to acceptable risk and radiation in space.

We hope as well, to involve you, the audience, in the discussion. If you glance through the program, you'll see that we will begin this morning with three overview papers covering the physical properties of the radiation environment in space, the biological effects of the associated exposures, and an historical overview of the development of radiation protection standards for space activities. After a break, we'll move to the topic of acceptable risk. This will include an examination of the technical, social, and philosophical perspectives regarding that elusive concept. Three risk analysts will have a go at it before lunch and, after a break, we will continue with presentations by three individuals who have been intimately involved in the space program: a flight surgeon and two astronauts. We will conclude with a panel and audience discussion, followed by a summary by our rapporteur, Dade Moeller.

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# The Space Radiation Environment

Donald E. Robbins
University Space Research Association

## Abstract

There are three primary sources of space radiation: galactic cosmic rays (GCR), trapped belt radiation, and solar particle events (SPE). All are composed of ions, the nuclei of atoms. Their energies range from a few MeV $u^{-1}$ to over a GeV $u^{-1}$.[1] These ions can fragment when they interact with spacecraft materials and produce energetic neutrons and ions of lower atomic mass.

Absorbed dose rates inside a typical spacecraft (like the Space Shuttle) in a low inclination (28.5 degrees) orbit range between 0.05 and 2 mGy $d^{-1}$ depending on the altitude and flight inclination (angle of orbit with the equator). The quality factor of radiation in orbit depends on the relative contributions of trapped belt radiation and GCR, and the dose rate varies both with orbital altitude and inclination. The corresponding equivalent dose rates range between 0.1 and 4 mSv $d^{-1}$.

In high inclination orbits, like that of the Mir Space Station and as is planned for the International Space Station, blood-forming organ (BFO) equivalent dose rates are as high as 1.5 mSv $d^{-1}$. Thus, on a 1 y mission, a crew member could obtain a total dose of 0.55 Sv. Maximum equivalent dose rates measured in high altitude passes through the South Atlantic Anomaly (SAA) were 10 mSv $h^{-1}$.

For an interplanetary space mission (*e.g.*, to Mars) annual doses from GCR alone range between 150 mSv $y^{-1}$ at solar maximum and

[1] $u^{-1}$ *stands for "per atomic mass unit."*

580 mSv $y^{-1}$ at solar minimum. Large SPE, like the October 1989 series, are more apt to occur in the years around solar maximum. In free space, such an event could contribute another 300 mSv, assuming that a warning system and safe haven can be effectively used with operational procedures to minimize crew exposures. Thus, the total dose for a 3 y mission to Mars could exceed 2 Sv. The maximum free space equivalent dose rate during the large solar particle event in 1989 was estimated to be 40 mSv $h^{-1}$ behind 10 g $cm^{-2}$ of shielding.

In general, radiation exposures during space missions are in the high-dose regime, *i.e.*, greater than 0.1 Sv annually but, if managed operationally, are less than the high-dose rate regime of 0.1 Sv $h^{-1}$ or greater.

## Introduction

This paper is not intended to be a detailed review of the physics of the space radiation environment. Rather it seeks to describe the different types of space radiation so experts in radiobiology and risks can recommend exposure limits for United States' astronauts. The last comprehensive review of the space radiation environment was written in 1988 (Benton and Parnell, 1988). This author and colleagues have written less comprehensive reviews (Robbins *et al.*, 1997; Robbins and Yang, 1994; Nicogossian and Robbins, 1994). A revision of the National Council on Radiation Protection and Measurements' (NCRP) Report No. 98 (NCRP, 1989) which contains a section on space radiation is also being prepared.

There are three primary sources of space radiation: galactic cosmic rays (GCR), trapped belt radiation, and solar particle events (SPE). Space radiation is primarily ions, the nuclei of atoms. Secondary radiation is produced by nuclear interactions between the primary particles and spacecraft materials or constituents of the atmosphere. This secondary radiation consists of ions as well as neutrons.

Space radiation risks for astronauts during a space mission can be expressed mathematically as the product of two probabilities, the probability that the astronaut will receive a certain exposure, and the probability that this exposure will produce a detrimental effect (short- or long-term). This paper addresses the first of these two probabilities. In general, it is not feasible to provide a probability distribution versus expected exposure. Thus, space physicists compute a "best estimate" of the radiation exposure as well as an estimate of its uncertainty.

## Galactic Cosmic Rays

Galactic cosmic rays consist of energetic ions which originate outside the solar system. Their fluxes, which are isotropic, are modulated by changes in the interplanetary magnetic fields during the solar cycle. The energy range of the ions of greatest biological concern are <1,000 MeV $u^{-1}$. (MeV $u^{-1}$ is an SI unit for energy per atomic mass unit, where u stands for the atomic mass unit and MeV stands for million electrons volts. Thus, a proton with a u of approximately one and an energy of 100 MeV $u^{-1}$ has a total kinetic energy of 100 MeV; whereas under the same conditions a 100 MeV helium ion with u of approximately four has a total kinetic energy of 400 MeV.) The flux of lower energy ions varies by a factor of 10 over a solar cycle. At higher energies (>10 GeV $u^{-1}$), solar cycle variations are less than 20 percent. Because GCR fluxes near earth are inversely proportional to the sunspot number (a general measure of solar activity), their fluxes are higher during solar minimum due to the change in the magnetic fields surrounding the earth due to solar activity.

GCR fluxes are reduced within the Earth's magnetosphere because they are partially deflected by the stronger magnetic field of Earth. Figure 1 (Mewaldt, 1988) shows the "free space" relative abundance of primary GCR near solar minimum. ("Free-space" denotes conditions outside the Earth's magnetic field, *i.e.*, in interplanetary space.) Primary GCR ions are totally ionized. The ions which contribute most to the biological dose are $^{1}H$, $^{2}He$, $^{6}C$, $^{8}O$, $^{14}Si$ and $^{26}Fe$.

Anomalous cosmic rays (ACR) are produced when neutral atoms are ionized by solar ultraviolet light and subsequently accelerated by shock waves in interstellar space. ACR are singly ionized and consist predominantly of He, C, N, O, Ne and Ar ions. They are also modulated by solar activity and are observed more readily during solar minimum. Their energies are generally <100 MeV $u^{-1}$. At one astronomical unit from the sun, they contribute negligibly to the total GCR dose. ACR account for about five percent of the total GCR He flux >10 MeV $u^{-1}$ and less than one percent of the He flux >100 MeV $u^{-1}$.

Figure 2 (Simpson, 1983) shows the energy spectra of the more abundant primary GCR. It should be noted that ions with energies >1 GeV $u^{-1}$ can penetrate a meter of water and have a mean free path between nuclear interactions of approximately 10 g $cm^{-2}$.

Figure 3 (Badhwar *et al.*, 1994) illustrates the effectiveness of shielding in reducing "free-space" GCR dose rates. The calculated 5 cm water dose equivalent rate is shown as a function of aluminum shielding thickness for several solar cycles. Results are shown for solar maxima that

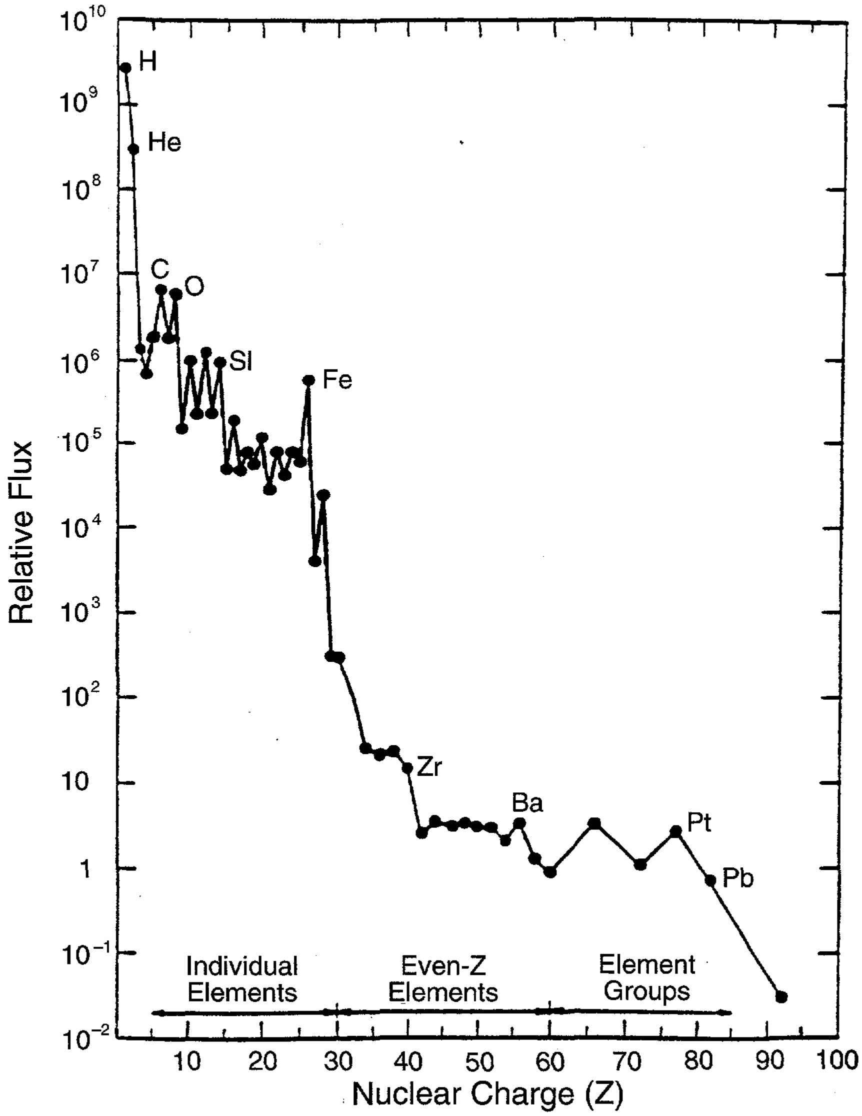


**Fig. 1.** Relative flux of GCR ions as a function of nuclear charge (Mewaldt, 1988). The flux of silicon (Si) is assumed to be $10^6$.

occurred in the years 1958, 1970, 1981 and 1989, and solar minima that occurred in the years 1965 and 1977. Differences between solar minimum and solar maximum are a factor of approximately three. The solar minimum of 1977 was the most intense yet observed; the solar maximum in 1989 was the least intense. A shielding thickness of 20 g $cm^{-2}$ reduces the equivalent dose rate by about 40 percent; however, adding another 20 g $cm^{-2}$ reduces it only by an additional 15 percent. A model was

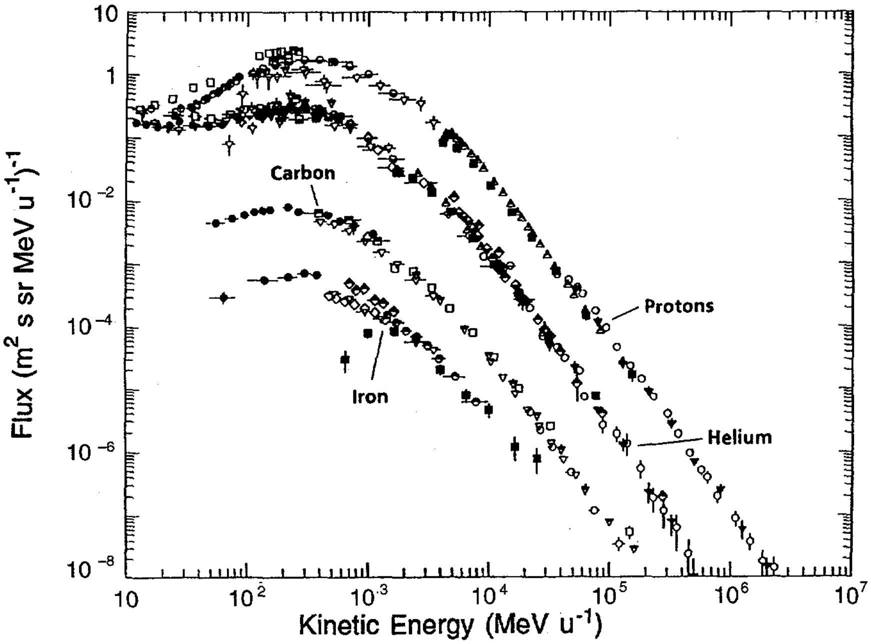


**Fig. 2.** *Energy spectra of major GCR ions as a function of kinetic energy (Simpson, 1983).*

recently developed (Badhwar and O'Neill, 1992; 1996) that agrees with GCR flux measurements obtained during the past four solar cycles within about 10 percent. It employs neutron monitor rates and sunspot numbers as the predictors of future solar activity.

Figure 4 shows the percentage of the 0 cm (skin) equivalent dose contributed by GCR ions of charge 0 (neutrons) to charge 28 ($^{28}$Ni) for shielding thicknesses of 0, 3, 10 and 30 g cm$^{-2}$ for the 1977 solar minimum.

Figure 5 shows the percentage of the 5 cm blood-forming organ (BFO) equivalent dose contributed by GCR ions for shielding thicknesses of 1, 3, 10 and 30 g cm$^{-2}$ for the 1977 solar minimum. For a smaller shielding thickness, the greater contributions are from charges $_1$H, $_2$He, $_8$O, $_{12}$C, $_{14}$N and $_{26}$Fe. For thicker shielding the higher charge ions are fragmented. Thus, neutrons, protons and He contribute most to the resulting dose.

Figure 6 illustrates the change in the free-space GCR LET[2] spectrum for shielding thickness of 1, 3, 10 and 30 g cm$^{-2}$ for the 1977 solar minimum.

[2]LET stands for linear energy transfer.

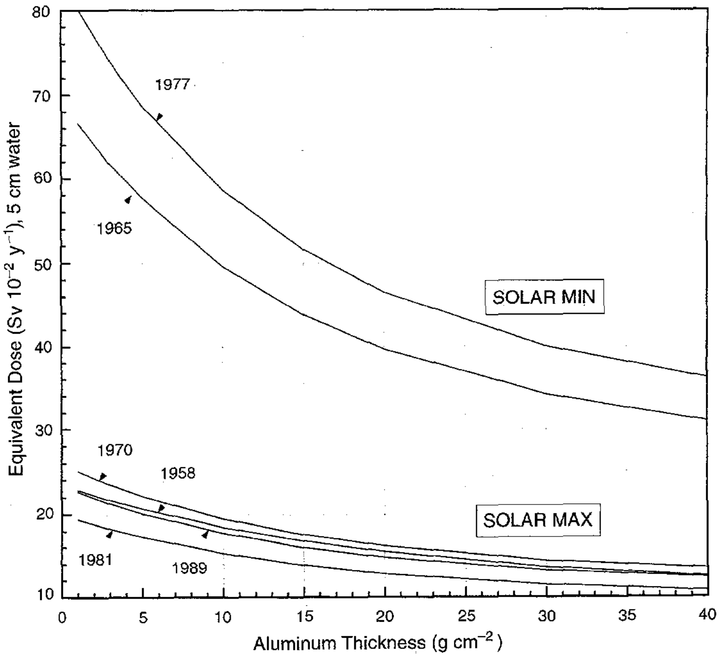


**Fig. 3.** Effectiveness of shielding in reducing GCR equivalent dose rates at solar minimum and solar maximum (Badhwar *et al.*, 1994). Dates refer to times of solar minima and maxima.

Significant reductions are seen above about 5 g $cm^{-2}$. These occur because at such shielding thickness nuclear interactions become important.

Figure 7 shows the fractional dose and equivalent dose from GCR as a function of LET for measurements made in the payload bay of the Space Shuttle during STS-63 (51.6 degrees inclination; 400 km altitude) using a Tissue Equivalent Proportional Counter, referred to in this paper by the acronym, TEPC (Badhwar *et al.*, 1992). Ninety percent of the absorbed dose is contributed by radiation with LET <30 keV $mm^{-1}$; 90 percent of the equivalent dose is contributed by radiation with LET <300 keV $mm^{-1}$.

Figure 8 (Badhwar *et al.*, 1996a) shows the GCR LET spectrum measured inside a Space Shuttle locker on STS-63. The smooth curve is from a model calculation using the NASA Langley Research Center HZETRN transport code (Wilson *et al.*, 1995).

Although the free-space quality factor for GCR is about 4.6, the GCR quality factor calculated from TEPC measurements made during the

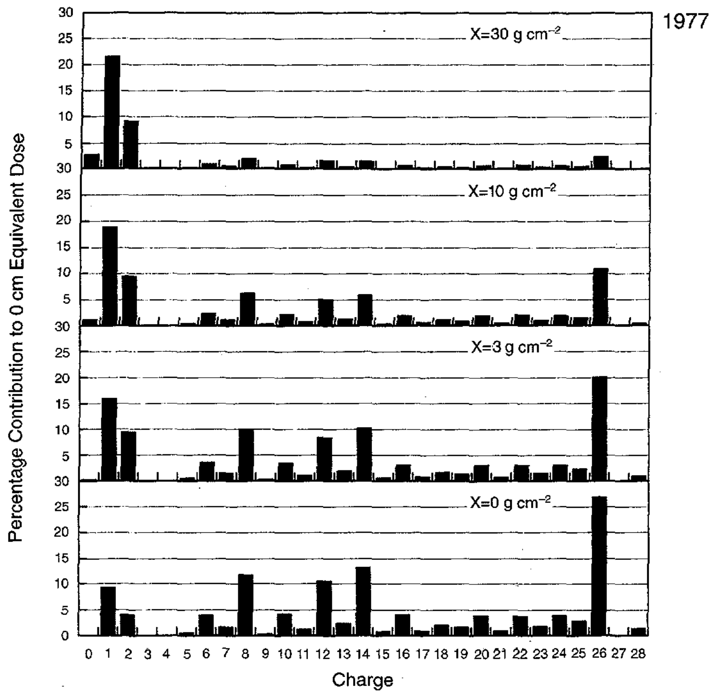


**Fig. 4.** Percentage contribution of GCR ions to 0 cm (skin) equivalent dose versus nuclear charge for 0, 3, 10 and 30 g $cm^{-2}$ of shielding for the 1977 solar minimum.

United States/Russian Mir-18 mission (March 2 through June 18, 1995) was 3.2. A portion of the GCR flux is deflected from low Earth orbit by the Earth's magnetic field and Earth-shadowing. A value of 2.9 was assumed for earlier work (NCRP, 1989). The difference is believed to be due to errors in the transport codes used earlier which did not include contributions from secondary particles. Significant improvements have been made in transport codes in the past 5 y.

Figure 9 (Badhwar *et al.*, 1995a) gives an estimate of the uncertainty in calculating exposures for space missions. The scatter diagram shows observed dose rates from 15 Space Shuttle flights made during the last half of the current solar cycle versus calculated dose rates. The straight line is a least-squares fit. The root mean square (RMS) difference is about 17 percent. The absolute uncertainty in the measured dose rate is believed to be about five percent. This indicates that GCR dose rate estimates can be made with a total uncertainty less than 20 percent.

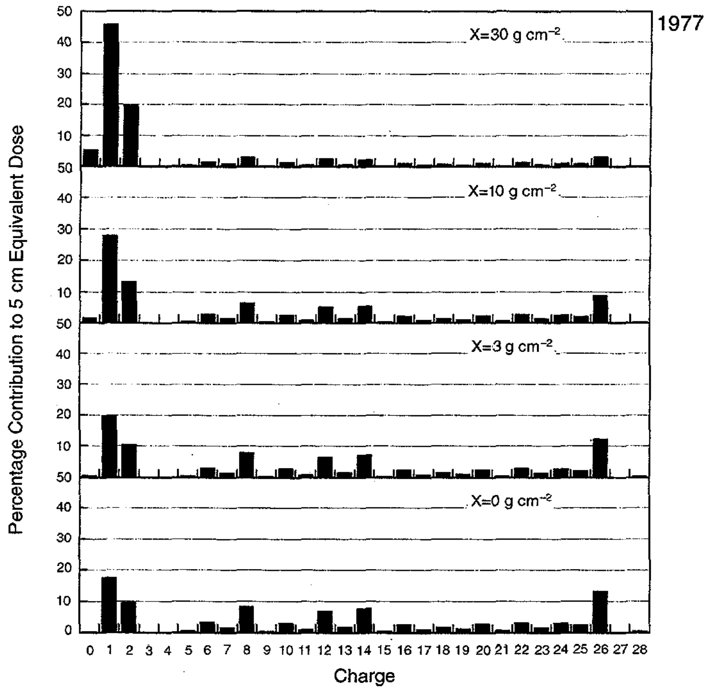


**Fig. 5.** Percentage of the 5 cm (BFO) equivalent dose versus GCR nuclear charge for 1, 3, 10 and 30 g cm$^{-2}$ of shielding for the 1977 solar minimum.

## Trapped-Belt Radiation

The physics of the trapped-belt is not discussed here. Nor is a description given of the outer belt electrons since they represent a minor risk for human space flights. Outer belt electrons do contribute a small dose for interplanetary space missions which pass through them. The inner belt, however, is a major source of radiation exposure for low Earth orbit missions.

The inner belt consists principally of protons, although small fluxes of other ions have been observed. These, however, do not contribute significantly to crew exposures. Figure 10 shows proton spectra obtained from the AP-8 model (Sawyer and Vette, 1976) at solar minimum and solar maximum for an orbit of 51.6 degrees inclination and 470 km. (The International Space Station will have a 51.6 degrees inclination and will have an altitude between 370 and 470 km.)

Figure 11 illustrates the effectiveness of shielding in reducing the absorbed dose from trapped belt radiation in low inclination

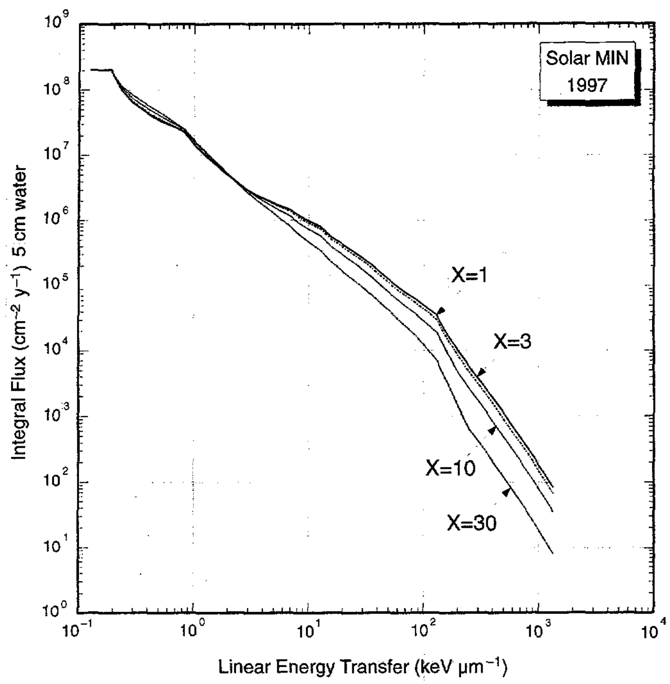


**Fig. 6.** GCR LET spectra behind 1, 3, 10 and 30 g $cm^{-2}$ of shielding for the 1977 solar minimum.

(28.5 degrees) orbits. Data are given for three altitudes: 296, 400 and 500 km. Because the proton spectrum is so hard, significant reductions in dose are not obtained for shielding thicknesses greater than about 1 g $cm^{-2}$.

Figure 12 (Badhwar *et al.*, 1995a) shows a LET spectrum from the trapped protons measured by the TEPC in the Space Shuttle mid-deck on STS-63.

Figure 13 shows the fraction of absorbed dose and equivalent dose from trapped belt radiation measured in the Space Shuttle mid-deck during STS-63 versus LET. Ninety percent of the absorbed dose is from radiation with LET <10 keV $\mu m^{-1}$; 90 percent of the equivalent dose is contributed by radiation with LET <120 keV $\mu m^{-1}$.

The mean quality factor for trapped belt radiation was calculated to be 1.9 from TEPC measurements obtained during the Mir-18 mission. NCRP (1989) used a value of 1.3 for "protons and secondaries encountered in the South Atlantic Anomaly." Inaccuracies in the trapped belt model

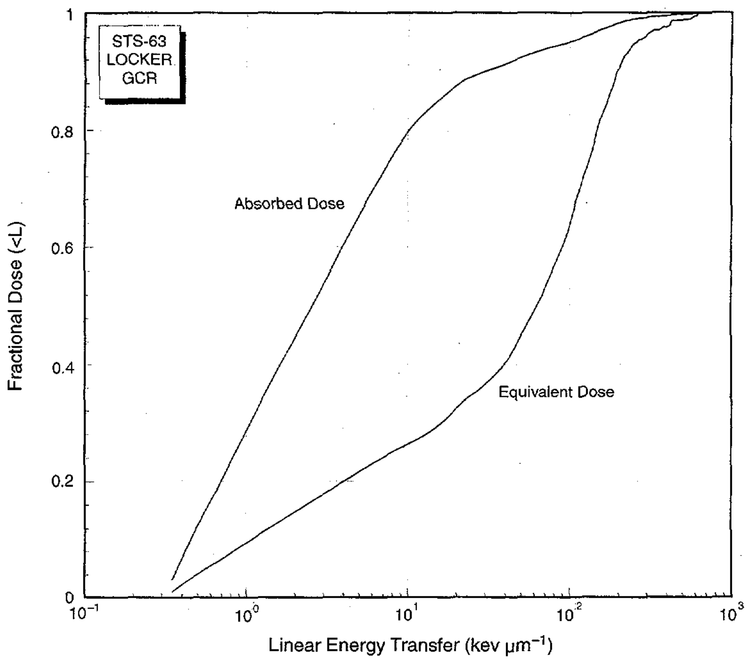


**Fig. 7.** Fraction of absorbed dose and equivalent dose contributed by GCR versus LET (Badhwar *et al.*, 1996a).

probably account for this difference. The AP-8 model was formulated using measurements from 23 satellites obtained over the period 1958 to 1970. Uncertainties in the model are quoted to be a factor of two. However, based on dose measurements made on a large number of human space flights, mission planners have learned how to use the model to estimate mission integrated exposures within 25 to 30 percent. The largest error in the model is that it does not account for anisotropies (*e.g.*, the East-West asymmetry) in the trapped belt fluxes. Measurements made on the Long Duration Exposure Facility (LDEF) yielded doses 1.7 to 2.5 times higher on the trailing edge than on the leading edge (Armstrong *et al.*, 1990; Harmon *et al.*, 1992).

Solar activity induced variations in trapped belt proton fluxes can be normalized by relating them to the atmospheric density (Pfitzer, 1990). Figure 14 (Golightly *et al.*, 1996) shows a "log-log" plot of dose rate versus atmospheric density. The solid line is a fit to the measurements made on Space Shuttle flights with a 57 degrees inclinations. The dotted lines are 90 percent confidence limits.

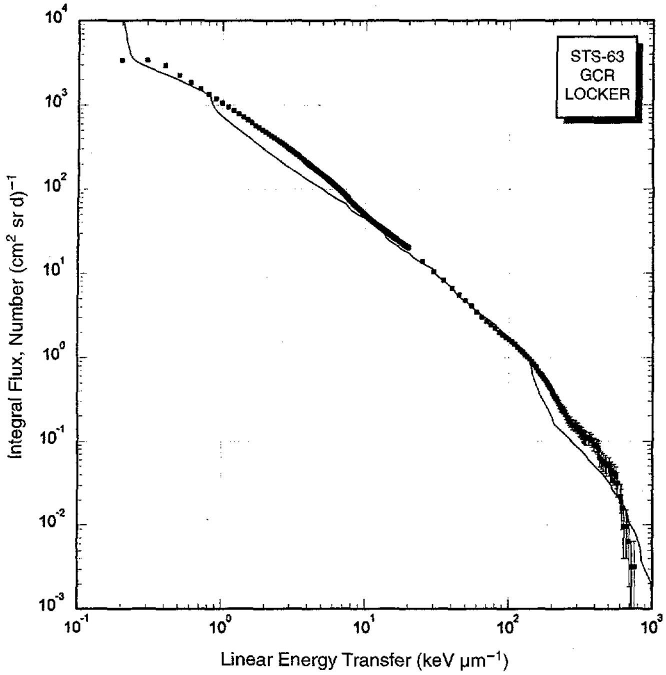


**Fig. 8.** LET spectrum of GCR measured using TEPC in Space Shuttle mid-deck locker on high inclination orbit of STS-63 (Badhwar *et al.*, 1996a).

## Solar Particle Events

Solar particle events (SPE) pose a significant threat to interplanetary space missions (*e.g.*, to the moon and Mars). Occasionally, space missions in high inclination orbits, like those of the Mir Space Station and International Space Station, receive radiation due to SPE.

SPE are composed predominantly of protons. However, a 10 percent contribution from He ions has been observed during some SPE. Neither the time of an SPE occurrence nor its size can be predicted. However, it is believed that a warning system can be devised to give astronauts a few hours to take refuge in a "safe haven" before accumulated doses become significant.

SPE are only one of the many manifestations of solar flares which occur more frequently during the years of solar maximum. Figure 15 (Smart, 1988) illustrates the propagation of high-energy protons from the region of the sun's surface where they are accelerated during the associated solar flare. While electromagnetic radiation, such as visible light, x rays and radiofrequency radiation, travels in a straight line from the sun to

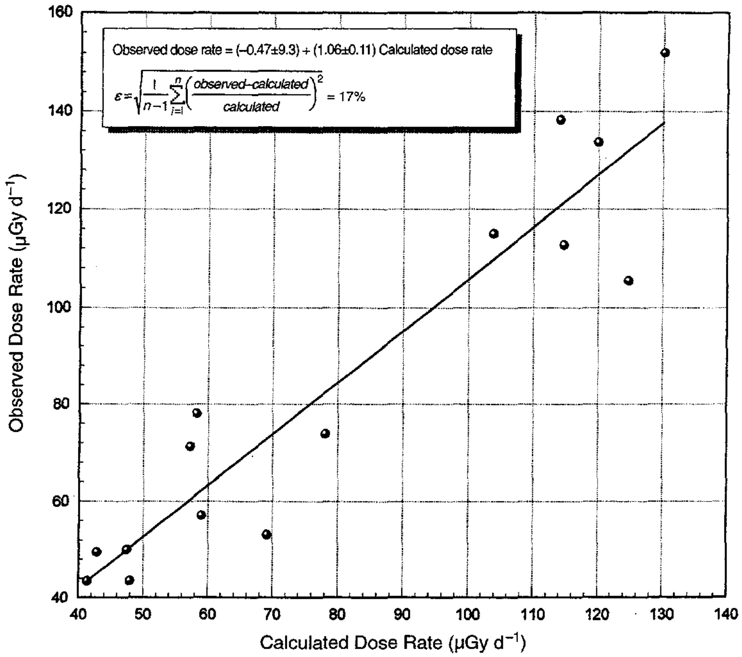


**Fig. 9.** Uncertainty in GCR dose calculations. RMS differences average 17 percent (Badhwar *et al.*, 1995a).

Earth in 8 min, charged particles follow the interplanetary magnetic field lines which emanate from the sun in the configuration of a spiral like that shown in the figure. In addition, the bulk of the particles travel at less than the speed of light. Thus, a significantly longer time is required for protons to propagate out from the solar surface to Earth. It more often occurs that the interplanetary magnetic field tube, which serves as the guiding center for the protons as they move outward into space, carries them away from Earth.

On those occasions when the location of the solar flare and the interplanetary field tube allows protons to propagate to the region of the Earth, the time distribution of proton flux is as characterized in Figure 16 (Smart, 1988). Propagation delay times, the time between the solar flare's occurrence on the sun's surface and the onset of the proton flux, are typically several hours. Several hours more are required before the proton flux peaks. For large SPE, the decay of the proton flux from the peak is exponential over a period of several days.

Thus, radiation exposures from SPE are highly probabilistic and must be managed using operational procedures. It follows that if operational

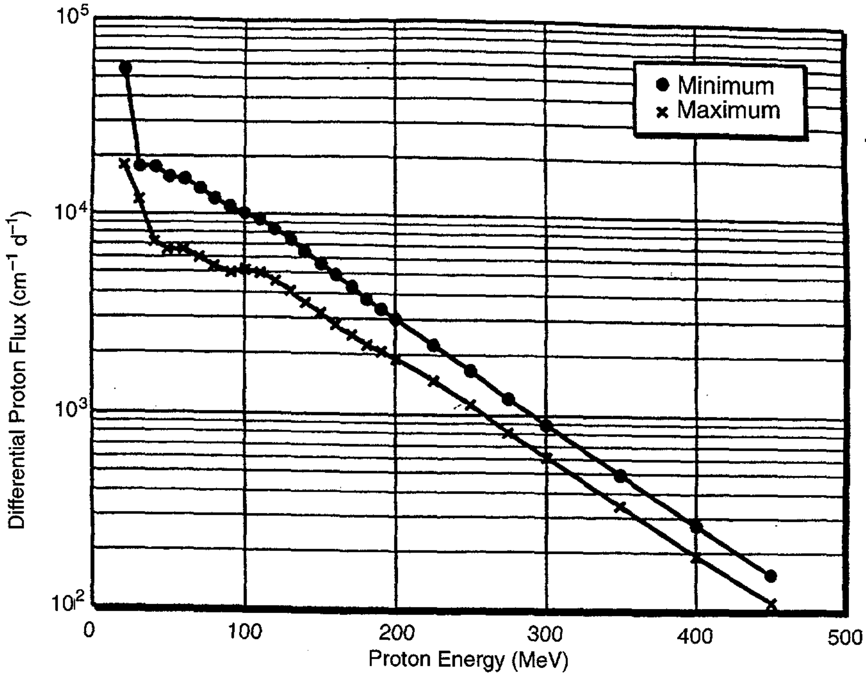


**Fig. 10.** Trapped belt proton spectra for maximum altitude (470 km) of International Space Station from AP-8 model for solar minimum and solar maximum.

procedures are not employed for interplanetary missions, crew members could receive very high exposures from SPE.

The group of SPE which occurred from October 19-27, 1989, produced one of the most severe interplanetary environments in the last 50 y.

Figure 17 (Lobakov *et al.*, 1992) shows dose rates measured in low Earth orbit inside the Mir Space Station using Russian ion chambers (solid line) and 39 to 82 MeV fluxes measured on the GOES-7 NOAA satellite (brackets). The dose rate increased by a factor of 1,000, from $3 \times 10^{-5}$ to $3 \times 10^{-2}$ Gy $d^{-1}$ within 4 h. The cumulative exposure inside the Mir Space Station during this 4 h period was about $2.5 \times 10^{-3}$ Gy. If provided adequate warning, astronauts might take refuge in a safe haven to reduce their exposure from such severe environments. (It should be understood that it is only during high latitude parts of the orbit that SPE radiation is measurable inside a spacecraft; exposures in free-space would have been much higher.) Figure 18 (Simonsen *et al.*, 1991) shows the free-space BFO equivalent dose integrated over the duration of the October 19-27, 1989, SPE as a function of aluminum shielding thickness. The BFO exposure behind 1 g $cm^{-2}$ shielding was reduced to approximately

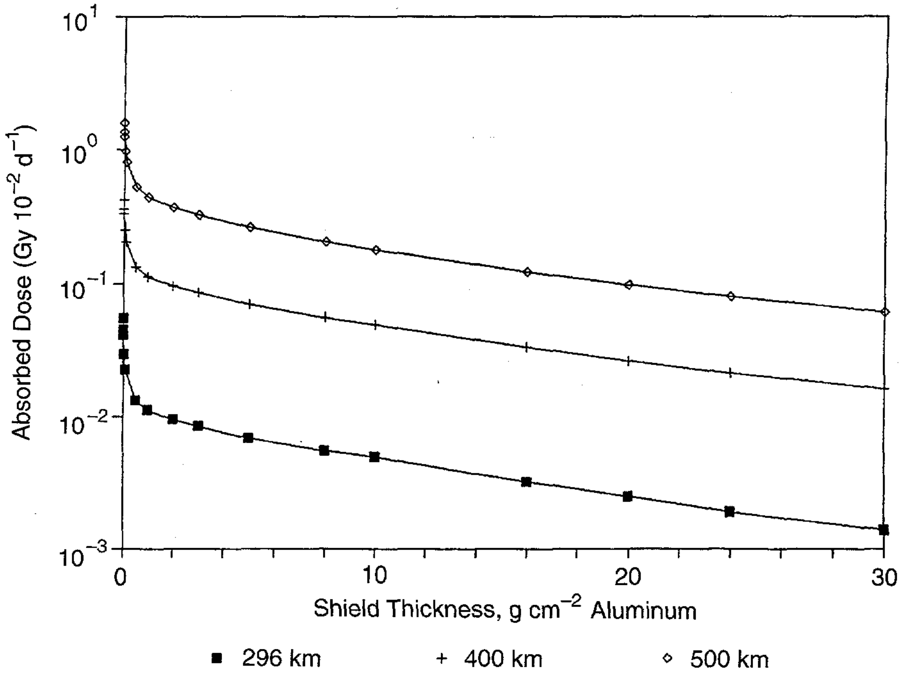


**Fig. 11.** Effectiveness of shielding in reducing absorbed dose rates in low inclination (28.5°) orbit at 296, 400 and 500 km.

1 Sv; the exposure behind 10 g $cm^{-2}$ was reduced to about 0.2 Sv. If a substantial portion of the SPE is spent in a safe haven with 20 g $cm^{-2}$ of shielding, exposures could be reduced to the range of 0.1 Sv. The maximum skin dose rate behind 10 g $cm^{-2}$ is estimated to be 0.04 Sv $h^{-1}$.

## Secondary Neutrons

A few measurements of neutrons during human space flights have been made (Badhwar *et al.*, 1995b; 1996c). Neutrons of energy 1 to 15 MeV produced an equivalent dose rate between $5.3 \times 10^{-5}$ Sv $d^{-1}$ at 290 km and $1.7 \times 10^{-4}$ Sv $d^{-1}$ at 462 km altitude. Benton and Parnell (1988) estimate the equivalent dose rate contribution for neutrons with less than 1 MeV energy to be about $2.2 \times 10^{-5}$ Sv $d^{-1}$. Model calculations (Armstrong and Colborn, 1992; Keith *et al.*, 1992) suggest that this energy range contributes only about half the total neutron equivalent dose. Thus, total neutron equivalent dose rates could contribute as much as $4.0 \times 10^{-4}$ Sv $d^{-1}$ at 462 km.

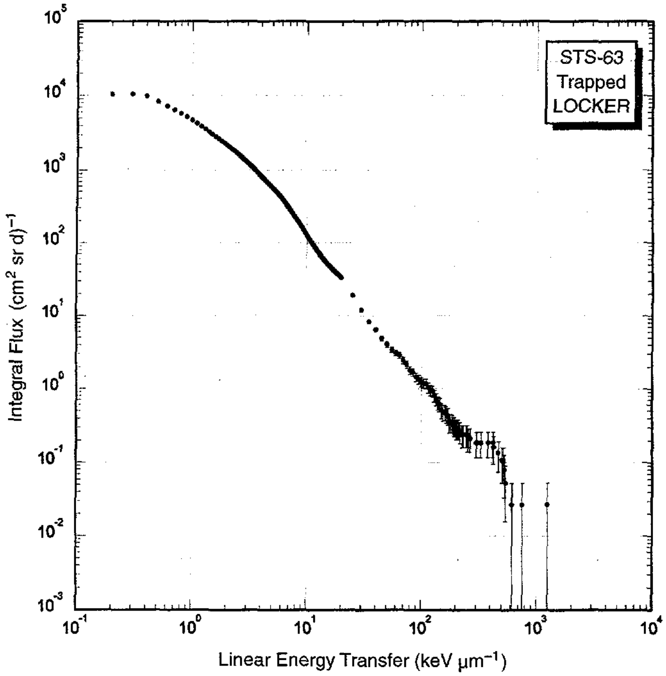


**Fig. 12.** Trapped belt radiation LET spectrum measured inside Space Shuttle mid-deck during STS-63.

## Exposures on Typical Space Missions

### *1. Low Inclination Space Shuttle Missions*

The maximum dose rates measured to date in the trapped belts on a low inclination mission were on STS-61 which flew in a 28.5 degrees inclination at an altitude of 594 km. Figure 19 (Badhwar *et al.*, 1996b) shows measurements of the TEPC. The peak rates during passes through the South Atlantic Anomaly (SAA) were approximately $1.0 \times 10^{-4}$ Gy $min^{-1}$. Typical transit times for each of six orbits per day which pass through the SAA are about 15 min. Thus, maximum dose rates are substantially less than the "high-dose rate" regime of 0.1 Sv $h^{-1}$ or greater.

Figure 20 shows maximum crew exposure rates, measured using thermoluminescent dosimeters (TLD), on low-inclination (28.5 degrees) Space Shuttle missions as a function of altitude. Absorbed dose rates range between $5 \times 10^{-5}$ Gy $d^{-1}$ and $2 \times 10^{-3}$ Gy $d^{-1}$. The mean quality factor was approximately 1.8. Thus, equivalent dose rates were between $1 \times 10^{-4}$ Sv $d^{-1}$ and $4 \times 10^{-3}$ Sv $d^{-1}$. Since the TLD were worn on the clothing of the crews, these exposures correspond to skin doses.

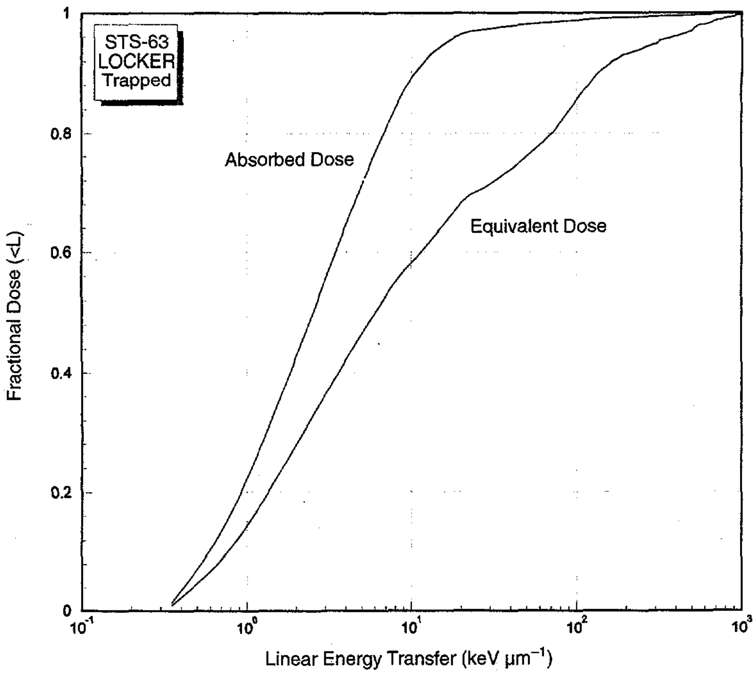


**Fig. 13.** Fraction of trapped belt radiation absorbed dose and equivalent dose versus LET.

## *2. High Inclination Space Shuttle Missions*

Figure 21 shows maximum crew exposures measured by TLD during high-inclination (49.5 to 61 degrees) Space Shuttle missions as a function of altitude. High-inclination missions have not been flown as high in altitude as low-inclination missions. The highest dose rate measured on a high-inclination flight was about $6 \times 10^{-4}$ Gy $d^{-1}$ on STS-27.

As seen earlier, it is possible to receive an exposure from SPE in high-inclination orbits. Based on Russian measurements made in the Mir Space Station during the October 19-27, 1992, SPE, cumulative doses of a few mSv are possible. The actual amount of radiation that penetrates to the Mir orbit is very difficult to estimate because it depends on the configuration of the interplanetary magnetic field between the sun and Earth. It seems that to obtain a significant SPE exposure in a high-inclination orbit, there must be an accompanying magnetic storm whose shock front significantly compresses the Earth's magnetosphere.

It is clear that high inclination missions do not represent a high-dose rate hazard.

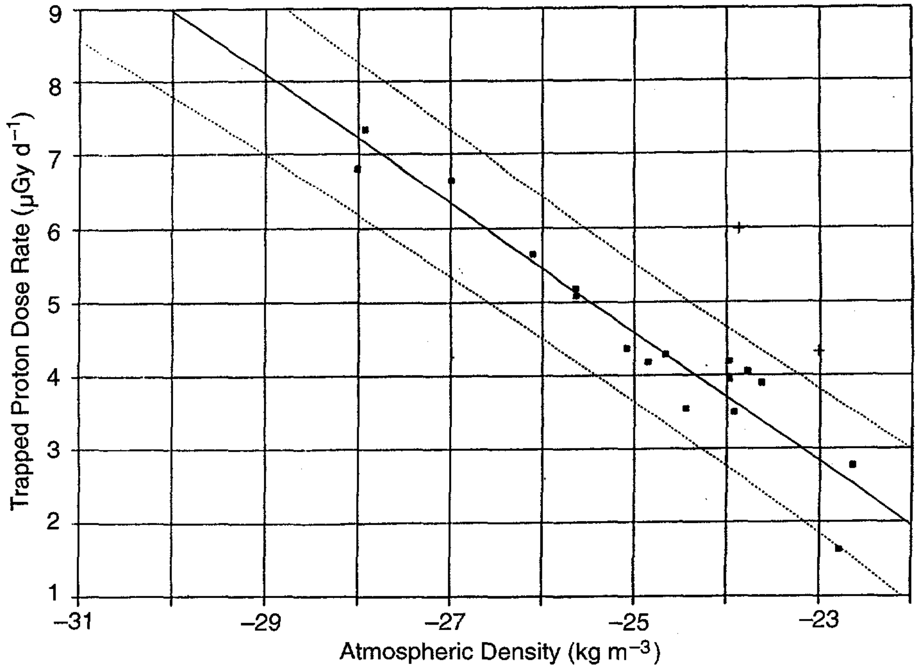


**Fig. 14.** Trapped belt radiation dose rates versus atmospheric density (Golightly *et al.*, 1996). *Solid curve is a least squares fit; dotted curves indicate 90 percent* confidence levels.

## *3. Mir Space Station Missions*

Figure 22 shows the mission integrated (GCR plus trapped-belt proton) LET spectrum inside the core module obtained using the TEPC on the 115 d Mir-18 mission. Results of plastic nuclear track detectors (PNTD) are shown for comparison. The sensitivity of PNTD is diminished at lower LET.

Figure 23 shows calculations of skin and BFO equivalent dose rates as a function of altitude inside the Mir Space Station, using the AP-8 trapped belt model to obtain the relative altitude dependence. Uncertainties in the model data have been minimized by normalizing the calculations to measurements made on the Mir-18 mission at 400 km. At the maximum altitude of the International Space Station (470 km) the BFO equivalent dose rate is approximately $1.5 \times 10^{-3}$ Sv $d^{-1}$. For a *1 y mission,* an astronaut would receive a *total BFO equivalent dose of 0.55 Sv.* Indeed, a few Russian cosmonauts have spent a year or more in the Mir Space Station.

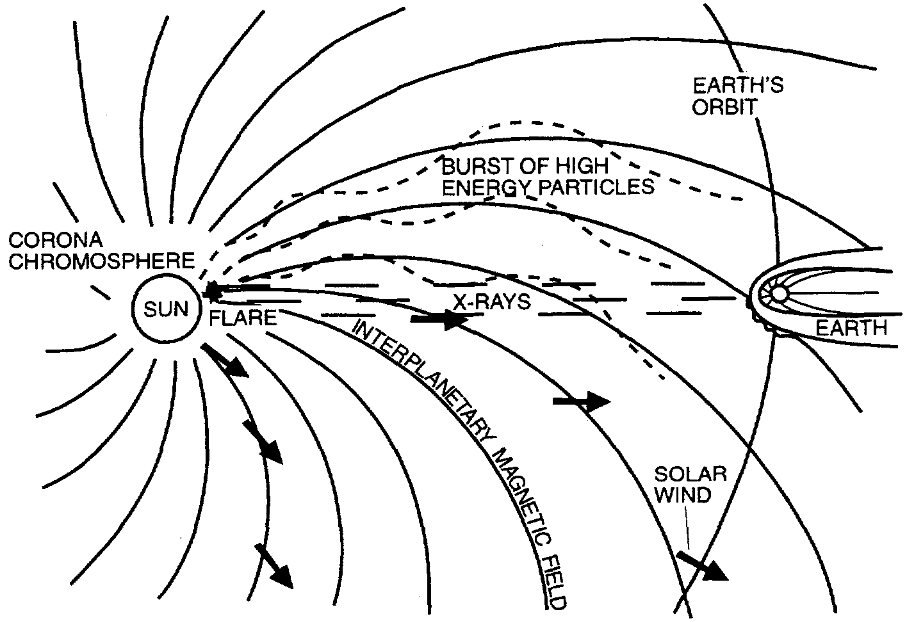


**Fig. 15.** Illustration of sun's magnetic field lines which are ordered by the solar wind in interplanetary space. Protons accelerated at solar surface travel along field-line tubes, sometimes to the vicinity of Earth (Smart, 1988).

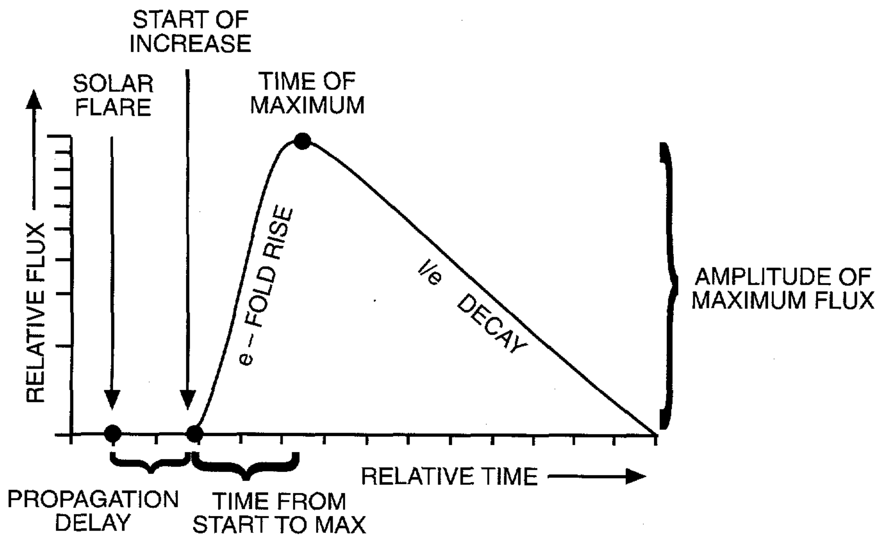


**Fig. 16.** General characteristics of SPE flux versus time (Smart, 1988).

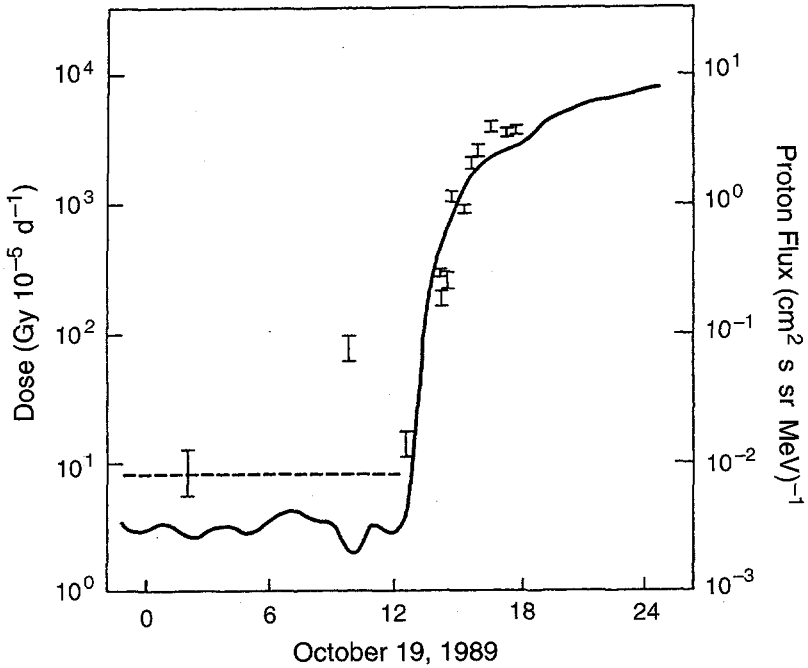


**Fig. 17.** Measurements by Russian ion chamber (solid line) and NOAA GOES satellite spectrometer during onset of protons from the October 1989 SPE (Lobakov *et al.*, 1992).

An average quality factor of 2.7 has been calculated, using the ICRP (1977) relationship versus LET and measurements of the TEPC on Mir-18.

TLD measurements at six locations inside the Mir Space Station yielded absorbed doses ranging between $3.1 \times 10^{-4}$ and $5.9 \times 10^{-4}$ Gy $d^{-1}$. The range of values is indicative of effects of the different shielding at the various locations. Using an average quality factor of 2.7, equivalent dose rates are between $8.4 \times 10^{-4}$ and $1.6 \times 10^{-3}$ Sv $d^{-1}$. For the 115 d mission, total exposures at these locations ranged between 0.096 and 0.18 Sv. Since these were bare dosimeter measurements, they correspond more closely to skin doses. (The TLD doses are not corrected for a 20 percent error due to decreased sensitivity at high-LET.) The absorbed dose and equivalent dose rates measured by TEPC inside the more heavily shielded core cabin of the Mir-18 mission were $3.0 \times 10^{-4}$ Gy $d^{-1}$ and $7.8 \times 10^{-4}$ Sv $d^{-1}$, respectively.

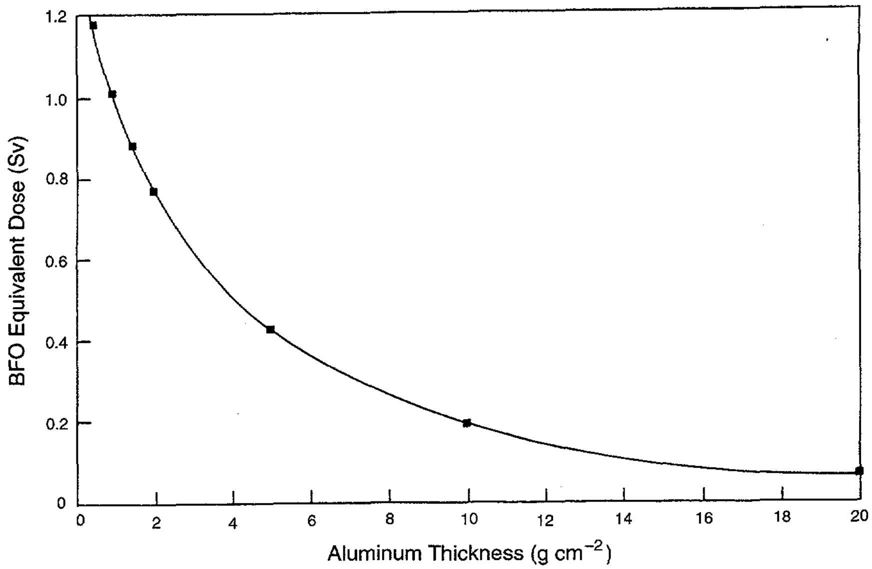


**Fig. 18.** Effectiveness of shielding in reducing BFO equivalent dose from October 1989 SPE (Simonsen *et al.*, 1991).

While missions to the Mir Space Station do not represent a high-dose rate hazard, it is clear that missions of 60 to 100 d duration could produce exposures in the high-dose regime.

## *4. International Space Station Missions*

It is impossible to accurately estimate the expected crew exposures for the International Space Station because final shielding is not known for locations inside the various modules. In many cases the bulk of shielding will be provided by rack-mounted equipment and stowed supplies. The latest estimates of space station exposures by the NASA Johnson Space Center's Space Radiation Group are given in Table 1. The space station can be flown at a lower altitude near solar minimum, thereby reducing the exposure. Near solar maximum the drag becomes greater and more time must be spent at higher altitudes.

It should be noted that extravehicular activity (EVA) to construct and maintain the International Space Station will be extensive. The cumulative EVA time for the Gemini, Apollo, Skylab and Space Shuttle programs has been approximately 50 h. It is estimated that the total EVA time to construct the International Space Station could be as large as 400 h. This, of course, will be a task shared by more than 20 astronauts. To limit exposures during EVA, there is a flight rule that limits EVAs to orbits

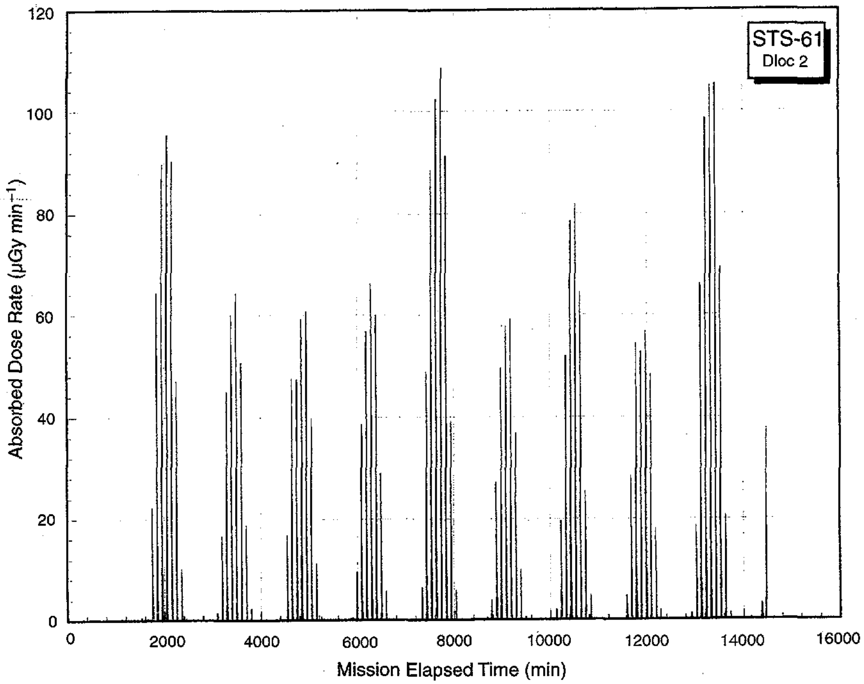


**Fig. 19.** Absorbed dose rates measured in Space Shuttle mid-deck during passes through SAA of trapped belts for low inclination (28.5°) orbit of STS-61 (Badhwar *et al.*, 1996b).

which do not pass through the SAA. Another factor that makes it difficult to estimate EVA exposures is knowledge of where such activities will take place, not just geographically, but whether the astronaut will be shielded to any extent from the anisotropic trapped belt fluxes. If an astronaut is protected by as little as 1 g $cm^{-2}$ of shielding by a space suit, the exposure will *not* be substantially greater than at a lightly shielded location inside the space station. It can be assumed that EVA exposures will be managed by operational procedures that carefully account for individual astronaut career exposures, among other things.

While dose rates estimated for the International Space Station are not in the high-dose rate regime, total exposures for mission durations greater than five months can exceed the high-dose regime.

## *5. Interplanetary (Moon and Mars) Missions*

Interplanetary missions are exposed to two principal sources of radiation, GCR and SPE. Exposures will depend strongly on the length of the mission, the period in the solar cycle in which it is carried out, and other

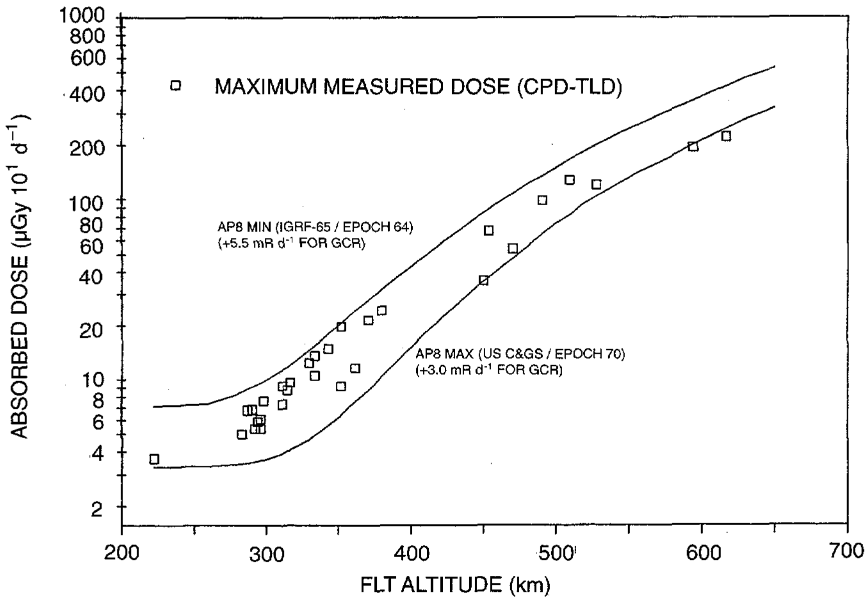


**Fig. 20.** Maximum measured crew absorbed dose rates during low inclination orbits of Space Shuttle missions as a function of altitude. The solid lines are from calculations using the AP-8 model for solar maximum and solar minimum (Hardy, A.C., 1996, private communication).

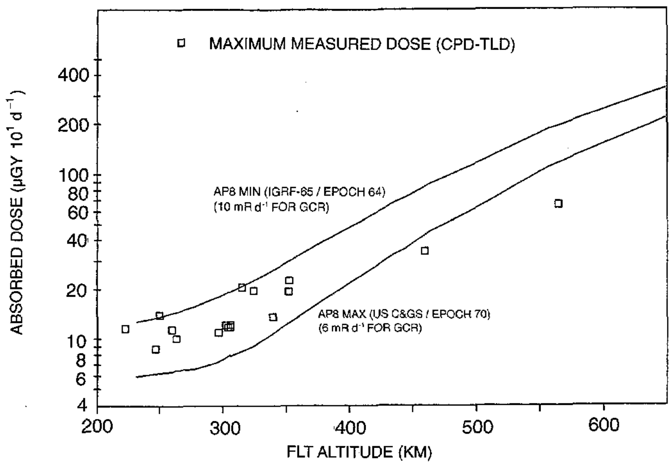


**Fig. 21.** Maximum measured crew absorbed dose rates during high inclination orbits of Space Shuttle missions as a function of altitude. The solid lines are from calculations using the AP-8 model for solar maximum and solar minimum (Hardy, A.C., 1996, private communication).

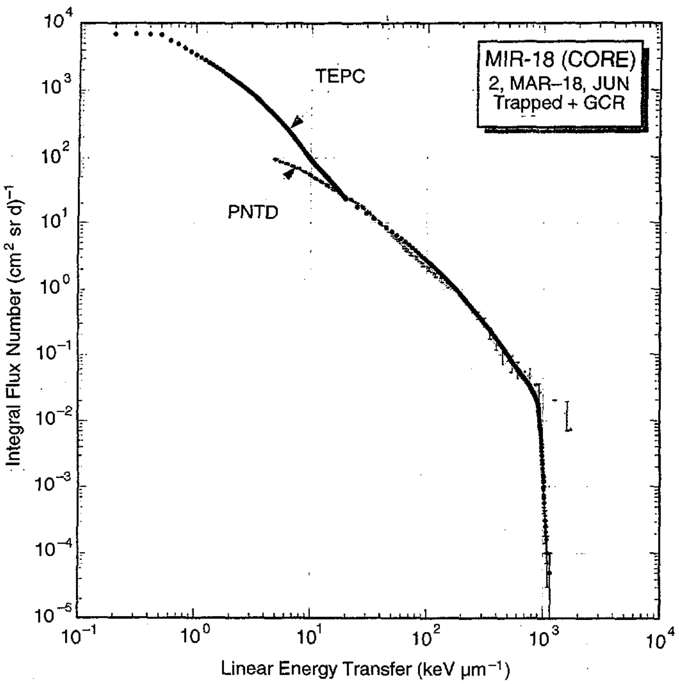


**Fig. 22.** Integrated (GCR and trapped belt) LET spectrum measured during 115 d Mir-18 mission. Measurements of TEPC and PNTD are compared.

particulars of the mission that define both shielding protection and operational procedures.

It can be assumed that interplanetary spacecraft will not be unlike human spacecraft that have been flown in the past, as far as the shielding protection which they afford. Assuming a spacecraft with an average shielding thickness of 10 g $cm^{-2}$, the GCR 5 cm water equivalent dose rates will range from 0.15 Sv $y^{-1}$ at solar maximum to 0.58 Sv $y^{-1}$ at solar minimum.

Likewise, SPE exposures for an interplanetary mission can vary from zero to as much as 0.3 Sv per event, assuming that effective operational procedures are employed. A Mars mission will require on the order of 3 y. Thus, maximum total mission exposures for a Mars mission might exceed 2 Sv.

SPE that occur during interplanetary missions have the capability of exposing astronauts to the high-dose rate regime. However, with good operational procedures and even a simple warning system, it should be possible to reduce SPE hazards so that such exposures are avoided. It

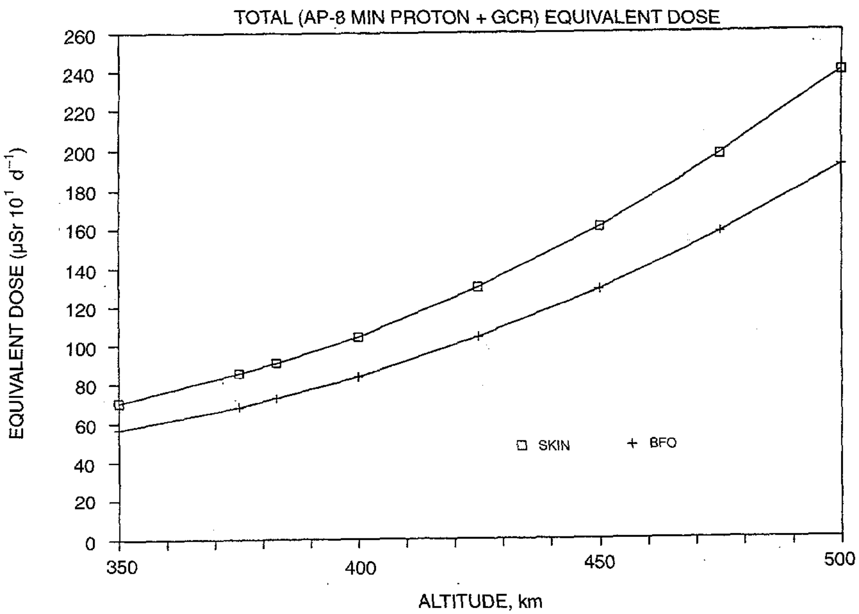


**Fig. 23.** Mir crew dose equivalent rates versus altitude. Skin and BFO rates calculated using the AP-8 trapped belt model, normalized to measurements obtained during Mir-18 mission at 400 km.

Table 1—*Expected BFO dose levels in the International Space Station.*

| Altitude | Solar Minimum<br>370 km<br>(Sv/month) | Solar Maximum<br>500 km<br>(Sv/month) |
|---|---|---|
| End node location | $8 \times 10^{-3}$ | 0.023 |
| Habitation module | $6 \times 10^{-3}$ | 0.017 |

seems, however, that at present, it will be impossible to reduce total mission exposures on an interplanetary mission below the high-dose regime. In a paper Dr. John Garrick (1996) will present later in this program, additional information will be given on operational procedures.

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# Biology Relevant to Space Radiation

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## Abstract

There are only very limited data on the health effects to humans from the two major components of the radiations in space, namely protons and heavy ions. As a result, predictions of the accompanying effects must be based either on (1) data generated through studies of experimental systems exposed on earth at rates and fluences higher than those in space, or (2) extrapolations from studies of gamma and x rays. Better information is needed about the doses, dose rates, and the energy and LET spectra of the radiations at the organ level that are anticipated to be encountered during extended space missions. In particular, there is a need for better estimates of the relationship between radiation quality and biological effects. In the case of deterministic effects, it is the threshold that is important. The possibility of the occurrence of a large solar particle event (SPE) requires that such effects be considered during extended space missions. Analyses suggest, however, that it is feasible to provide sufficient shielding so as to reduce such effects to acceptable levels, particularly if the dose rates can be limited. If these analyses prove correct, the primary biological risks will be the stochastic effects (latent cancer induction). The contribution of one large SPE to the risk of stochastic effects while undesirable will not be large in comparison to the potential total dose on a mission of long duration.

## Introduction

The biological effects of the ionizing radiations to which the general and working populations on earth are exposed are becoming known with an increasing degree of detail. This knowledge is the basis of the estimates of risk (NCRP, 1993a; UNSCEAR, 1993) that, in turn, foster a comprehensive and evolving radiation protection system (ICRP, 1991; NCRP, 1993b).

This substantial body of information has been, and is being, applied to questions about the biological effects of radiation in space and the associated risk estimates.

The purpose of this paper is not to recount all the biological effects of radiation but to concentrate on those that may occur as a result of exposures encountered in space. In general, the biological effects of radiations in space are the same as those on earth. However, the evidence that the effects on certain tissues by the heaviest-charged particles can be interpreted on the basis of our knowledge about other high-LET radiation is equivocal. This specific question will be discussed in greater detail later.

It is important to point out that there are only very limited data of the effects on humans of two components of the radiations in space, namely protons and heavy ions. Thus, the predictions of effects on the crews in space are all based either on: (1) experimental systems exposed on earth at rates and fluences that are higher than those encountered in space or (2) the effects of gamma or x rays with estimates of the equivalent doses using quality factors.

## Factors That Influence the Biological Effects

Dr. Robbins has described the radiation environments and the component types of radiation, in particular protons and their secondaries, as well as the small but important component of galactic cosmic radiations (GCR), namely heavy ions. The characteristics that are important to the understanding of their biological effects and the assessment of the risk are: (1) total doses that may be incurred on particular missions, (2) dose and fluence rates, (3) protraction, and (4) LET, energy, and track structure of the particles.

## Total Dose

The factors that influence the total equivalent dose during missions in low-earth orbit are: (1) duration, (2) altitude, (3) orbital inclination, and (4) shielding. In the case of deep space missions, the radiation from sporadic solar particle events (SPE) must also be taken into account.

The total doses incurred on the United States' space missions have been low because, with the exception of Skylab, the durations of the missions have been short. In contrast, the exposure during a 3 y interplanetary mission could result in the accrual at a low-dose rate of an equivalent dose of about 1 Sv which is in excess of the limit recommended by the

NCRP for the working lifetime of a radiation worker on earth. Both altitude and orbital inclination influence the amount and quality of the radiation, and shielding becomes increasingly important with the duration of the mission.

## Biological Effects of Concern

In the context of this symposium, the biological effects of concern are those that pose a risk as a result of exposure to the radiation environments in space. The effects of concern for the adventurers in space are considered under two categories, deterministic effects and stochastic effects. Radiation protection limits for terrestrial radiation workers are set at levels to prevent the occurrence of deterministic effects and to limit stochastic effects to what is considered an "acceptable" level. The selection of what is acceptable, is, of course, the subject of this symposium.

In the case of deterministic effects, it is the threshold dose that is important. For radiation protection purposes, threshold doses are those below which any effects that occur are either not easily detectable or are not of clinical significance. Threshold doses are significantly higher for most all deterministic effects if the exposure is protracted, a possible exception being effects on the testes. For example, the equivalent dose limit recommended for protection against deterministic effects for exposures in low-earth orbit over a 1 y period was 0.5 Sv (NCRP, 1989) which translates into an equivalent dose rate of $9 \times 10^{-7}$ Sv $min^{-1}$. The effects of an equivalent dose of this magnitude at this low-dose rate are much less than they would be at a high-dose rate.

Acute deterministic effects, such as those on the bone marrow and those on the gastrointestinal tract (resulting in nausea and vomiting), will not occur in either low-earth orbit or as a result of the ambient radiation in deep space. It is in the case of a large SPE that the possibility of acute effects must be considered. The total dose, but particularly the dose and fluence rates, determine the probability of the occurrence of acute deterministic effects.

## Dose and Fluence Rates

The equivalent dose rates that will be experienced in low-earth orbit, while higher than on earth, are low. The highest rates are during the traversal of the South Atlantic Anomaly in which the dose rate of proton irradiation may reach about 0.002 mGy $min^{-1}$ at an altitude below 300 km. Integrated over a day the equivalent dose rate could be about 0.23 mSv, whereas, at greater than 600 km, the daily rate could be about 1.6 mGy (Badhwar *et al.*, 1992).

The dose rate of the protons and the fluence rates of heavy ions in deep space are also at low-dose rates. The definition of low-dose rate has varied with time as can be seen from Table 1. There is a considerable diversity of opinion in what is a low-dose rate. This is, in part, because the committees opining on the question were considering different aspects. In Figure 1, one can see that, in the case of survival of clonogenic cells in the gut, there is a marked reduction in the cell killing at a dose rate of 7.2 Gy $d^{-1}$. The results of *in vitro* studies suggest the maximal effect of reducing the dose rate is reached at about 5.2 Gy $d^{-1}$ (Bedford and Mitchell, 1973).However, in the case of life shortening, with exposures at low-dose rates at which the cause of life shortening is considered to be excess mortality from tumors, the dose rate at which the effect becomes dose-rate independent (slope 1 on the log-log scale for mortality rate as a function of radiation dose rate) is about 0.2 Gy $d^{-1}$ or 73 Gy $y^{-1}$. Based on this result, the UNSCEAR (1993) choice of 0.1 mGy $min^{-1}$ or about 53 Gy $y^{-1}$ seems reasonable when stochastic effects are being considered. The unanswered, but very important, question is what should be the dose-rate effectiveness factor applied at such dose rates for purposes of radiation protection. ICRP (1991) chose a factor of two for stochastic effects but did not select a factor for deterministic effects.

The effect of dose rate is, of course, important in estimating the risks of both stochastic and deterministic effects. In low-earth orbit all radiations are at a low-dose rate. In deep space the only occasion in which a potential exists for exposure at a high-dose rate is at the peak of a very large SPE. The radiation in an SPE is almost entirely composed of protons which vary greatly in energy. It is assumed that the biological effects of protons are reduced at low-dose rates to a similar degree as that found for gamma rays.

Table 1—*What is a low dose rate?*

| | |
|---|---|
| NCRP (1980) | 0.05 Gy $y^{-1}$ |
| ICRP (1991) | 0.1 Gy $h^{-1}$ (876 Gy $y^{-1}$) |
| UNSCEAR (1993) | 0.1 mGy $min^{-1}$ (52.56 Gy $y^{-1}$) |

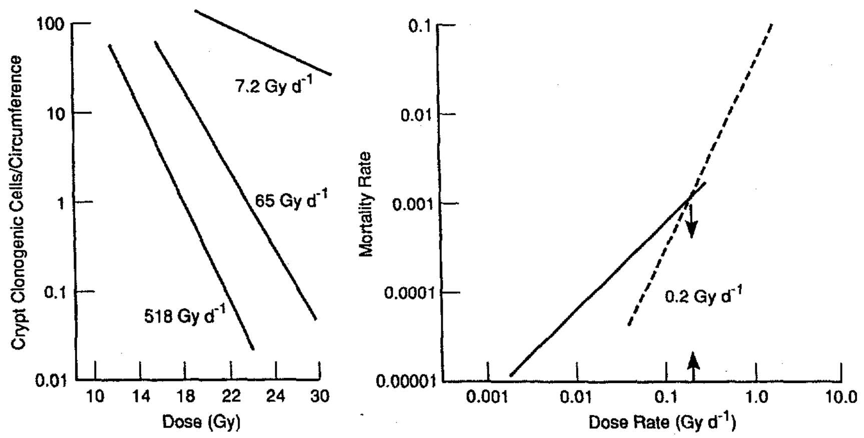


**Fig. 1.** Left-hand panel. *Clonogenic cells in the crypts of liberation in the small* intestine per circumference of histological cross sections of the gut as a function of dose at 7.2 Gy $d^{-1}$, 65 Gy $d^{-1}$ and 518 Gy $d^{-1}$ (Fu and Phillips, 1975).

Right-hand panel. Mortality rate of mice as a function of daily (10 to 11 h) dose rate on a log-log plot. The arrow indicates the approximate dose rate below which the life shortening becomes independent of dose rate and is dependent on total dose. This is the interpretation of the change from a slope = 1 to that of 2 at the higher dose rates (Sacher and Grahn, 1964).

On long-duration missions, not only will the dose rates be low, but the irradiation will be protracted over long periods, and the total dose becomes a prime consideration (Carnes and Fritz, 1991). The influence of total dose has been seen in the survival of cells *in vitro* (Bedford and Mitchell, 1973) and in the induction of thymic lymphoma (Ullrich and Storer, 1979). In both cases the effect increased when a specific dose was reached.

It is not known what the maximum dose rate could be in the most intense particle events that might occur on a 3 y mission to Mars. The analysis of Simonsen *et al.* (1991), based on the SPE in October 1989 (Figure 2), suggests that with 10.0 g $cm^{-2}$ of shielding the peak dose rate could have reached about 0.4 Sv $d^{-1}$, but for less than a day These results suggest that even in the case of a very large SPE it is feasible to provide sufficient shielding such that the dose rates in a space vehicle will be low in terms of deterministic effects. Many of the predictions of the severity of the effects of SPEs appear to have been based on the assumption that the exposures would be at a high-dose rate. As a result they have over-estimated the risk of acute effects. However, better estimates of both the total doses and the dose rates that might be experienced in the worst-case SPE are needed. Similarly, better estimates of the effects of dose

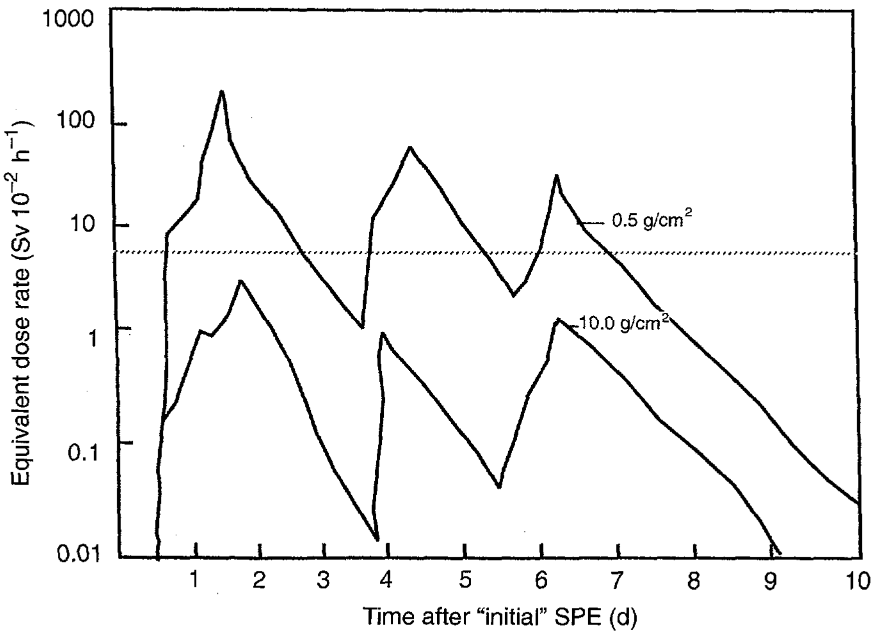


**Fig. 2.** The equivalent dose rate is shown as a function of time after the onset of the SPE that occurred in October 1989 assuming a shielding of 0.5 and 10.0 g $cm^{-2}$ of aluminum (Simonsen *et al.*, 1991).

rate on the relevant biological effects, such as damage to skin, gut, and marrow, should be obtained.

The contribution of one large SPE to the risk of stochastic effects, while undesirable, will not be large in comparison to the potential total dose on a mission of long duration.

## The Relationship of Radiation Quality and Biological Effects

The assessment of the biological effects of the radiation environment in deep space is complicated by the complexity of the types of radiation. Both the spectra of energies and of LETs are very much broader than in the terrestrial radiation environment. Biological effects are dependent on the energy, LET, and track structure of the radiation involved.

It is a tenet of radiobiology, at least as it is applied to radiation protection, that the effects of different types of radiation are qualitatively alike and only quantitatively different. This is assumed to hold for both deterministic and stochastic effects. However, there are a number of significant differences between the effects of high-LET radiations and other types of radiation. These differences become marked when heavy-charged particles with LETs of the order of about 30 keV $\mu m^{-1}$ and higher are considered. That the residual damage to DNA is different with very high-LET radiations, such as alpha particles or iron ions compared to gamma rays, is not surprising when the density of ionization is considered (Figure 3). Not only is the spectrum of DNA lesions, which is so important in determining the occurrence and nature of chromosome aberrations and mutation different (Ward, 1994; Rydberg *et al.*, 1994), but the ability to repair efficiently and without error also changes with LET (Ritter *et al.*, 1977). As can be seen in Figure 4, although the RBEs for DNA double-strand breaks decrease with LET, the RBE for cell inactivation increases (Rydberg *et al.*, 1994). The explanation appears to lie in the fact that the

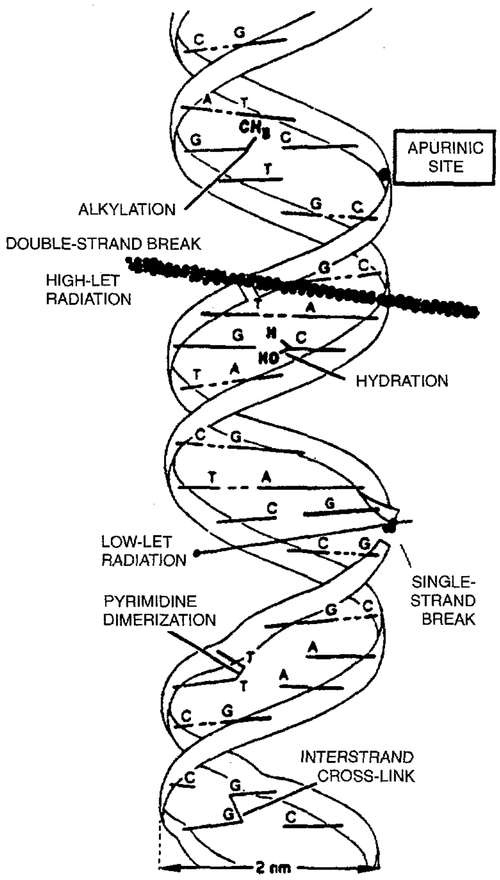


**Fig. 3.** Schematic of DNA showing the ionization density for high-LET radiation (dense) and low-LET radiation (sparse) and the possible types of damage that radiation can induce.

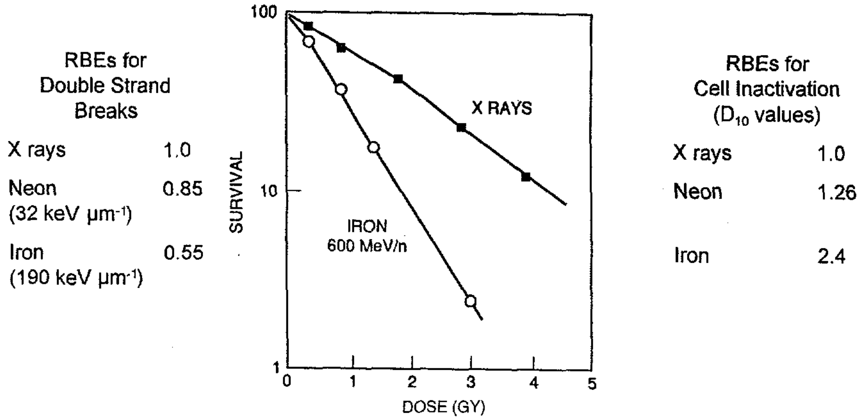


**Fig. 4.** Cell inactivation of human fibroblasts as a function of the dose of x rays and 600 MeV $u^{-1}$ iron ions. The RBEs for DNA double-strand breaks and inactivation for x rays, neon ions, and iron ions are also shown (data from Rydberg *et al.*, 1994).

clustering of DNA damage, which increases with LET, results in an increase in the time required for repair and in the frequency of errors in the repair.

The relative frequencies of different types of DNA damage and of different types of mutation are LET-dependent. However, apart from the identification of a specific mutation in *p53* induced by UV radiation (Brash *et al.*, 1991), specific mutations induced by radiation have not been identified unequivocally. The search for signature lesions continues.

The RBE for cell inactivation *in vitro* and for deterministic effects *in vivo* involving cell killing increases with LET reaching a peak of about two at about 100 keV $\mu m^{-1}$ (Figure 5 ). In proliferative tissues the loss of proliferative capacity explains the relationship of LET to RBE. In the case of tissues with a large population of cells that do not divide, such as the central nervous system (CNS), acute effects should be minimal with low doses of protons, unless interphase death is more frequent than currently assumed. Since the dose rate of the protracted exposures to protons either in low-earth orbit or in deep space is low, the deterministic effects with the total doses that are envisaged should not be a limiting factor.

In the case of heavy ions, there is much less known about the risk of either acute or late effects. Since the fluence rates are low, in particular for the particles of the higher Zs and higher energies, acute deterministic effects will not occur. Late deterministic effects may be another matter. Questions that need to be answered include: (1) will there be a significant

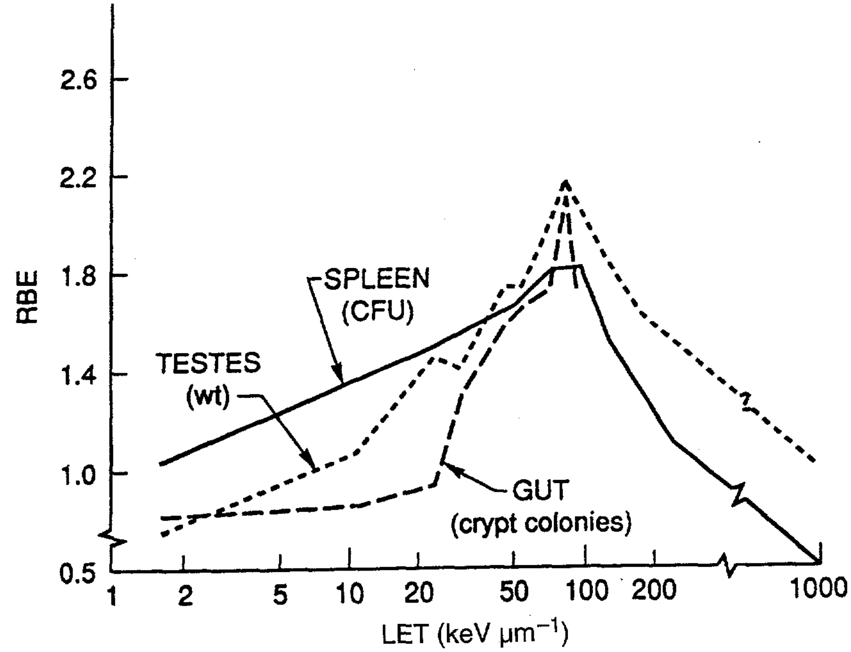


**Fig. 5.** The RBE for inactivation of (1) the clonogenic cells in the testis of the mouse, as indicated by loss of weight, (2) the clonogenic cells in the crypts of the small intestine of the mouse and (3) the colony-forming units in the spleen (CFU-S) of the mouse as a function of LET keV $\mu m^{-1}$ (redrawn from Ainsworth, 1986).

level of residual damage resulting in an age-related loss of neurons and (2) does the nature of the particle track, with a distribution of energy deposition quite distinct from that of other types of radiation (Figure 6 ), determine the occurrence and severity of late occurring effects? Little is known of the late effects on the CNS, but results suggest that late breakdown of DNA may occur (Williams and Lett, 1994; 1996). Results also suggest that heavy ions can cause neurochemical changes and alterations in behavior at relatively low doses (Rabin *et al.*, 1994).

## Protons and High-Z and High-Energy Particles

### *Deterministic Effects*

The available data for RBE values for protons, while restricted to energies of 200 MeV and less, does cover DNA damage, mutations, tumor induction, and deterministic effects on tissues in animals based on laboratory

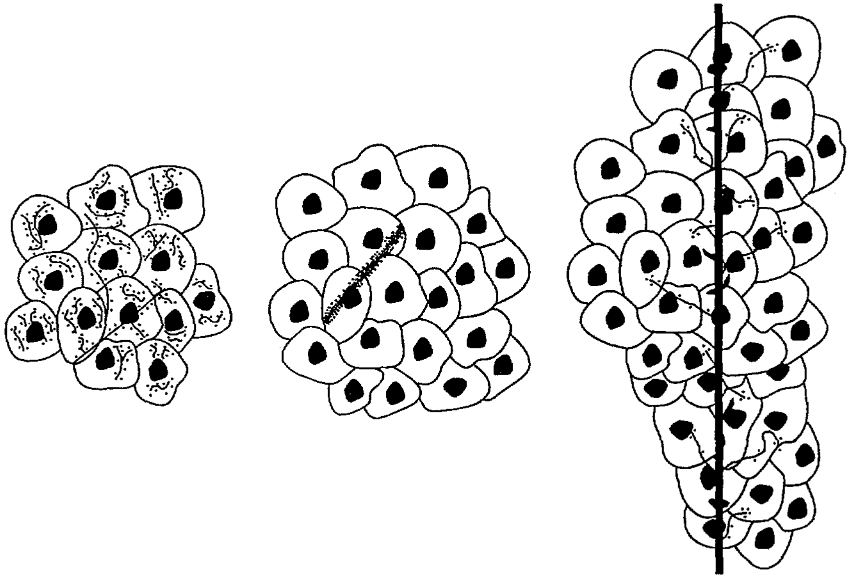


**Fig. 6.** Schematic to illustrate the difference in the deposition of energy at the tissue level between a low dose of low-LET radiation and two types of high-LET radiation, 1 MeV neutron, and an iron particle.

studies. The data indicate that the RBEs are close to one relative to gamma rays. The experience with radiotherapy with protons suggests that an RBE of about one is reasonable for acute effects on normal human tissues. This means that the probability of risk of deterministic effects of protons can probably be based on the data for such effects caused by gamma rays.

There are two effects that may occur with accrual of sufficient exposures to proton radiation, namely, effects on fertility and cataract induction. In contrast to other biological effects, protraction of the exposure does not reduce and may increase the effect on fertility in the male. Temporary reduction of the production of sperm can occur with relatively low doses (Figure 7), and with increasing doses the time required for recovery increases (see Meistrich and van Beek, 1990). The best estimates of the risk of sterility in women are shown in Table 2 . It should be noted that the estimates are based on fractionated doses for radiotherapy and may overestimate the effects of protracted low-dose rate exposures.

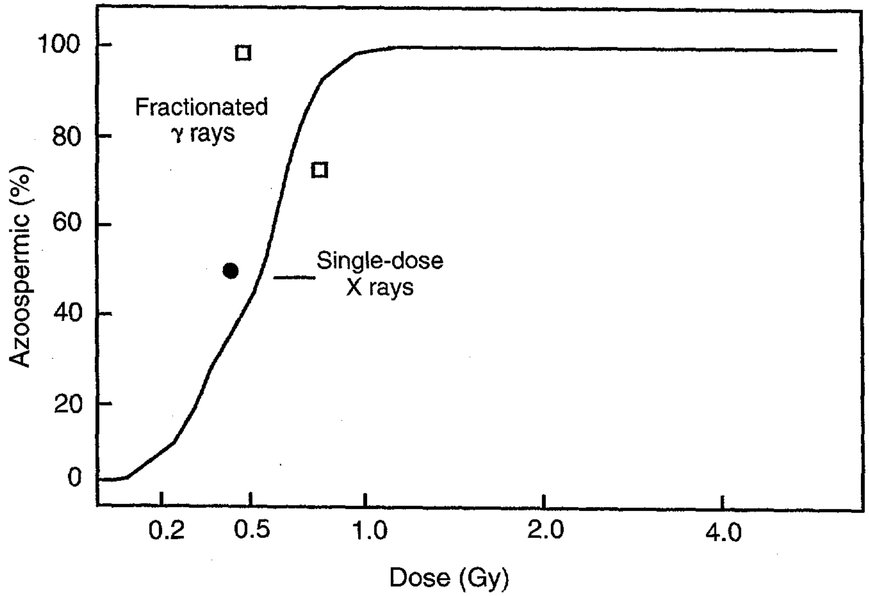


**Fig. 7.** The percentage azoospermia in men as a function of a single dose of x rays, ●; and and fractionated gamma rays, □ (data from Meistrich and van Beek, 1990).

Table 2—*Total doses that cause permanent sterility in women with multiple exposures (from Ash, 1980; Damewood and Grochow, 1986)*

| Dose (Sv) | 15 to 40 y of Age | Over 40 y of Age |
|---|---|---|
| 0.6 | "No effect" | "No effect" |
| 1.5 | "No effect" in most women | Some risk of sterilization |
| 2.5 to 5.0 | About 60% permanently sterilized | — |
| >8.0 | Nearly 100% permanently sterilized | — |

Cataract induction in humans has been studied in both radiotherapy patients (Merriam and Focht, 1957; Merriam *et al.*, 1972) and atomic-bomb survivors (Otake and Schull, 1990). Assuming that the influence of fractionation and dose rate on the effects of proton radiation is comparable to that of gamma rays, the cataractogenic dose would be 4 Sv or more. Studies on monkeys exposed to single doses of protons (Lett *et al.*, 1991) suggest that doses below 2 Gy do not induce cataracts that would limit vision significantly. Since there are no data for cataract induction in humans by heavy ions, risk estimates must be extrapolated from animal studies. High RBE values have been reported for neutrons (Otake and Schull, 1991; Worgul *et al.*, 1996). In the case of heavy ions, Merriam *et al.* (1984) reported an RBE of 40 at 0.05 Gy for $^{40}Ar$ ions, and Brenner *et al.* (1991) suggest from their analysis of these data that a quality factor of 50 would be more appropriate than 20 for heavy ions. Subsequent data for the effect of iron ions substantiate the high RBE at a dose of 0.01 Gy (Brenner *et al.*, 1993). Unfortunately no estimates of the number of cells traversed by such a low fluence are given. Clearly the number of potentially abnormal fibres must be low.

There is some risk of some degree of lens opacification occurring as the result of the exposure that could occur on a Mars mission. However, the lesion would probably not interfere with vision significantly much before age-related cataracts are likely to occur.

### *Stochastic Effects*

The effectiveness of protons in the induction of cancer in humans is not known, but based on data from monkeys (Wood, 1991), rats (Burns *et al.*, 1975; 1989), and mice (Clapp *et al.*, 1974), it is reasonable to assume that risk estimates for gamma irradiation can be applied. Therefore, risk estimates based on the data from atomic-bomb survivors adjusted with an appropriate dose-rate effectiveness factor are considered applicable. In the case of heavy ions, the problem of estimating the probability of cancer induction is more complex. Not only are there no data for the induction of cancer in humans by any heavy ion, there are data from laboratory studies for only one animal system (Alpen *et al.*, 1994).

To use the cancer induction data obtained from populations exposed to low-LET, radiation quality factors ($Q$) for the spectrum of heavy-charged particles must be applied. Theoretically, an average Q can be obtained by integration of the relationship of Q to LET. In 1990, ICRP modified this relationship from that recommended in 1977 (see Figure 8 ). The three important changes were: (1) the value for $Q$ increased somewhat more steeply, reaching a maximum of 30 (as compared to 20 in the 1977 version), (2) the maximum value for $Q$ was reached at an LET value somewhat less than the 100 keV $\mu m^{-1}$ in 1977), and (3) the value for Q descended from its peak to a value of about 10 for an LET of 1,000 keV $\mu m^{-1}$ (in contrast to the curve proposed in 1977 which showed $Q$ values reaching a plateau of 20 for LET values in excess of about 100 keV $\mu m^{-1}$). This latter part of the curve is described by the expression 300 $L^{-0.5}$ where L is the LET of the radiation expressed in keV $\mu m^{-1}$.

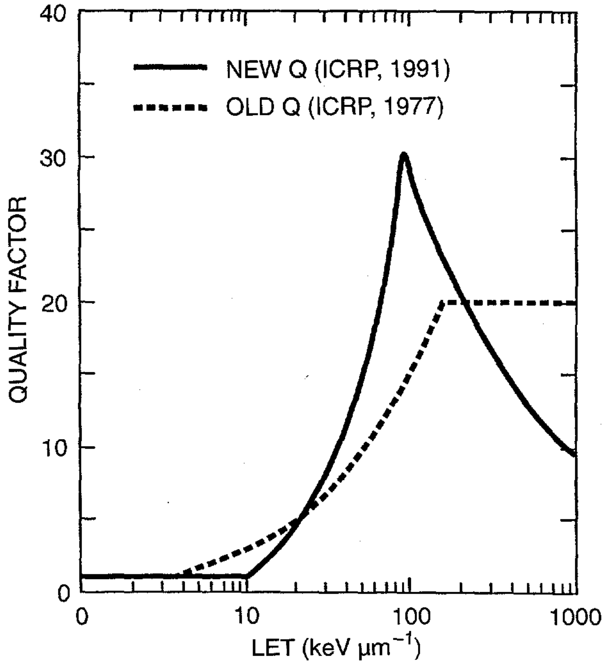


**Fig. 8.** Quality factor as a function of LET (keV $\mu m^{-1}$) proposed by ICRP in 1977 and 1991 (Sinclair, 1996).

The only data that address the questions of the Q-L relationship for radiations >100 keV $\mu m^{-1}$ are those for the induction of tumors of the Harderian gland (Figures 9 and 10). It can be seen that the effectiveness in this case increases when the prevalence of tumors is plotted as a function of LET or fluence, reaching a maximum of about 30 at about 100 keV $\mu m^{-1}$ (Figure 9 ) and a fluence between $5 \times 10^{-2}$ to $1 \times 10^{-2}$ particles $\mu m^{-2}$. There is no evidence, as yet, in this tumor system that the effectiveness decreases significantly at LETs considerably greater than 100 keV $\mu m^{-1}$. These results are in contrast to the ICRP (1991) *Q*-L relationship. There is a need for data for the induction of tumors in other and more representative tissues.

Whether absorbed dose, quality factor, and equivalent dose are the appropriate approach has been called into question (Bond *et al.*, 1985; Zaider and Brenner, 1985). Curtis *et al.* (1992; 1995) suggested using risk cross sections for estimating the risk of cancer induction by galactic cosmic rays. The risk cross section is defined as the probability per unit fluence of a particle of a particular type and energy, or LET, to induce a specific cancer. Figure 10 illustrates the types of data that are required.

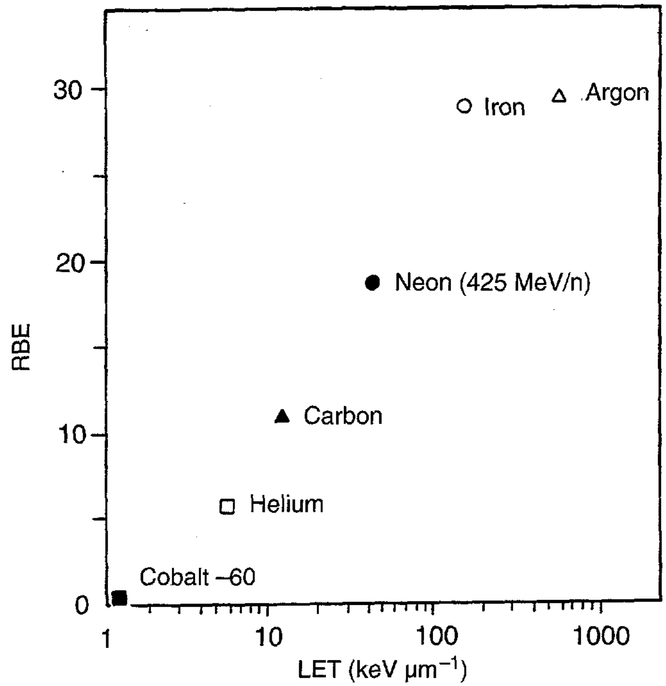


**Fig. 9.** RBE as a function of LET (keV $\mu m^{-1}$) for induction of Harderian gland tumors in mice (data from Alpen *et al.*, 1994; Fry *et al.*, 1985).

Since risk cross sections for different types of radiation are not yet known for representative types of cancer, quality factors still have to be used.

## Conclusion

On missions of long duration in both low-earth orbit and deep space, acute effects are not of concern with the exception of exposures to astronauts who are not protected by shielding of the space vehicle or shielding on, say, the surface of the moon. Warning systems, mission management, and shielding should preclude the likelihood of what has been termed a "show stopper" event. Estimates of the danger that large SPEs pose do not appear to have taken into account the dose-rate effect. However, better information about the dose, dose rate, and the energy and LET spectra of the radiation at the organ level is required for planning the necessary shielding.

Estimates of the late effects can be made, but the uncertainties are high because of lack of knowledge of both the stochastic and deterministic

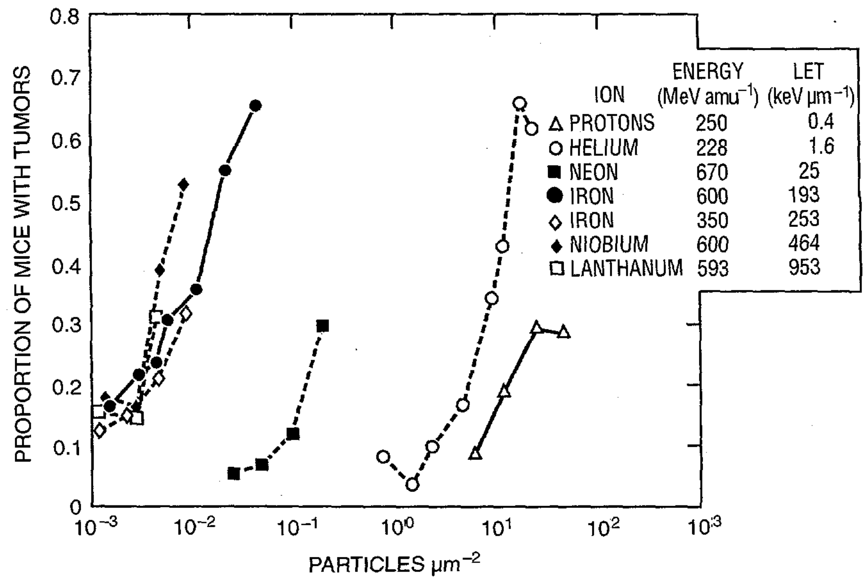


**Fig. 10.** Proportion of mice with Harderian gland tumors as a function of fluence (particles $\mu m^{-2}$). The types of radiation are indicated on the figure (data from Alpen *et al.*, 1994).

effects of heavy ions. Currently, stochastic effects at low-dose rates are considered to be a factor of about two less than at high-dose rate. It is important to establish the difference in the effect of prolonged protraction of exposures from the effect of acute high-dose rate exposure so that a more accurate adjustment for the low-dose rates of space radiation can be made.

The question that is pertinent to the aims of this symposium is, can we determine the risks sufficiently well to address the question of whether the risk is acceptable? The answer is yes, but to do so, some well-directed research is required to determine the effects of heavy ions.

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# History of the Development of Radiation Protection Standards for Space Activities

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NCRP

## Abstract

Initial recommendations for limitations on radiation exposures in space were made in 1970 by the Radiobiological Advisory Panel of the Committee on Space Medicine, National Academy of Sciences/National Research Council (NAS/NRC). Using a risk-based approach and taking into consideration a range of factors, the Panel recommended an overall career limit of 4 Sv. Because it was assumed that only small numbers of people would be involved, most of whom would be in excess of 30 y of age, the question of genetic effects did not appear to be of concern. On the basis of subsequent epidemiological findings, the values of the risk coefficients were increased. As a result of this and other considerations, NASA in the early 1980s asked the NCRP to re-examine both the risks and the philosophy for protecting astronauts. In undertaking this task, the NCRP decided to treat the radiation exposures of crew members and payload specialists as an occupational hazard and to evaluate their risks in terms of those to radiation workers and to workers in other industries. Noting that in the less safe but not the most hazardous occupations, workers had an average lifetime risk of mortality of about three percent, the NCRP concluded that a reasonable career limit for astronauts should be based on a lifetime absolute excess risk of mortality of three percent. Using this as a base, the NCRP recommended a career limit for 25 y olds

of 1 Sv for females and 1.5 Sv for males. Since the risk decreases the older the age at which the exposures begin, the limits culminated with a career limit of 3 Sv for females and 4 Sv for males whose initial exposure occurred at age 55. These recommendations were based on an assumed nominal value of a lifetime risk of fatal cancers for all ages of about $2 \times 10^{-2}$ $Sv^{-1}$. During the period from 1988 to 1993, substantial revisions were made in the estimates of the risks of fatal cancers due to ionizing radiation. As a result, the values for the risk coefficients were increased, once again. For this and other reasons, NASA has requested that the NCRP re-examine the situation. At the present time, the ICRP recommendations for radiation workers on earth would, at the limit, permit a lifetime fatal cancer risk of nearly four percent. The corresponding NCRP limits would permit a risk of about three percent. Thus, in comparison with radiation workers on the ground, it does not appear reasonable to limit astronauts to a lifetime risk of less than about three percent. These features, and perhaps others, will need to be considered by the NCRP before new recommendations on career limits are made.

## Introduction

Radiation standards in space have followed a somewhat different path from that of radiation standards on the ground. Exposures in space were identified to be much higher than natural exposures on earth due to the galactic cosmic radiation, trapped radiation belts near earth and solar particle events (SPE) (Robbins, 1996). Radiation exposures in space are difficult to reduce (as compared with controlling man-made sources on the ground) and impossible to eliminate entirely. Furthermore, other risks to humans of the hostile environment in space may be more acute or drastic than those of radiation. This puts a different perspective on radiation hazards. First, are there likely to be acute radiation effects on humans that could interfere with the accomplishment of a space mission? The answer to this is almost certainly no, although the potential effects of a very large solar flare should be guarded against. In addition, some limitation of organ exposures may be needed to avoid direct deterministic effects. The main radiation hazard in space, nevertheless, is the accumulation of relatively low levels of exposure, perhaps of the order of 100 mSv in a 90 d mission, for example, and the consequent risk of stochastic effects. The stochastic effects at issue will be mainly the induction of cancer. Genetic effects are less likely because most child bearing takes place by the age of 30 and astronauts tend to be older than this when fully trained. Counseling can also limit effects.

To place the development of space radiation standards in context, it is useful to consider the development of radiation protection standards for exposures on the ground.

## Radiation Protection Standards on Earth

Radiation protection standards for workers in radiation related occupations and for the public inadvertently exposed to man-made sources have been well developed over the past 100 y. They have been based on common sense principles of avoiding exposure to ionizing radiation to the extent possible, ensuring that exposures do not exceed threshold levels for acute biological (deterministic) effects and limiting the risk of delayed (or stochastic) effects to reasonable values. Professional bodies such as the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) in the United States have taken the lead in assessing the biological information relevant to radiation protection and providing recommendations for standards for the benefit of radiation users and ultimately for governments to use in framing their regulations.

Today, the controlling factor in the development of these standards is the risk of stochastic effects, namely genetic effects and cancer induction. The assumption is made that at low doses the frequency of the induction of cancer or genetic effects is proportional to the dose. While there is much evidence that this assumption is probably correct, the subject is still controversial mainly because of the statistical problems of observing small effects at very low doses. Quantitatively, the risk of inducing a fatal cancer can be related to the dose and is presently estimated to be about $5 \times 10^{-2}$ $Sv^{-1}$ on average for a population of all ages. The corresponding risk of genetic effects is estimated to be $1 \times 10^{-2}$ $Sv^{-1}$. These two factors provide the main components of the health detriment at low doses which result in the NCRP recommendation that the dose for radiation workers be no more than 50 mSv in a year, and no more than a cumulative total of age (in years) × 10 mSv at any stage of his/her career (NCRP, 1993). For members of the public, the NCRP recommends that the dose be no more than 5 mSv in any 1 y and an average of no more than 1 mSv $y^{-1}$ over a longer period (NCRP, 1993). Additional limitations are recommended on certain individual organ exposures to avoid deterministic effects in these organs.

These limitations result in workers receiving no more than an average of about 2 mSv $y^{-1}$ and the public receiving less than 0.5 mSv on average from man-made sources excluding medical. Both workers and members of the public are exposed to background radiation from cosmic rays, terrestrial gamma rays and internal radionuclides including radon to an average level of about 3 mSv $y^{-1}$ in the United States (NCRP, 1987). An average member of the public receives about another 0.6 mSv $y^{-1}$ from man-made sources including medical sources (NCRP, 1987).

## Early Space Radiation Standards

An early text on some radiation problems of space conquest was published by Wright Langham in 1960 (Langham, 1960) but the first detailed consideration of the biological hazards of radiation in space was in a volume entitled "Radiobiological Factors in Manned Space Flight" which was produced by a panel convened by the National Academy of Sciences and edited by Wright Langham. This volume was issued in 1967 and is a comprehensive treatment summarizing radiobiological knowledge at the time (NAS/NRC, 1967). It did not propose radiation standards specifically but discussed many of the relevant features that must be considered in managing radiation exposures of humans in space.

The concept of the risk of induced cancer and its importance in radiation protection was already becoming well developed (ICRP, 1969; NCRP, 1954) when in 1970 the Radiobiological Advisory Panel of the NAS/NRC, Space Science Board's Committee on Space Medicine was requested to formulate radiation protection guides for use in space. The Panel was well aware that the other risks of leaving earth and traveling in space were substantial and radiation risks were not a paramount concern. (This has since well proven to be the case.) Nevertheless, the principal radiation risk, the delayed effect of induced cancer, would continue for a long time after the astronauts had returned to earth and some of the other more acute hazards had been survived. Thus, a reasonable basis for some guidance needed to be developed. The Panel decided on what they called a reference risk. "It seems reasonable to recommend a primary reference risk that may be used as a point of normalization for plans and operations involving different numbers of personnel, different risk-versus-gain evaluations and different degrees of operational complexity." Continuing these ideas, the Panel (NAS/NRC, 1970) concluded as follows:

> "Specifically, the Panel proposes that *the primary reference risk should correspond to an added probability of radiation-induced neoplasia over a period of about 20 years that is equal to the natural probability for the specific population under consideration.* The Panel is of the opinion that *this added risk is probably low in comparison with the total risk from all sources associated with missions*; however, the Panel expressly wishes to *avoid making the judgment that this*

*degree of added risk is allowable for a given mission or that this added risk is offset by expected gain."*

The Panel then determined from the United States' statistics of that time that the risk of a fatal cancer for males of age 35 to 55 over the 20 y period was about 2.3 percent. Therefore, they stated the dose to cause a doubling of this risk is as follows:

> "Assuming that the risk from radiation induction of leukemia is $1.5 \times 10^{-6}$/rem/year and that the risk from all other neoplasms is the same (total risk = $6 \times 10^{-5}$/rem/20 y), the whole-body exposure required to double the natural risk of neoplastic disease during the age interval from 35 to 55 years would be $2{,}300 \times 10^{-5} \div 6 \times 10^{-5} = 383$ rem. It is proposed, therefore, that *the exposure associated with the primary reference risk (i.e., an additional risk equivalent to the natural risk of death from malignant disease in the U.S. white male population over the 20-year period age 35 to 55) to be taken as a dose-equivalent of 400 rem at the average depth of the bone marrow (5 cm)."*

In addition to this career limit the Panel provided other limits (Table 1) for specific organs which may result from shorter term exposures such as, for example, from an SPE.

Table 1—*Suggested exposure limits and exposure accumulation rate constraints for unit reference risk condition.*[a]

| | | Ancillary Reference Risks | | | |
|---|---|---|---|---|---|
| Constraint | Primary Reference Risk | Bone Marrow (rem at 5 cm) | Skin (rem at 0.1 mm) | Ocular Lens (rem at 3 mm) | Testes (rem at 3 mm) |
| 1 y average daily rate | | 0.2 | 0.6 | 0.3 | 0.1 |
| 30 d maximum | | 25 | 75 | 37 | 13 |
| Quarterly maximum[b] | | 35 | 105 | 52 | 18 |
| Yearly maximum | | 75 | 225 | 112 | 38 |
| Career limit | 400 | 400 | 1,200 | 600 | 200 |

[a]From NAS/NRC, 1970.

[b]May be allowed for two consecutive quarters followed by six months of restriction from further exposure to maintain yearly limit.

These recommendations provided guidance to the National Aeronautics and Space Administration (NASA) for almost 20 y.

## New Space Radiation Standards (1989)

In the interim, risk estimates for cancer induction by radiation were changing as more information became available from studies such as those of the ankylosing spondylitic patients in the United Kingdom and the atomic-bomb survivors in Japan (NAS/NRC, 1972; 1980; UNSCEAR, 1972; 1977). It was first pointed out by Sinclair (1983) that even if the same basic tenet of a reference risk were adopted, risk estimates current in 1982 would require the career limit to be reduced to about 235 rem for chronic exposures (accumulated) or about 94 rem for an acute exposure (Table 2).

Considerations of this kind led NASA, in the early 1980s, to ask the NCRP to re-examine the question of radiation risks in space and to make recommendations on a suitable approach to career limits. The NCRP report that resulted from this work (NCRP, 1989) reviewed the radiation environments in space, the radiobiological effects to be expected, the basis of risk estimates by age and sex and recommendations on career limits, the latter specifically for low earth orbits. It was recognized that the radiation exposures in space were an occupational hazard but for various reasons dose limits recommended for workers on the ground were not appropriate. The principle of restricting exposure to levels as low as reasonably achievable (ALARA) continued to be recommended.

Table 2—*Comparison for risk estimates 1982 versus 1970.*[a]

| | Leukemia 20 y ($Sv^{-1}$) | Solid Tumors 20 y ($Sv^{-1}$) | Total Cancers 20 y ($Sv^{-1}$) | Natural Risk Age 35-55 y | Dose to Double Natural Risk (Sv) |
|---|---|---|---|---|---|
| 1970 | $3 \times 10^{-3}$ | $3 \times 10^{-3}$ | $6 \times 10^{-3}$ | $23 \times 10^{-3}$ | 4 |
| 1982 low dose | $2 \times 10^{-3}$ | $8 \times 10^{-3}$ | $10 \times 10^{-3}$ | $23 \times 10^{-3}$ | 2.4 |
| 1982 high dose | $5 \times 10^{-3}$ | $20 \times 10^{-3}$ | $25 \times 10^{-3}$ | $23 \times 10^{-3}$ | 0.9 |

[a]From Sinclair, 1983.

Cancer was the principal risk and the career limits were based on limiting the cancer risk to a three percent lifetime cancer mortality. This lifetime risk was about the same as for some, but not the safest, occupations on earth, but in any case less than for the most hazardous occupations. NCRP Report No. 98 (NCRP, 1989) discusses the basis for this choice. The differences in risk for different ages and sex were taken into account for the first time and instead of a single career limit, a table of career limits was established (Table 3). These could also be presented in the form of a figure (Figure 1) (NCRP, 1989) from which the career limits for ages other those given in the table can readily be obtained. The career limits ranged from about 1 Sv (for young women) to about 4 Sv (for older men). Short-term limits designed to avoid deterministic effects in critical organs were also provided (Table 4). These recommendations were adopted by NASA and approval of these supplementary standards was granted by the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor in 1990.

It is worth recording here the rationale that NASA used for adopting these supplementary standards. It was based on the following comments.

1. Exposed population limited in size: The supplementary exposure standards would apply only to flight crews involved in space activities. The benefit of advanced spaceflight programs exceeds substantially the risk incurred by an increased radiation exposure. The career limits for flight crews would be based on an increase in the risk of cancer mortality of three percent higher than the general population and these limits would apply only to flight crews during the actual performance of the mission.
2. Formal appraisal of radiation hazards: Before each mission NASA would conduct preflight exposure calculations, including exposures during extravehicular activity (EVA), etc. An extensive and sophisticated pre-mission determination of potential exposure would be

Table 3—*Career effective dose equivalent limits based on a lifetime excess risk of cancer mortality of $3 \times 10^{-2}$ (NCRP, 1989).*

| Age (y) | Female (Sv) | Male (Sv) |
|---|---|---|
| 25 | 1.0 | 1.5 |
| 35 | 1.75 | 2.5 |
| 45 | 2.5 | 3.2 |
| 55 | 3.0 | 4.0 |

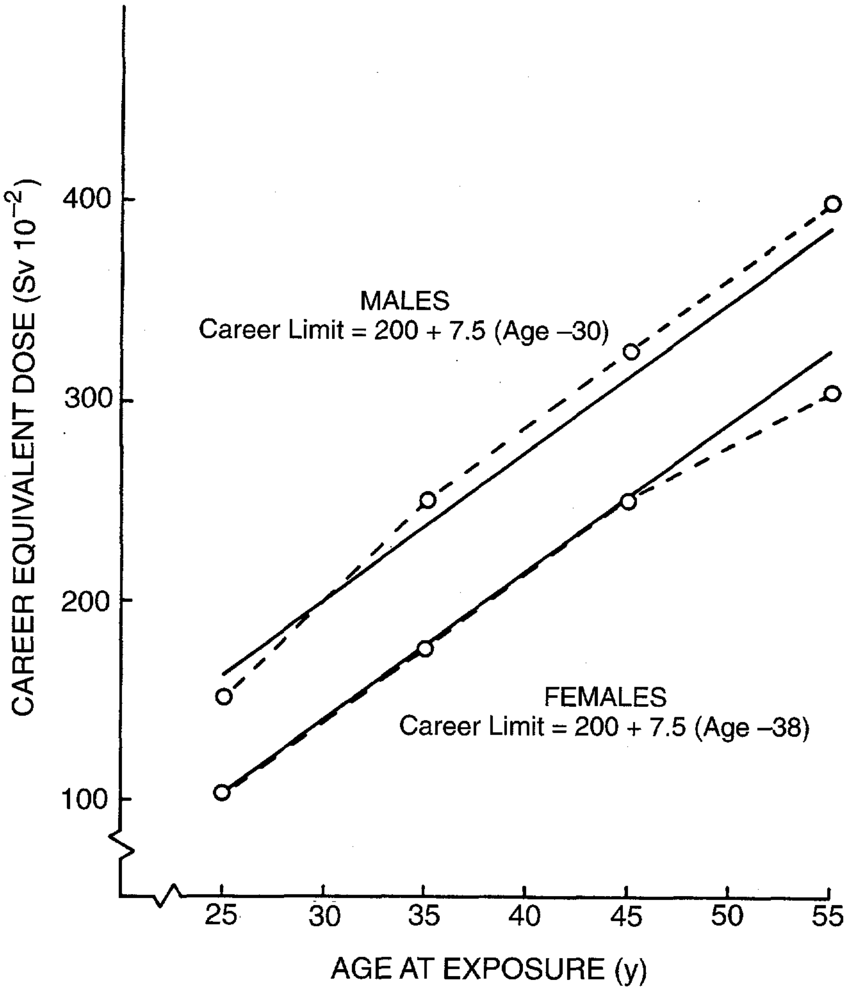


**Fig. 1.** Career limit versus age.

Table 4—*Short-term dose equivalent limits and career limits (Sv) for protection against deterministic effects (NCRP, 1989).*

| Time Period | BFO[a] | Lens of the Eye | Skin |
|---|---|---|---|
| 30 d | 0.25 | 1.0 | 1.5 |
| Annual | 0.50 | 2.0 | 3.0 |
| Career | see Table 3 | 4.0 | 6.0 |

[a]Blood forming organs. This term has been used to denote the dose at a depth of 5 cm.

made for each element of each mission. This appraisal is based on the proposed mission plan and time line, the model of the radiation environment, a detailed mass distribution model of the spacecraft, components, and inhabitants, and a radiation transport program. Each element has been developed and updated as appropriate.

3. Maintenance of exposure records: Passive dosimeters would be worn by every crew member during the mission. These dosimeters, which have been the backbone of the operational dosimetry program since the Mercury program, are continually evolving with the availability of new materials and techniques. International comparisons of calibrations are routinely performed. Advanced dosimetry systems are being conceived, developed, and evaluated. In addition, extensive records of both flight exposures and ground-based exposures are part of each crew member's medical history.
4. Adherence to the ALARA principle: The flight planning by NASA's Space Radiation Analysis Group would ensure crew exposures were "as low as reasonably achievable." The principle of ALARA has been the basis of the fundamental design, development, test, and operational elements of all radiation exposures to date. Mission and experiment scenarios are developed and evaluated to determine optimum mission success and crew safety.
5. Formal operational procedures: Formal protocols, including the use of calibrated active and passive measurement radiation systems, and flight rules covering any radiation exposure contingency have been developed and documented. On-call personnel are available for anomalous events and/or readings. Operational activities include interfacing directly with the Mission Flight Surgeon.

## Reappraisal of the Radiation Standards of 1989

At the time NCRP Report No. 98 (NCRP, 1989) and its new career limits were produced, it was already known that the cancer risk probability coefficients were likely to be increased soon thereafter and that this might require a revision in the NCRP risk estimates. These changes resulted from several factors: the new dominance over other sources of the risk estimates of the atomic-bomb survivors in Japan; the replacement of the old dosimetry system (T65D) with a new one (DS86); increases in the number of solid tumors with time exceeding those that were expected; and a preference for constant relative risk methods for projecting the observations in the population to a lifetime risk. The latter projection was from the 40 percent of the population evaluated for mortality up to 1985 to the remaining 60 percent in order to estimate a total lifetime risk. The new risk estimates were derived by UNSCEAR first in 1988 and again in 1994 (UNSCEAR, 1988; 1994) and by the BEIR V

Committee (NAS/NRC, 1990). They were used by ICRP (1991) and NCRP (1993) in setting new occupational standards for workers on the ground.

Although the NCRP has not yet reached a consensus on this subject, one possible approach is that shown in Table 5. From these risk estimates, career dose limits (based on effective dose) can be determined for any level of accepted lifetime risk. In Table 6 estimates of the career dose limit corresponding to an increased lifetime risk due to space radiation exposure (at the career limit) of one, three and five percent are given. A comparison of these with Table 2, the Report No. 98 career limits, shows a decrease of a factor of about two in career limits because of the increased risk estimatesThe career limits for three percent fatal cancer risk lifetime can also be plotted as shown in Figure 2. It will be noticed that the relative slopes of the lines are different from Figure 1 for male and female, reflecting further changes in the appraisal of risks as a function of age and sex. Career limits for other ages can be obtained from this figure.

It is, of course, necessary to consider also the changing base of comparison with accident rates from other industries and with radiation occupations on the ground as we progress in time from 1988-89 to 1996-97. A comparison of work accident rates for 1987 (used in NCRP Report No. 98) and 1994 (the latest available) (Table 7) indicates that both the "less safe" regular occupations, *viz.* agriculture, mining, construction, transportation and the "safe" occupations, manufacturing trade, services and government have lowered their accident rates by a factor of two during this 7 y time period, faster recently than in the previous 60 y in which the rate halved each 25 y.

Table 5—*Estimated excess cancer deaths, associated with chronic exposure totalling 10 mSv per year for 10 y, by sex and age at exposure.*

| Age at Exposure | 25-34 | | 35-44 | | 45-54 | | 55-64 | |
|---|---|---|---|---|---|---|---|---|
| | M | F | M | F | M | F | M | F |
| Mortality (%) | | | | | | | | |
| Solid cancers | 0.31 | 0.55 | 0.16 | 0.20 | 0.11 | 0.22 | 0.078 | 0.16 |
| Leukemia | 0.066 | 0.027 | 0.052 | 0.028 | 0.0330 | 0.28 | 0.023 | 0.021 |
| All cancers | 0.37 | 0.58 | 0.21 | 0.32 | 0.15 | 0.24 | 0.101 | 0.18 |

Table 6— *Career effective dose limits based on excess lifetime career risk*[a]

| Age at Exposure | Effective dose - Sv | |
|---|---|---|
| | Female | Male |
| A. 1% excess risk | | |
| 25 | 0.2 | 0.3 |
| 35 | 0.3 | 0.5 |
| 45 | 0.4 | 0.7 |
| 55 | 0.6 | 1.0 |
| B. 3% excess risk | | |
| 25 | 0.5 | 0.8 |
| 35 | 0.9 | 1.4 |
| 45 | 1.2 | 2.0 |
| 55 | 1.7 | 3.0 |
| C. 5% excess risk | | |
| 25 | 0.9 | 1.3 |
| 35 | 1.6 | 2.4 |
| 45 | 2.1 | 3.3 |
| 55 | 2.8 | 5.0 |

[a]For 10 y exposure starting at age indicated.

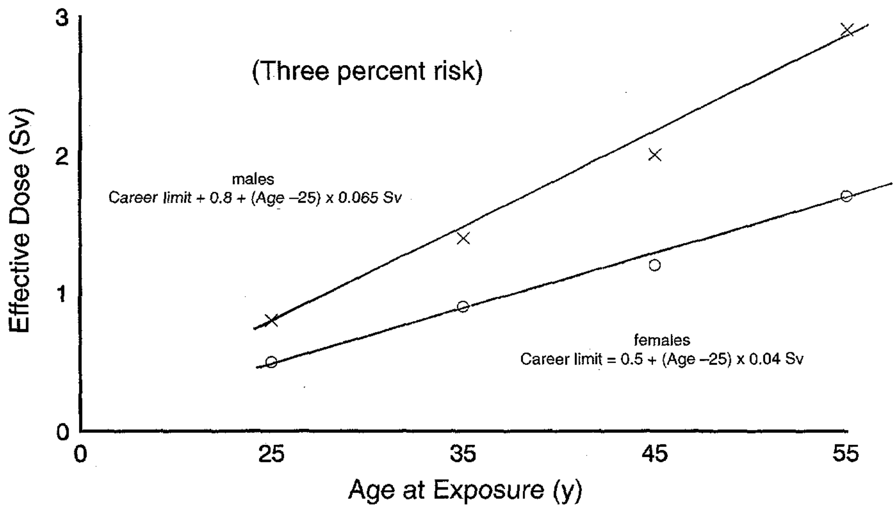


**Fig. 2.** Career limit versus age at exposure (10 y duration).

Table 7—*Work accident rates.*[a]

| | 1987 | 1994 |
|---|---|---|
| Agriculture | 49 | 26 |
| Mining | 38 | 27 |
| Construction | 35 | 15 |
| Transportation | 28 | 12 |
| Manufacturing | 6 | 4 |
| Trade | 5 | 2 |
| Services | 5 | 2 |
| Government | 8 | 3 |
| All[b] | 10 | 4 |

[a]Accident Facts, National Safety Council (NSC, 1988; 1995).
[b]Annual risk of 10 per 100,000 is $10^{-4}$ $y^{-1}$, for approximately 50 y, it is $5 \times 10^{-3}$ or 0.5 percent lifetime.

If this were our primary source of comparison, one might be inclined to lower the three percent fatal cancer lifetime risk by a factor of two (*i.e.,* from 3 to 1.5 percent). If so, the career limits would be as shown in Table 8, ranging only from 0.25 to 1.5 Sv. This may, however, be unnecessarily restrictive for space workers.Table A.1 in NCRP Report No. 116 (NCRP, 1993) provides a comparison of the risks to radiation workers on Earth who receive doses in accordance with the new limits recommended in 1991 by the ICRP and in 1993 by the NCRP.

Table 8— *Career effective dose limits. 1.5 percent excess risk.*

| Age | Effective Dose Sv | |
|---|---|---|
| | Female | Male |
| 25 | 0.25 | 0.4 |
| 35 | 0.5 | 0.7 |
| 45 | 0.6 | 1.0 |
| 55 | 0.8 | 1.5 |

The ICRP would at the limit allow a lifetime risk of nearly four percent and the NCRP about three percent, the NCRP's cumulative limit providing the cap. Thus, in comparison with radiation workers on the ground, it seems unreasonable to limit astronauts to a lifetime risk of less than about three percent. These features and perhaps others, have still to be considered by the NCRP's committee and by the NCRP itself before new recommendations are adopted. In this regard, comments by astronauts and others involved in NASA operations and philosophy, including some of those later on this meeting program, will be most useful to the NCRP.

Finally, it is important to point out that neither NCRP Report No. 98 (NCRP, 1989) or the report revision now being considered are the result of concern about current or past NASA practices with respect to radiation control. None of the United States' astronauts has received high exposures in space, and the doses incurred by United States' astronauts are only a small fraction of the limits recommended in NCRP Report No. 98 (NCRP, 1989). The highest average mission dose on Skylab has been 43 mGy. The astronauts have also received exposures from diagnostic x-ray and nuclear medicine procedures, at one time, total exposures of up to 50 to 90 mSv. In recent years, however, the doses from these procedures have been greatly reduced and were less than 3 mSv on average in 1990. A few Russian cosmonauts may have received markedly higher doses than the United States' astronauts. It is estimated (Robbins, 1996) that the exposure of the bone marrow in the Mir Space Station, for example, could amount to 0.55 Sv in a year. Some cosmonauts have spent longer than a year in the Mir Space Station. It is interesting too that the Russians are practicing ALARA by taking more shielded positions for crew members while passing through the higher dose rate South Atlantic Anomaly (Petrov, 1996)[1]. United States' missions to the Mir Station for periods like 115 d may range from 0.1 to 0.2 Sv on the skin.

It is clear that while United States' astronauts especially and others have not been exposed to doses close to current limits, the potential for doing so, even in low earth orbits, is considerable and that sensible, reasonable limits are very important as part of NASA and international policy for radiation exposure in space.

[1]Unpublished, Petrov, V. "ALARA in Russian space flights," presentation to NASA Meeting of Radiation Investigators. Riverside, California, May 14-16, 1996.

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# General Discussion

ALOKE CHATTERJEE: My name is Aloke Chatterjee, Lawrence Berkeley Laboratory. That was a very nice presentation. I'm interested in the quality of the beam, the Z of the particles. Is any attempt being made to unfold that information?

DON ROBBINS: We have flown a spectrometer into space and we have a pretty good idea about the nature and energy of the particles. Although we can always use more data, I believe we have pretty good information at the present time.

JOHN AINSWORTH: I'm John Ainsworth, Armed Forces Radiobiology Research Institute. You stressed the importance of neutrons that had passed through 30 grams per square centimeter of shielding material. Could you provide us some idea of what the resulting neutron spectrum would be like?

DON ROBBINS: I'm sorry but I do not recall. That information will be included in my paper.

WARREN SINCLAIR: If I interpreted his slides correctly, Dr. Robbins indicated that the difference between solar maximum and minimum, as far as dose rates from galactic cosmic rays are concerned, is a factor of about three or four. Depending on when it is scheduled, that would make a difference of a factor of three or four in the total exposure resulting from a mission to Mars. Do you think NASA will take this into account when the options for a Mars mission eventually are before us?

DON ROBBINS: At this time I doubt that we could estimate within 10 y the date when a Mars mission will be attempted. My experience with NASA is that the date they set for a mission is based on when they think they will be ready to go. To date, concern for the solar cycle has not been a major factor in this process. It's not unreasonable, however, to require that such a mission be attempted during a period of solar maximum, coupled with provisions to account for any solar particle events (SPE) that may occur. The probability of the astronauts receiving doses due to galactic cosmic rays is one. The probability of being exposed to a SPE is difficult to predict. If by scheduling the mission during a period of solar maximum you can reduce the dose from the galactic cosmic rays—

perhaps by as much as 0.22 to 0.25 Sv—that would appear to be the wise thing to do.

WALLACE FREEDBERG: I'm Wallace Freedberg from the Federal Aviation Administration. I thought those in attendance would be interested in the career doses that airline pilots receive and the associated risk. Calculations that I have made may be of interest. As a base case, I made the following assumptions—that the pilots flew from New York to Chicago, that they were exposed to the average galactic radiation dose rate over the time period since 1958, and that they flew 700 block hours per year. For this case, their total dose would be about 2.1 mSv per year. Over an assumed 30 y career, the total cumulative dose would be 63 mSv. That represents a lifetime risk of fatal cancer of 1 in 330—0.3 percent. As a worst case, I selected pilots flying from Athens to New York which would expose them to higher dose rates. Using the legal FAA limit for pilots—1,000 block hours per year, an amount that no pilot actually would fly—the estimated dose for 30 y was 153 mSv. The associated risk in this case is about 0.5 percent.

BRENT LEWIS: I'm Brent Lewis from the Royal Military College of Canada. I'd like to ask Dr. Robbins a question with regard to the neutron contribution to dose. As I understand it, perhaps as much as 50 percent of the dose to astronauts in the space station will be due to neutrons. How is this measured? Although you suggested that the spectrum is well known, I understand that at 40,000 feet there is still controversy whether the Hess or Hewit spectrum is correct. How well do we know the neutron spectrum? Could you comment?

DON ROBBINS: Both the U.S. and Russia have made measurements of neutrons in space. Our measurement knowledge, however, is not very good at this time. Certainly, more measurements need to be made. The 50 percent contribution from neutrons that you quoted is only for the very lowest altitude range where the neutron contribution is higher. My estimate of the maximum neutron dose rate was about $2 \times 10^{-3}$ mSv $d^{-1}$. It's really a relatively small dose. That is the best we know at this time.

TOM BORAK: I'm Tom Borak from Colorado State University. I'd like to ask Dr. Sinclair to what extent the new NCRP recommendations on risk include effects other than cancer?

WARREN SINCLAIR: The numbers that I gave were specifically for cancer. It is the primary concern at low doses. The other effects that Dr. Fry discussed, by and large, were deterministic in nature. Some noncancer effects, however, are now becoming evident in the Japanese population exposed during World War II. But not at doses below about 1.5 Sv, or so.

In general, I think that at the doses that astronauts are likely to receive, cancer—the stochastic effect—remains the primary problem.

HARRY ENG: I'm Harry Eng from Canada. My comments are directed to Dr. Fry. We are bound because of historical reasons to think in terms of risk, and to translate this risk into units of dose equivalent. That is, we talk about sieverts. In view of the comments you made about fundamental differences in the nature of the interactions with tissue of heavy ions, do you still believe that this particular quantity is perhaps the best unit to be using, when measuring the risk from radiations in space?

MICHAEL FRY: There are several people in the audience who have perhaps stronger views on this than I. One of the problems is that heavy ions cause lesions that are qualitatively not the same as those for other types of radiation. As a result, you do have a problem estimating the risk based on the same units because there is a fundamental assumption—when you go from one radiation to another—that there are only quantitative differences and that you can adjust for those. If you have any good suggestions on how to take these factors into account, please let us know. Presumably, you will have some estimate of the doses at which those risks become important. From a radiation protection point of view, you can still set limits sufficiently low to provide some confidence that you are providing adequate protection.

STANLEY CURTIS: I'm Stan Curtis from the Fred Hutchinson Cancer Research Center. I just want to say that quantities other than dose equivalent, or equivalent dose, are being evaluated. These include fluence related quantities. In fact, the NCRP has a committee reviewing this subject.

PAUL SLOVIC: Let me thank our three speakers for this morning's presentations and bring this session to a close. We'll now take a break and resume at 10:30.

# Analytic Concepts for Assessing Risk as Applied to Human Space Flight

B. John Garrick
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## Abstract

Quantitative risk assessment (QRA) principles provide an effective framework for quantifying individual elements of risk, including the risk to astronauts and spacecraft of the radiation environment of space flight. The concept of QRA is based on a structured set of scenarios that could lead to different damage states initiated by either hardware failure, human error, or external events. In the context of a spacecraft risk assessment, radiation may be considered as an external event and analyzed in the same basic way as any other contributor to risk. It is possible to turn up the microscope on any particular contributor to risk and ask more detailed questions than might be necessary to simply assess safety. The methods of QRA allow for as much fine structure in the analysis as is desired. For the purpose of developing a basis for comprehensive risk management and considering the tendency to "fear anything nuclear," radiation risk is a prime candidate for examination beyond that necessary to answer the basic question of risk. Thus, rather than considering only the customary damage states of fatalities or loss of a spacecraft, it is suggested that the full range of damage be analyzed to quantify radiation risk. Radiation dose levels in the form of a risk curve accomplish such a result. If the risk curve is the complementary cumulative distribution function, then it answers the extended question of what is the likelihood of receiving a specific dose of radiation or greater. Such results can be converted to specific health effects as desired. Knowing the full range of the radiation risk of a space mission and the contributors to that risk provides the information necessary to take risk management

actions [operational, design, scheduling of missions around solar particle events (SPE), etc.] that clearly control radiation exposure.

## Introduction

Analytic methods for the quantitative risk assessment of complex engineered systems have been evolving and practiced for over two decades, mostly in the nuclear power industry. The National Aeronautics and Space Administration (NASA) and the defense industry did much of the early work that provided the groundwork carried forward by the nuclear industry in the late 1960s and early 1970s. While NASA and the defense industry had the momentum to develop QRA as a result of their work in the reliability analysis field, it was the nuclear power industry that made the breakthrough that first surfaced the concept of probabilistic risk assessment (PRA), also referred to as QRA. Early work by the U.S. Atomic Energy Commission (Garrick and Gekler, 1967) and in the academic community (Garrick, 1968) signaled a growing interest in a more quantitative approach to safety analysis. The breakthrough came in 1975 with the completion of the Reactor Safety Study (NRC, 1975). The Reactor Safety Study together with the follow-on PRA for the Zion and Indian Point nuclear power plants (PLG, Inc., 1981; 1982) are two significant events in establishing PRA/ QRA as a viable engineering discipline.

While NASA had backed away from the use of QRA for safety assessment and design in the 1960s and 1970s, the Space Shuttle Challenger accident raised the whole issue of NASA's approach to safety analysis and the use of risk assessment. Both the Roger's Commission (Presidential Commission, 1986) and the National Research Council (NAS/NRC, 1988) recommended NASA make greater use of more advanced methods of risk assessment. Both were careful not to put the blame on the lack of using QRA methods as a reason for the accident. The circumstances of the accident were far too complex to be attributed to any single cause. If there was anything approaching a single cause, it was rooted in the pervasiveness of the culture of NASA and its impact on information processing and decision making.

Meanwhile, in the late 1980s, NASA began to show signs of moving towards the selective use of quantitative methods of safety analysis. The first sign of this was a proof-of-concept study (McDonnell Douglas Astronautics Company, 1987) to demonstrate the use of QRA methods on a critical system in the operation of the Space Shuttle. This has been followed by numerous other studies, perhaps the most recent of which is a broader scoped PRA of the space shuttle (NASA, 1995). Other work in the space field indicating an increased use of QRA methods has to do with the safety analysis "of space missions that utilize radionuclides in a significant quantity" (Frank *et al.*, 1996). Thus, there is movement towards quantitative methods of risk and safety analysis, but the application and scope are still limited. It is not yet a part of the fundamental NASA culture. Nevertheless, it is the purpose of this paper to take the position that the trend will continue towards greater use of QRA methods and address the issue of the risk of radiation in context with all other risks associated with space flight. In particular, we will define risk and the risk assessment process, propose a concept for analyzing the risk of spacecraft rooted in established methods and a pilot application to a Space Shuttle system, and finally, focus on the issue of radiation risk as an element of a full-scope risk assessment of spacecraft.

## Definition of Risk and Risk Assessment

In setting out to perform a QRA we have to know what we mean by "risk" before we can consider a process for its calculation. The definition that has been adopted for many applications to a wide variety of engineered and natural systems is the so called "set of triplets" definition (Kaplan and Garrick, 1981). Specifically, this definition asks the following three questions:

- What can go wrong with our system?
- What is the likelihood of that happening under the current plan?
- If it does happen, what are the consequences; *i.e.*, what is the damage?

The answers to these questions constitute a quantitative risk assessment. The answers might be arranged as in Figure 1.

| Scenario | Likelihood | Damage |
|---|---|---|
| $s_1$ | $l_1$ | $x_1$ |
| $s_2$ | $l_2$ | $x_2$ |
| $s_3$ | $l_3$ | $x_3$ |
| • | • | • |
| • | • | • |
| • | • | • |
| $s_N$ | $l_N$ | $x_N$ |

**Fig. 1.** Quantitative definition of risk.

The first column contains descriptions and names of scenarios. This is the answer to the first question above. The second column contains the likelihoods, l, of the scenario, s. The treatment of likelihood is central to the meaning of "quantitative." Candidate parameters are frequency, probability, and probability of frequency as defined in Kaplan and Garrick (1981). For most applications involving hazardous operations of complex engineered systems, the "probability of frequency" format has been adopted. The third column contains "damage state," also referred to as "performance measure," x, which is a measure of the consequences of the ith scenario.

Each row of the table thus constitutes a triplet:

$$< s, l, x > \qquad (1)$$

giving a scenario, its likelihood, and consequences. This triplet constitutes then one answer to the three questions. The table itself (*i.e.*, the set of all triplets denoted by the outer brackets) provides the total risk, R. In particular,

$$R = \{ < s_i, l_i, x_i > \} \qquad (2)$$

is the complete answer to the three questions. Therefore, this set of triplets is adopted as the definition of risk. This definition becomes the organizing principle for QRA. The goal is the identification of all possible significant scenarios and the characterization of their likelihood and consequences. Figure 2 indicates two frequently used forms for the results.

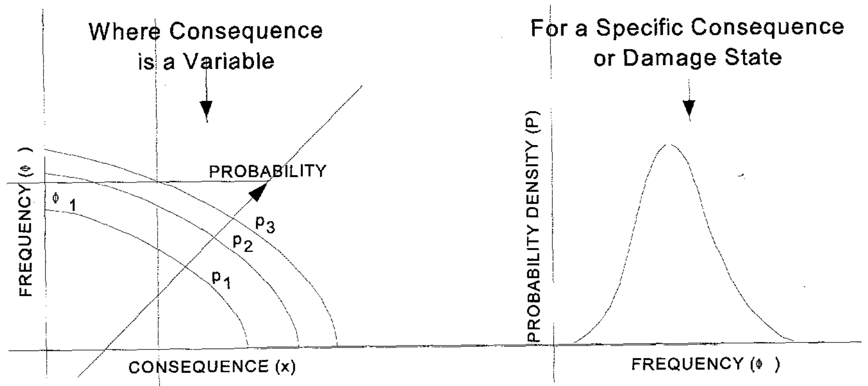



**Fig. 2.** Form of the results (complementary cumulative distribution function and probability density function).

The first form is called the complementary cumulative distribution function and the second is the probability density function. These functions are discussed in detail in the references.

## The Risk Assessment Process

Figure 3 gives a highly conceptualized diagram of the steps involved in a QRA. The vertical boxes denote the basic activities involved and the circular rectangles loosely identify the product(s) from those activities. Without describing in detail all of the steps involved, it is important to note that the central effort of a QRA is that having to do with structuring the scenarios, or in reference to Figure 3, the event sequence modeling activity. Since the number of possible scenarios for a complex spacecraft can be very large, it is important in carrying out the QRA to organize and categorize the set of triplets. This can be done in many ways. One way to organize the scenarios is in terms of the severity of the consequences. It is important to sort out those scenarios that lead to substantial decreases in performance of either the systems or the crew.

The best way to do this is to consider different damage states or scenario end states. For example, in addition to the end state of "loss of crew and spacecraft," there could be such less severe states as "radiation dose," "loss of a critical system," "loss of crew capability,"

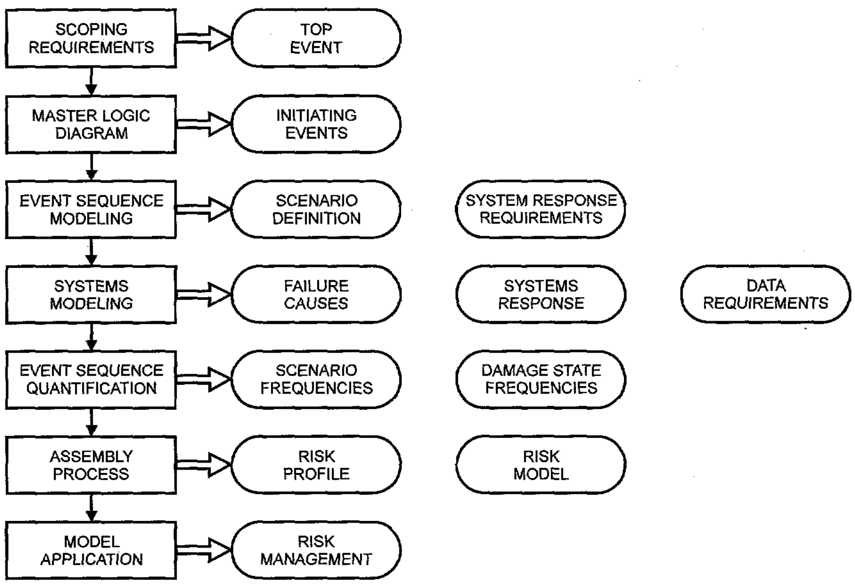



**Fig. 3.** Quantitative risk assessment process.

"aborted mission," and "launch delay." A second way to organize the scenarios is by the different phases of the mission such as "launch," "orbit," "interplanetary space," or "re-entry." Of course, these results could be matrixed to investigate different consequences within the different phases of the mission.

To better illustrate how a QRA is performed, consideration is now given to specializing the process to a specific application, namely a Space Shuttle example referred to earlier as a proof-of-concept study. We will then follow with a general concept for addressing the risk of radiation.

## Risk Assessment of Spacecraft

In the proof-of-concept study, we divided the Space Shuttle mission into phases. Figure 4 illustrates the phases involved in a Space Shuttle mission.

From a computational standpoint, it was unnecessary to consider more than five phases in the mission; *i.e.*, prelaunch, ascent, orbit, entry/landing, and post-landing to crew egress. The study performed considered a single system, the orbiter auxiliary power unit (APU) and solid rocket booster hydraulic power unit (HPU). Before focusing on the APU and HPU, let us back up and consider how we would put the contribution to risk from the APU and HPU in context with all other contributors to risk. The approach is to develop a model from the top down such that each step towards the analysis of specific systems is traceable to the total system. To illustrate the process, consider Figure 5.

In this case our objective is to determine the risk of losing the shuttle and crew and to importance rank the contributors to this event. In fact, Figure 5 is already an aggregation of results (remember this is only conceptual) since we really did not do an analysis for the whole shuttle. Results presented in this form, as probability density functions, indicate what the risk is and where it is coming from in terms of major systems and events. Buried under the category of "external events" would be the risk of radiation, the decomposition of which will be discussed later. To further illustrate the process if it were applied to the Space Shuttle, consider how we would get the results for one of the major systems in Figure 5, say the orbiter. Turning up the microscope on the risk assessment of the orbiter might look like Figure 6.

Some 17 subsystems are identified whose failure under specific conditions could initiate a scenario that if unmitigated could lead to a loss of crew and vehicle. Thus, all 17 systems would have to be analyzed and

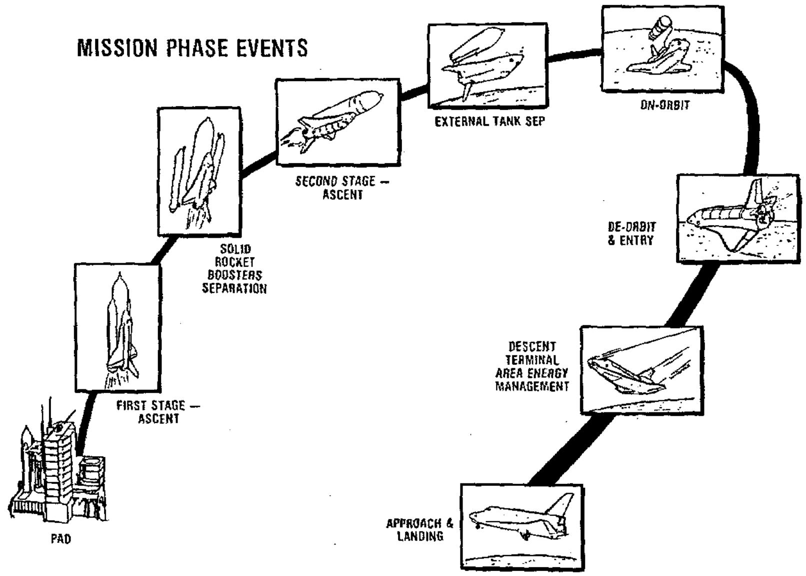



**Fig. 4.** Mission phase risk assessment.

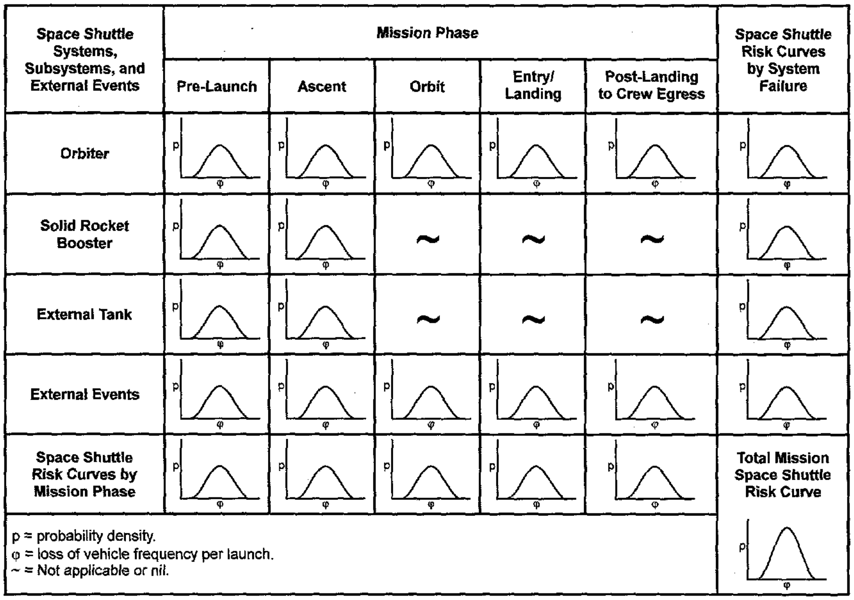



**Fig. 5.** Loss of vehicle frequency per launch. Risk decomposition into subsystems, external events, and mission phases.

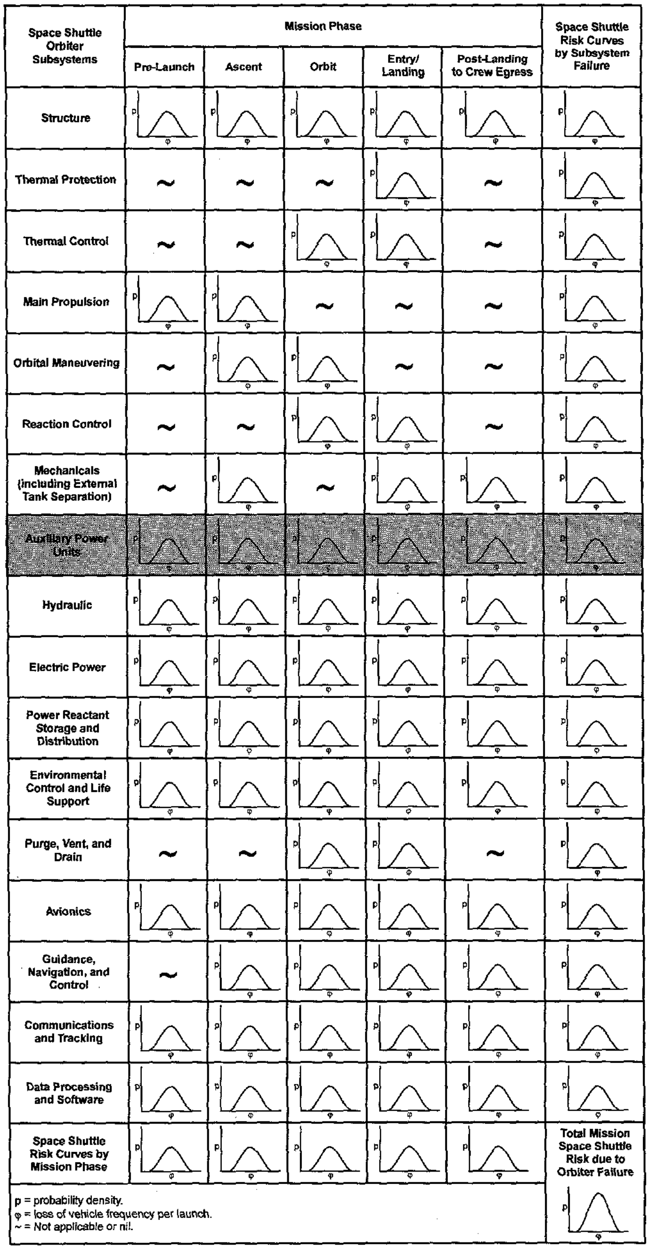



**Fig. 6.** Loss of vehicle frequency per launch due to orbiter events. Risk decomposition into orbiter events.

their risks appropriately summed to fill in the first row of Figure 5. Of course, there is much more to the analysis than even indicated by

Figure 6. For example, only one of the 17 systems was the subject of the proof-of-concept study. That system is labeled as APUs. Figure 7 is a brief word description of a scenario involving the APUs.

The requirement of a risk assessment is to develop a complete set of such scenarios associated with the failure of the APUs and, based on the best information available, quantify the frequency of occurrence of the scenarios ending in the chosen damage state, in this case the loss of vehicle and crew. The various scenarios involving the APUs are appropriately summed and constitute the results for the row in Figure 6 labeled Auxiliary Power Units. The result for this row is of the form of Figure 8.

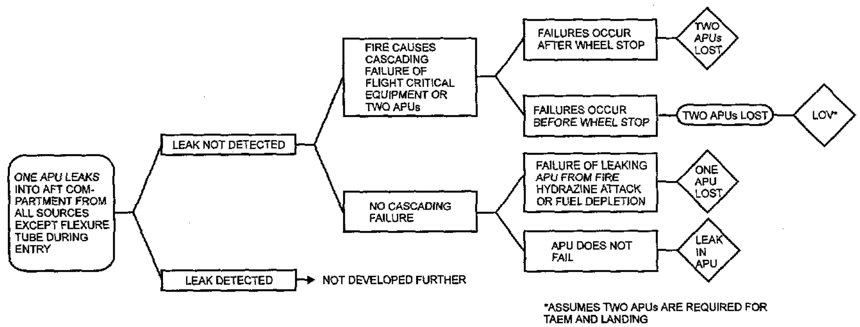



**Fig. 7**. Scenario quantification.

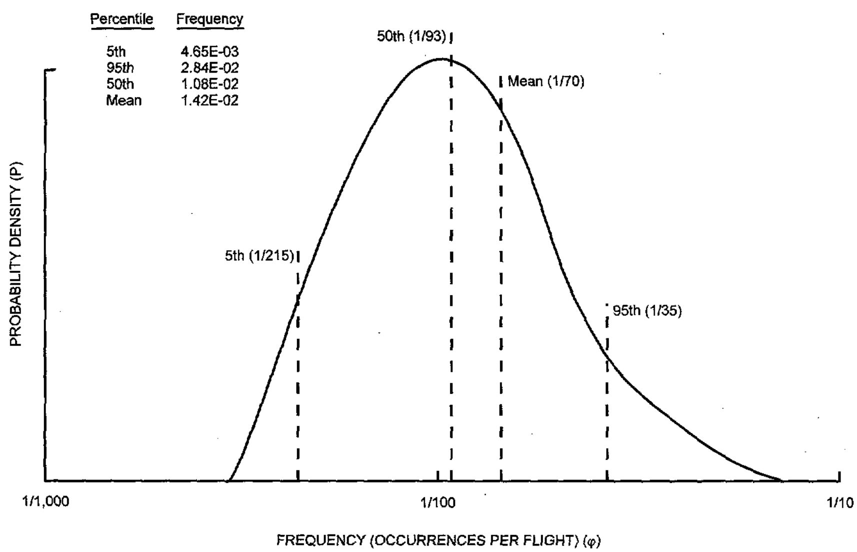



**Fig 8.** APU—loss of crew/vehicle—entire mission.

Similarly, for the fourth row of Figure 5 having to do with external events a detailed analysis of the form of Figure 6 would have to be performed. It is suggested that radiation be treated as an external event similar to space debris, lightning, wind shear, etc. That brings us to the specific issue of an analytical framework for assessing radiation risk.

## Analytical Framework for Assessing Radiation Risk

Returning to Figure 5 and the fifth row entry of External Events, we now want to decompose this entry into its component parts. Again, this is done conceptually in Figure 9.

Obviously, the external events are dependent on the system and its environment. Thus, those identified in Figure 9 are believed to be those that could occur in the total mission environment of the Space Shuttle.

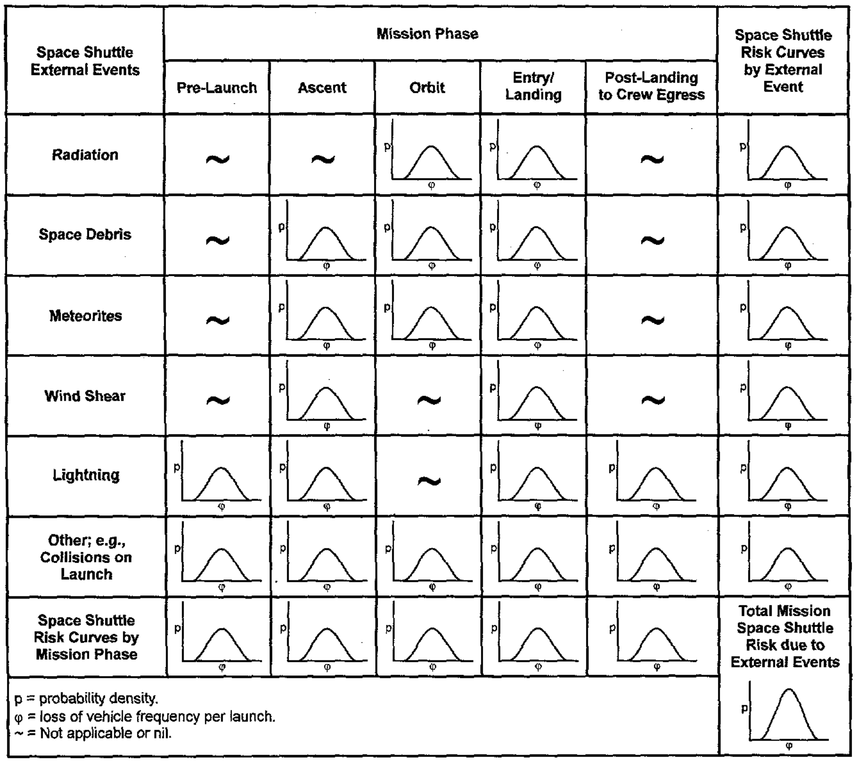



**Fig. 9.** Loss of vehicle frequency per launch due to external events. Risk decomposition into various external events.

Now we want to turn our attention to the external event of the first row of Figure 9; namely, Radiation. To make the decomposition and analysis of the radiation external event more interesting, consider a more ambitious space mission than provided by the Space Shuttle. In particular, we will conceptualize the case of the radiation risk to astronauts on an interplanetary mission to Mars. As before, we are trying to keep all the components of risk in perspective through a traceable decomposition process. Figure 10 is a first level decomposition of space radiation risk into three types of radiation: galactic cosmic rays, trapped belt radiation, and SPEs. Of course, further decomposition is possible, but since our objective is only to suggest the concept of an analytic framework, we will spare additional complexity.

The form of the results discussed so far have been probability density functions (PDF). PDFs are an excellent way to convey our state of knowledge about the risk of a specific consequence, such as loss of vehicle or a specific level of damage. The complementary cumulative distribution function (CCDF), see Figure 2, is the better form when it is desirable to vary the consequence.

The CCDF answers the very important risk question of what is the likelihood of receiving a certain level of damage or greater. Thus, we can treat radiation as a variable damage state and determine, in principle, the full range of damage and their likelihoods. As to how this is done we refer

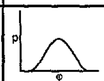
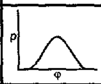
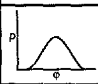
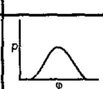
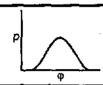
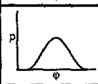
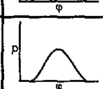
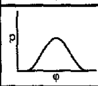
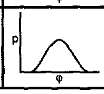
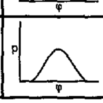
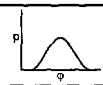
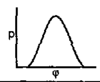
| Spacecraft Radiation Events | Mission Phase | | | | | Spacecraft Risk Curves by Radiation Type |
|---|---|---|---|---|---|---|
| | Pre-Launch | Ascent | Orbit | Entry/ Landing | Post-Landing to Crew Egress | |
| Galactic Cosmic Rays | ~ | ~ |  | ~ | ~ | |
| Trapped Belt Radiation |  |  | ~ |  |  | |
| Solar Particle Events | ~ |  |  |  | ~ | |
| Spacecraft Risk Curves by Mission Phase |  |  |  |  |  | Total Mission Spacecraft Risk due to Radiation Events |
| p = probability density.<br>φ = loss of vehicle frequency per launch.<br>~ = Not applicable or nil. | | | | | |  |

**Fig. 10.** Astronaut risk of high radiation doses for interplanetary mission to Mars. Risk decomposition into various types of radiation and mission phases.

back to Figure 1. The procedure is to order the radiation scenarios in order of increasing dose and "cumulate" the likelihoods from the bottom to the top as a function of dose. Plotting the results on log-log scale creates a CCDF of the radiation risk.

Quantitative risk assessment provides extremely valuable insights on opportunities for managing risk. A result of QRA is not only a quantification of what the risk is but the importance rank of different risk contributors for different damage states. Knowing what is driving the risk sets the stage for an effective allocation of resources for risk management. For example, what operational procedures should we implement to minimize radiation risk? Such procedures may involve scheduling of flights around solar minimums or maximums, spacecraft attitude adjustment criteria, time spent in shielded areas, extravehicular activity limitations, course adjustments, etc. How many resources should be allocated to develop better SPE warning systems or radioprotective drugs? How far can we go with flight rules in this process? Should radiation risk affect crew selection? Of course this same type of thinking applies to all the sources of risk and must be done in context. A full-scope risk assessment permits this important type of decision making. It makes no sense to spend a major part of the risk management resources on something that may be only 1% of the risk. Because of the extremely high sensitivity to some dangers over others, such as the dangers of radiation, there is the need for QRA to put the dangers in their proper perspective.

## Conclusion

Quantitative risk assessment has matured to the point of providing a framework for putting contributors to risk in perspective. While the methods have matured, they have not been universally accepted. NASA is in transition on this point. Radiation risk as a component of the overall risk can be made a part of the QRA process. The concept proposed while not yet generally applied to human space flight has been practiced extensively in other industries, including the nuclear power and chemical industries.

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# Approaches to Acceptable Risk

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ICF Kaiser

## Abstract

Several alternative approaches to address the question "How safe is safe enough?" are reviewed and an attempt is made to apply the reasoning behind these approaches to the issue of the acceptability of radiation exposures received in space. The approaches to the issue of the acceptability of technological risk described here are primarily analytical, and are drawn from examples in the management of environmental health risks. These include risk-based approaches, in which specific quantitative risk targets determine the acceptability of an activity, and cost-benefit and decision analysis, which generally focus on the estimation and evaluation of risks, benefits and costs, in a framework that balances these factors against each other. These analytical methods tend by their quantitative nature to emphasize the magnitude of risks, costs and alternatives, and to downplay other factors, especially those that are not easily expressed in quantitative terms, that affect acceptance or rejection of risk. Such other factors include the issues of risk perceptions and how and by whom risk decisions are made.

## Introduction

It has long been recognized that significant radiation doses can be received in space, and appropriate limitations on radiation exposures received through space activities have been considered over the past three decades. As the agenda for the NCRP symposium indicates, analysis of the issue has a rich history from both a technical and policy perspective. The topic this paper addresses is policy-related: *what approaches are reasonable to consider for the purpose of defining an acceptable level of radiation exposure from space activities?*

In addition to the technical and psychological perspectives provided by other speakers in this symposium, the question of an acceptable level of risk generally involves consideration of, first, the framing of the issue that defines the relevant considerations in terms of objective, appropriate analyses and comparisons, legal requirements and agency history, and second, consideration of the value judgments that apply to that framing (*e.g.*, how much we will spend for a specified increment of risk reduction, where we draw the line at asking anyone to take such a risk).

This paper describes several alternative approaches to the first of these issues, the framing of the problem. The perspectives from which we have historically considered the question "How safe is safe enough?" are reviewed and an attempt is made to apply the reasoning behind these approaches to the issue of the acceptability of radiation exposures received in space. The approaches to the issue of the acceptability of technological risk described here are primarily analytical, and are drawn from examples in the management of environmental health risks. However, it is important to note that analysis provides only a limited perspective on the acceptability of a technological risk, and that other important and potentially conflicting perspectives exist.

The analytical approaches to the acceptability of risk such as cost-benefit or decision analysis generally focus on the estimation and evaluation of risks, benefits, costs and other characteristics of a technology or activity, as well as consideration of alternatives and their risks and costs. These analytical methods tend by their quantitative nature to emphasize the magnitude of risks, costs and alternatives, and to downplay other factors, especially those that are not easily expressed in quantitative terms, that affect acceptance or rejection of risk.

## Nonanalytical Approaches

I recently reread an article that provides an example of an entirely different approach that may actually be more relevant to the issue of acceptable risks from radiation in space than are the legalistic and analytical methods used in regulatory settings. In a paper given in a 1979 symposium sponsored by General Motors, Thompson (1980) describes the risk perspective of those who engage in high standard Himalayan mountaineering. The objective risk of being killed trying to climb Mount Everest, at least at the time of Thompson's paper, was around 1 in 8 or 1 in 10 per expedition. Having climbed Mount Everest, Michael Thompson was able to consider his own perspective on the risk. The framework he chose for doing so was culture (this is perhaps not surprising given that he is an anthropologist).

Without describing Dr. Thompson's paper in detail, it is fair to say that the anthropologist's perspective is that risk-taking and risk-avoiding behavior only makes sense within the context of culture. Readers of *The Right Stuff* should not find this observation surprising. One aspect of the explanatory power a cultural perspective brings to the question of acceptable risk is that it highlights that even within a risk-avoiding and risk-averse bureaucratic organization, risks and risk-takers are evident, if not even essential.

## Analytical Approaches

The acceptability of risk is a complex subject. Judgments of acceptability are made at many levels—by individuals, families and other groups, and by society at large. A risk may be acceptable to the consumer of a product or technology, but those who receive no benefit but some risk from the technology may disagree. A risk accepted in prospect may become unacceptable in hindsight, once consequences have become more evident.

Traditionally in engineering activities, acceptable risk has been judged by whether good engineering practice has been followed, both in the application of appropriate design standards and in analyses resulting in engineering decisions where no standards apply precisely. Similarly, the courts rely on tradition-based standards in tort law to define a risk-maker's responsibility to avert risk and a risk-bearer's right to be free from significant risk impositions.

A substantially different perspective holds in welfare economics, where risk is viewed as a social cost, and where acceptability depends to a significant degree on the costs of avoiding risk. Risk can be considered analytically from either perspective: as a matter of costs and benefits, or as a matter of rights and responsibilities.

The useful purpose of such analyses is not to proclaim one risk to be acceptable and another not. While analysis provides insight into values and trade-offs implicit in alternate social choices, analysis is not generally an acceptable way to make important public choices. Analysis does not define the risk management agenda, however it can help shape the response to evolving public opinion about which risks are too high and about which are of little concern. One need only note the ongoing toughening of laws governing drunk driving and smoking in public places to see that the public definition of acceptable risk is dynamic.

There are many ways to approach acceptable risk, and conflicts over risk may reflect the diverse objectives that enter into the judgment of acceptability. The rights versus cost viewpoint is a common basis for disagreement. In addition to the rights and costs perspectives, risk acceptability may be judged by the legitimacy of the decision process for controlling risk, independent of the outcome of the decision process. Clearly, another major factor in political decisions regarding acceptable public risk are the perceptions of the public, both with regard to the level of risk and the public confidence in the competence and integrity of risk management institutions.

There is no clear boundary for determining where equity concerns, associated with a rights framework, are of primary concern, and where costs and efficiencies are a dominant consideration. Two court cases illustrate the conflict. In the controversy about the safety of the Ford Pinto gas tank design, several courts made it clear that they found the marginal cost-effectiveness basis on which Ford based its decision to be unacceptable, at least in hindsight with identified victims. Not only did this lead to the imposition of large civil damages, it led to criminal charges against Ford engineers. (A senior Ford engineer was acquitted of criminal charges reportedly because he had bought his daughter a Pinto.) In effect, the view of the courts was that Ford had applied an unacceptable decision process to the design decision. While Ford's cost-effectiveness analysis may have been acceptable as an input to the design in prospect, the analysis was unacceptable in hindsight. The second case concerns a woman injured by a foul ball at a Houston Astros baseball game. Since there is no historical duty to protect fans from foul balls, one might expect that, on rights grounds that no award would be made. However, this was not the case; the woman received $180,000 for her injuries. Although court awards are often justified with rights-based arguments, in this case the decision, which presumably will cause the price of baseball tickets to reflect the risks to fans of injury, was compatible with the internalization-of-costs principle of welfare economics.

While the engineering profession has long been concerned with risk as a matter of professional responsibility, a more general interest in social definitions of acceptability became evident only in the past several decades. This is largely because safe engineering practice was defined by engineers as a professional issue, not as a public issue. This perspective began to be challenged in the 1960s and 1970s, when the public nature of health and safety decisions became more apparent, and when public willingness to delegate decision-making authority over risk questions began to erode. Under the traditional engineering approach, engineers looked to their peers for a determination of acceptable risk in engineering practice. Under the more recent approach, public participation in risk decisions, and particularly in the value judgments that determine the acceptability or nonacceptability of risk in a particular context is recognized as essential. This may not be relevant, however, to the acceptability of space exposures to radiation, where the public is not at risk.

One, if not the major, motivation for using quantitative risk assessments for risk management is that such an approach permits a conceptual separation between the technical factors which determine risk and the political factors which bear on risk management. Implementation of this separation is still in progress. A primary consequence of this change is that acceptable risk, especially for newer technologies, is difficult to determine and defend. Yet the question of risk acceptability is inescapable in most technological undertakings.

The long-term historical definition of acceptable risk is briefly described in the following section; a subsequent section reviews comparative and analytical approaches proposed to develop workable definitions of acceptable risk, including publicly derived risk criteria. Finally, the way in which diverse objectives for risk management become apparent in risk standard setting is described.

## A Historical Overview

Hammer (1980) describes legal milestones in product liability from ancient times to the present in terms of the broad trends that have occurred; this provides a useful perspective on our current situation. According to Hammer's review, the balance between an individual's right to be free from imposed risks and the right of a producer to make less-than-perfectly- safe products has undergone two basic transitions. The ancient ethic of "an eye for an eye," as codified in the Code of Hammurabi, established that a person was liable and required to suffer the same injury he caused, whether or not the injury was intentional. The implementation of this rule seems unfair from our present perspective, *e.g.*, if a house fell down and killed the son of the owner, the builder's son would be put to death. Hammer notes how, with time, the law evolved to permit financial restitution in place of punishment where harm was unintentional. Presumably, such compromises provided for houses that did not fall down for the most part, and also permitted sufficient incentives for people to be builders.

Under the British law that followed the onset of the Industrial Revolution and on which American law was in part based, this balance of rights and responsibilities was dramatically altered. The need to follow good safety practices and to compensate injured parties was seen as an impediment to progress. Industrial development was regarded as an unmixed blessing much more then than now, and it followed that obstacles to such development, such as claims by injured parties, were not regarded as socially desirable. A major British Court decision in 1842, referred to as the Rule of Privity, established that a seller is liable for injuries caused by his product only with those with whom he has a contract, *e.g.*, the direct purchaser of the product. The case at issue is somewhat relevant to the purpose of this symposium on space radiation, in that it involved an occupational injury. The ruling in this case was that a coach driver for the mail service was not due compensation for an injury caused by a defective wheel, because the driver's contract was with the mail service, not with the coach builder. While the driver had a contract with the mail service, it was the coach builder and not the mail service that manufactured the defective wheel, so neither the mail service nor the coach builder was liable. Hammer quotes the decision by Lord Arbinger in the landmark case: "every passenger, or even any person passing along the road, who was injured by the upsetting of the coach, might bring a similar (legal) action. Unless we confine the operation of such contracts as this to the parties who entered into them, the most absurd and outrageous consequences to which I can see no limit would ensue."

Since the mid-nineteenth century, the law has shifted substantially. Many laws and court decisions have established consumers rights and producers responsibilities, and the Rule of Privity has been eliminated. In particular, in the United States during the 1960s and 1970s, many changes occurred which strengthened consumer's rights to protection and recovery of damages. Much responsibility for safety was shifted back onto the producer; laws and courts extended protection to bystanders and employees as well as to customers, and restricted a producer's ability to avoid responsibility through warnings or contract provisions.

Many other changes in social risk management have occurred in the past several decades. The use of government regulation, in place of and in addition to the tort system, has been one such change. This is partially due to the recognition that many modern risks are not well managed by the trial and error method embodied in tort law. The recent emphasis on risk from a rights perspective, coupled with improvements in analytic capabilities to measure extremely small risks, has created new areas for tort law that are still being untangled. And the increasing recognition that laws and court decisions intended to help consumers can have perverse effects (as by reducing the number of producers or insurers) is influencing efforts to find a socially acceptable way to make acceptable risk decisions. It is against this evolving perspective that analytical approaches to determine acceptable risk have emerged.

## Risk Comparisons

One basic way to consider the acceptability of a risk is to compare it to other risks. Comparisons, in their simplest form, serve as benchmarks for the calibration of intuition. Where the mathematical expression of risk is unfamiliar, as with an annual probability of death of $10^{-6}$, a comparison can help, *e.g.*, "the risk is twice as great as being struck and killed by lightning," or "the same chance of death as driving 100 miles, on average." While these are perhaps familiar reference points, the use of comparisons for judging the acceptability of risk is controversial. One criticism concerns the comparison of dissimilar risks, as Kirk Smith notes (Smith, 1980):

> ."...a risk assessment procedure must demonstrate the relevance of the comparison. If tonsillectomies, for illustration, are less dangerous per hour than open-heart operations, it doesn't necessarily mean that the latter are too risky or that hospitals should be encouraged to remove more tonsils and to open fewer hearts. Nor does it mean that a particular energy system is acceptable merely because it is less dangerous than a tonsillectomy. The social benefits of these activities are so different that direct comparisons of their risks are nearly meaningless."

A different point of view was expressed by Lord Rothschild in an opinion piece in The Wall Street Journal in 1978 (Rothschild, 1978): "There is no point in getting into a panic about the risks of life until you have compared the risks which worry you with those that don't, but perhaps should" (Rothschild, 1978).

These perspectives are not necessarily in conflict. Smith's point is simply that the existence of a large risk does not excuse a small one when the benefits and other contextual factors are different; Lord Rothschild's point is that social concern and attention to risk should bear some relation to the magnitude of risk. What these contrasting quotes illustrate is that risk comparisons, while helpful for describing a risk situation, can also be used to promote a point of view that a risk should be accepted since it is smaller than some other, accepted risk. But when the context between the two risks is different, for example, when the benefits from the underlying activities are not the same, this type of comparison can be seen as manipulative.

One source of confusion regarding risk comparisons is that risk can be measured many ways. There are conflicting views among risk analysts regarding the appropriate expression for risk, quite separate from the complex way in which the characteristics of risk correspond to its public perception. Risk analysts frequently describe a risk by its expectation;

sometimes referring to this value as societal risk. This measure is appropriate when the primary objective of risk management or of a risk-related decision is to minimize consequences over a large population, in which the risk to any individual is very small. But surprisingly few risk standards and decisions appear to be based solely or even primarily on expectation. More often, individual risk is the risk measure of interest in regulation.

The description of a risk by its expectation or by individual levels of risk is not just an arbitrary question of units. The choice of a measure refers to the rights versus efficiency perspective described above. Individual risk is used where the primary concern is whether individuals are being exposed to inequitably high risks. Expected risk consequences, *e.g.*, fatalities or disability days are appropriate when the focus is efficiency, *i.e.*, to minimize social consequences when no individual is at an inequitable level of risk.

For occupational radiation exposures, dose limits are generally expressed as an annual limit and some cumulative limit such as lifetime (NCRP, 1993) or 5 y (ICRP, 1991). For space activities, the limit has been expressed in terms of 30 d, quarterly, annual and career (NCRP, 1989). The perspective obtained from proposed limits may differ significantly depending on which measure is used. For example, some recreational activities that are quite risky on an hourly basis (*e.g.*, rock climbing) do not stand out on an annual basis because few hours are spent engaged in the activity per year, on average. Although one commonly sees these risks expressed as annual averages, a different perspective is obtained from the hourly basis. In Chauncey Starr's influential paper (Starr, 1969) the hourly basis was selected since, Starr reasoned, this more closely resembled the decision basis for voluntary, recreational risks. On this basis, Starr noted a significant difference between the level of risk accepted from self-imposed risks and involuntary exposures. As Starr put it, "we are loathe to let others do unto us what we happily do to ourselves."

A frequently made comparison for radiation exposures is to compare anthropogenic sources with natural sources. The implied logic, occasionally made explicit (see Adler and Weinberg, 1978) is that since we are indifferent to small variations in natural exposures, we should also be insensitive to man-made exposures smaller than the natural variance. In the case of the dose limits accepted for space activities, the incremental doses are not small in comparison to background, so the utility of these comparisons is not as great as for setting standards for the general public.

A major difficulty of using risk comparisons as an aid to judging risk acceptability was noted by Kirk Smith in the quote above: the relevance of the comparison must be established. Even when a relevant comparison can be made, often other factors are important to a decision. Decisions which depend solely on risk are rare. For example, it is frequently noted that commercial air travel is safer than travel by automobile. But this does not mean that one should fly even when it is cheaper and more convenient to drive. Risk may be the only significant consideration in the selection of a medical treatment, but cases in which risk is the only factor that matters are rare. Risk is not judged to be acceptable or not, technologies are. However, risk can be a disqualifying factor for a technology, regardless of other characteristics.

## Analytical Approaches

The revealed preferences method to understand acceptable risk was suggested by Starr (1969). The approach is based on an interpretation of actual, observable social risk acceptance, generalized to reveal the implied risk-taking values of the observed patterns, applicable to new risk contexts. Starr's primary conclusion was that risk-taking increased with increasing benefit, subject to an apparently significant distinction between the acceptability of voluntary and involuntary risks. There are several limitations with this approach. As Starr notes, "this empirical approach provides some interesting insights into accepted social values relative to personal risk. Because this methodology is based on historical data, it does not serve to distinguish what is 'best' for society from what is 'traditionally acceptable.'" Even so, the revealed preferences approach has been useful in illuminating social values toward risk taking.

A common analytical approach to questions of acceptable risk is cost-benefit analysis. While this method provides an accounting framework for project evaluation and comparison, it does not directly provide insight into the acceptability of risk—values regarding risk taking must be imported into the analysis. The common way in which this has been done is by analyses of willingness-to-pay for risk reduction, typically based on evidence from wage premiums paid to workers in hazardous occupations. This is a revealed preference approach constrained to fit an economic model. A difficulty with such studies is that jobs, like technologies, are not evaluated on risk grounds alone. In particular, high risk jobs may be held by workers with limited alternative employment opportunities and poor education; the degree to which this evidence regarding risk-taking values can be extrapolated to the general population is disputable. For the case of the highly competitive occupation of astronaut, it seems likely that the risk does not act as a deterrent to the many benefits associated with the occupation, including excitement, prestige and an opportunity to win a place in history.

Decision analysis provides another analytic framework useful for evaluating risk decisions. But, as with cost-benefit analysis, the values regarding social risk taking are exogenous to the method. A contribution of decision analysis to the issue of acceptable risk has been to challenge whether the question is meaningful—whether acceptable technology is not a more relevant perspective than acceptable risk, for example. Decision analysts regard the risk associated with the preferred decision alternative as acceptable. This view which attempts to seek numerical meaning for risk acceptability is meaningful only in context even though it seems to be widely held among those who study social values related to risk concerns.

The limited degree to which people understand the level of risk they face, and their lack of detailed knowledge of the availability and costs of methods to reduce that risk, is a limitation in all revealed preferences studies. It is more likely that people act on their perceptions of risk. There is a rich psychological literature on the subject; two points are particularly relevant to the issue of acceptable risk. First, psychological surveys show that subjective rankings of risk differ from expected fatality estimates in a consistent way. Perceived risk rankings are elevated for risks which are highly uncertain and believed to be catastrophic, among other characteristics (Fischhoff *et al.*, 1978). Another persistent pattern in perceived risk is a scale compression (Lichtenstein *et al.*, 1978). Low probability risks are seen as being relatively more likely than they are.

The analytical approaches to define acceptable risk are logically sound and self-consistent, and make explicit the decision structure, assumptions and value judgments of the analysis. This can be extremely useful when detailed documentation of a decision is required, or when the same decision is preferred under a wide range of value judgments or analytical assumptions. But applications of analytic approaches to social risk decisions have important limitations. Often political compromises can best be made when values are not made explicit, and in some cases Congress has established regulatory approaches in which cost-benefit balancing is not permitted. The menu of decision options a competent analyst might develop can be inconsistent with regulatory structure, as when responsibilities to regulate different decision options are distributed to different agencies. Finally, analytic decision methods, applied to public problems, are difficult to apply when facts are in dispute and analysts face difficulties in determining which risk weights or values to use.

## Setting Risk Standards—The Criteria

Although there are many approaches to regulate risks, a common list of considerations applies. The relative emphasis given to each decision factor shapes the regulatory approach. Important factors are:

- Risk: Risk means different things under different laws, just as it means different things to different risk analysts. In some cases, it can refer to the severity of damages without regard to probability (*e.g.*, the Delaney Clause regarding food additives);[1] in other cases it includes consideration of the likelihood of impact. As noted above, risk sometimes refers to individual risk, at other times to anticipated or expected consequences in a population.
- Benefit: In the historical usage, benefit refers to the social benefits of technology, against which risks are considered. This is the prevailing usage in cost- benefit studies of water resource issues, where benefits often include new recreational opportunities and reduced flood losses. However, as decisions have come to be made on marginal risk control, benefit has come to mean the benefits associated with a risk reduction.
- Alternative Risks: Often a decision to reduce or control one risk requires acceptance of an alternative risk. In such cases, the potential for risk reduction may be determined by such alternative risks. Failure to recognize and examine alternative risks can lead to risk-increasing actions; this is a problem associated with fragmented regulatory responsibility (Whipple, 1985).
- Risk Control Opportunities: Clearly the characteristics of risk control alternatives, notably their efficacy and cost, are important factors in risk management. One approach to risk regulation is to simply prescribe which control alternatives are to be applied. A drawback with this method is that it provides little incentive for finding innovative methods for reducing risk.
- Statutory, Political and Practical Considerations: It is apparent that the concern many people express regarding various sources of technological risk does not proportionately reflect the health impacts arising from that risk. Perceptions and attitudes toward risk are influenced by a variety of risk characteristics (*e.g.*, newness, uncertainty) as well as by the context in which exposures to risk occur. Statutory requirements and political pressures often reflect these attitudes in the way in which risk management responsibility is defined.

[1]Editor's Note: The Delaney Clause was repealed by the Food Protection Act of 1996.

In some cases, the admissible array of decision criteria are limited to risk measures, and other decision criteria (*e.g.*, economic factors) are not legitimately considered. Practical or institutional considerations in implementing a safety standard are also important; these include the political response by interested parties, the time and cost required to reach a decision, its enforceability, the degree to which the agency and its management will be open to criticism, even in hindsight, and the other issues competing for resources and attention.

## Setting Risk Standards—Approaches

The list of decision factors relevant to risk decisions, including standard setting, is long; to formally include all these factors in a decision would require elaborate and well articulated decision criteria, as well as time and money. However, these criteria are not precisely defined; they emerge from a number of laws, policies and past decisions over a period and are inconsistent, context-dependent and time-varying. While analysis may be useful in such problems, many decision factors are only considered judgmentally. But while no agency follows a recipe to set standards, there are three basic decision processes that frequently appear. These are cost-benefit or cost-effectiveness methods, risk-based approaches, and technology based standards. Each is briefly described below in terms of the degree of protection typically provided, the economic efficiency of the approach, its relation to risk substitutions, and the political factors important to its application. A somewhat more detailed version of what follows is available in Whipple (1984).

Risk standards appear in many forms—as speed limits, as allowable concentrations for a pollutant, as the number of hours per month an airline pilot may fly. Since it is usually necessary to have these standards in measurable units, it is generally not apparent how a standard was set. In fact, standards developed on one basis, for example, on the basis of available control technologies, can be and are justified in cost-benefit or risk-level terms.

- *Cost-Benefit*. Cost-benefit analysis is based on the principle that for any action (in this case, setting a standard), the benefit should exceed risk or cost, and that marginal costs equal marginal benefits. By definition, this approach is economically efficient. However, because the risk levels achieved through this process are driven by a marginal cost balance, the residual levels of risk remaining after control vary widely, and may not be considered acceptable or equitable. This approach does not generally focus attention on alternative actions even when they exist, since the major premise of cost-benefit is that a decision can be made given information about benefits and risks. Finally, marginal cost-effectiveness analysis, applied to health and safety decisions, is very difficult to justify politically when there are identified victims (*e.g.*, the Pinto gas tank).

- *Risk-Level Approaches*. A risk level or safety goal approach generally is based on the objective of ensuring that individual risks are acceptably low—where what is acceptable depends on the specific context. The advantages of this approach is that predictable levels of risk result, and that innovation in risk control is encouraged. However, such an approach does not provide for marginal balancing of cost and benefit. Because risk level approaches are often developed in conjunction with risk comparisons, the method encourages the examination of alternatives and their risks. Politically, this approach is defensible on equity grounds, however it places great weight on the credibility of risk estimates.
- *Technology Based Approaches*. Technology based approaches have long been used for setting safety standards; good engineering practice, best available control technology, as low as feasible are all examples of terms used to describe technology-based approaches. In recent applications, these methods have tended toward effective controls (*i.e.*, low risk residuals), but at a high price. Where accidents are likely to lead to identifiable victims, this approach permits the regulator to claim that the best control technology was applied.

## Applying These Approaches to Radiation Protection in Space Activities

There is a general philosophy of radiation protection endorsed by the NCRP and ICRP that involves three aspects: (1) justification—there should be no avoidable exposure to ionizing radiation without the anticipation of an offsetting benefit; (2) exposures should be limited as is appropriate for the circumstances; and (3) optimization—exposures should be as low as reasonably achievable (ALARA). In the context of the previous discussion, points (1) and (3) reflect cost-benefit and cost-effectiveness considerations, respectively, and point (2) is motivated by equity concerns.

Because the circumstances of space exposure involve a very small population at potentially high doses, there seems to be little value in considering the issue from an overall cost-benefit perspective. Even including the concept of ALARA is unlikely to have a significant effect in reducing exposures.[2] This is because, under a cost-benefit framework, the imputed social cost of exposing a flight crew to several sieverts of radiation will almost certainly be in the noise level of the cost of a mission. For example, the Nuclear Regulatory Commission has used a value of $1,000 per person-rem averted ($100,000 per person-Sv averted) to determine cost-effective actions to reduce radiation exposure. Since this value dates from the 1970s, adjustment for inflation and perhaps for an increased aversion to radiation exposure may justify a higher value, *e.g.*, $500,000 per person-Sv. At $500,000 per person-Sv averted, and a risk of fatal cancer of $5 \times 10^{-2}$ per Sv, the value works out to $10 million per fatal cancer averted. Elimination of exposures of 2 Sv to a 5 person flight crew would be justified under ALARA if it could be done for $10 million; smaller increments of reduction would justify smaller expenditures.

For a small population at high doses, equity considerations become dominant. In comparison to a cost-benefit approach, a more appropriate framework for radiation exposures in space is to establish a limit on exposure based on the avoidance of a risk that is simply too high to be accepted. This approach has been the basis for past limits. In its 1989 report, NCRP recommended a three percent lifetime risk limit, based in part on comparisons with high-risk occupations; As Dr. Sinclair pointed out earlier today, the logic used in this report would probably provide for a somewhat lower limit today because occupational risks have fallen steadily.

An issue regarding the relevance of the comparison of radiation exposures in space to hazardous occupations should be noted: Occupational risks that can be reliably counted involve accidental fatalities, not delayed health risks of increased cancer. These risks differ in many characteristics that are important factors in how risks are perceived.

An alternate point of comparison was noted in a 1967 NAS report (NAS/NRC, 1967) where it considered the incremental risks of radiation in relation to the overall mission risks. If the radiation adds only a small increment to otherwise high but acceptable mission risk, then the small radiation risk increment should not be a determining factor.

[2]There may be, however, isolated situations where the application of ALARA would result in decreased exposure at small cost,*e.g.,* scheduling of extravehicular activities at times of low exposure dose rates.

## Conclusions

The definition of acceptable risk is a political judgment, dependent on context. Analysis can contribute to the process that determines what risk will be accepted in a given situation, but only as an aid to judgment. It is in this role that analytical methods, including cost-benefit approaches and comparisons of risk are helpful to current risk decisions. No analytical approach so far identified has proved practical for dealing with the complex objectives common to risk decisions, although such methods can help explain and defend decisions and can identify weaknesses with judgmentally developed approaches.

The perspective of the Himalayan mountaineer noted at the beginning of this paper provides a paradox: The risks from radiation exposures received in space activities are significant when viewed from the conventional perspective of other occupational risks, but this is not a perspective of a Himalayan mountaineer.

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# Perception and Acceptance of Risk from Radiation Exposure in Space Flight

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## Abstract

There are a number of factors that influence how a person views a particular risk. These include whether the risk is judged to be voluntary and/or controllable, whether the effects are immediate or delayed, and the magnitude of the benefits that are to be gained as a result of being exposed to the risk. An important aspect of the last factor is whether those who suffer the risks are also those who stand to reap the benefits. The manner in which risk is viewed is also significantly influenced by the manner in which it is framed and presented. In short, risk does not exist in the world independent of our minds and cultures, waiting to be measured. Assessments of risk are based on models whose structure is subjective and associated evaluations are laden with assumptions whose inputs are dependent on judgments. In fact, subjectivity permeates every aspect of risk assessment. The assessment of radiation risks in space is no exception. The structuring of the problem includes judgments related to the probability, magnitude, and effects of the various types of radiation likely to be encountered and assumptions related to the quantitative relationship between dose and a range of specific effects, all of which have associated uncertainties. For these reasons, there is no magic formula that will lead us to a precise level of acceptable risk from exposure to radiation in space. Acceptable risk levels must evolve through a process of negotiation that integrates a large number of social, technical, and economic factors. In the end, a risk that is deemed to be acceptable will

be the outgrowth of the weighing of risks and benefits and the selection of the option that appears to be best.

## Introduction: The Psychometric Paradigm

What do we know about the perception and acceptance of risk from radiation and other hazards and what are the implications of this knowledge for acceptance of radiation exposure in space?

Research on perception and acceptance of risk had its origin in a stimulating article in *Science* by Starr (1969) titled "Social Benefit Versus Technological Risk." Starr's paper sought to develop a method for weighing technological risks against benefits to answer the fundamental question, "How safe is safe enough?" His *revealed preference* approach assumed that, by trial and error, society arrives at an essentially optimum balance between the risks and benefits associated with any activity. Under this assumption, one may use historical or current risk and benefit data to reveal patterns of "acceptable" risk/benefit trade-offs. Examining such data for eight industries and activities, Starr concluded that (1) acceptability of risk from an activity is roughly proportional to the third power of the benefits from that activity; (2) the public will accept risks from voluntary activities (such as skiing) that are roughly 1,000 times as high as it would tolerate from involuntary activities (such as food preservatives) that provide the same level of benefits; and (3) the acceptable level of risk is inversely related to the number of persons exposed to the risk.

My colleagues and I decided to replicate Starr's work by asking people directly about their perceptions of risk and benefits and their *expressed preferences* for various kinds of risk/benefit trade-offs. These studies, in what has come to be known as the "psychometric paradigm," showed that expressed preferences also supported Starr's argument that people are willing to tolerate higher risks from activities seen as highly beneficial. But, whereas Starr concluded that voluntariness of exposure was the key mediator of risk acceptance, expressed preference studies have shown that other (perceived) characteristics such as familiarity, control, catastrophic potential, equity and level of knowledge also seem to influence the relationship between perceived risk, perceived benefit, and risk acceptance (Slovic, 1987).

Various models have been advanced to represent the relationships between perceptions, behavior and these qualitative characteristics of hazards. As we shall see, the picture that emerges from this work is both orderly and complex.

## Factor-Analytic Representations

Many of the perceived characteristics of risk are highly correlated across a wide range of hazards. For example, hazards judged to be "voluntary" tend also to be judged as "controllable"; hazards whose adverse effects are delayed tend to be seen as posing risks that are not well known. Investigation of these relationships by means of factor analysis has shown that the broader domain of characteristics can be condensed to a smaller set of higher-order characteristics or factors.

The factor space presented in Figure 1 has been replicated across groups of lay people and experts judging large and diverse sets of hazards. Factor 1, labeled "dread risk," is defined at its high (right-hand) end by perceived lack of control, dread, catastrophic potential, fatal consequences, and the inequitable distribution of risks and benefits. Nuclear weapons and nuclear reactor accidents score highest on the characteristics that make up this factor. Factor 2, labeled "unknown risk," is defined at its high end by hazards judged to be unobservable, unknown, new and delayed in their manifestation of harm. Chemical technologies score particularly high on this factor. A third factor, reflecting the number of people exposed to the risk, has been identified in several studies. Making the set of hazards more or less specific (for example, partitioning nuclear power into radioactive waste, uranium mining, and nuclear reactor accidents) has had little effect on the factor structure or its relationship to risk perceptions.

Research has shown that lay people's risk perceptions and attitudes are closely related to the position of a hazard within this type of factor space. Most important is the horizontal factor "dread risk." The higher a hazard's score on this factor (the farther to the right it appears in the space), the higher its perceived risk, the more people want to see its risks reduced, and the more they want to see strict regulation employed to achieve the desired reduction in risk. In contrast, experts' perceptions of risk are not closely related to any of these various risk characteristics or factors. Instead, as noted earlier, experts appear to see riskiness as synonymous with expected annual mortality. As a result, many conflicts concerning "risk" may result from experts and lay people having different definitions of the concept.

## Perception of Radiation Risk

Numerous psychometric surveys conducted during the past decade have examined perceptions of risk and benefit from various radiation technologies. This work shows that there is no general pattern of

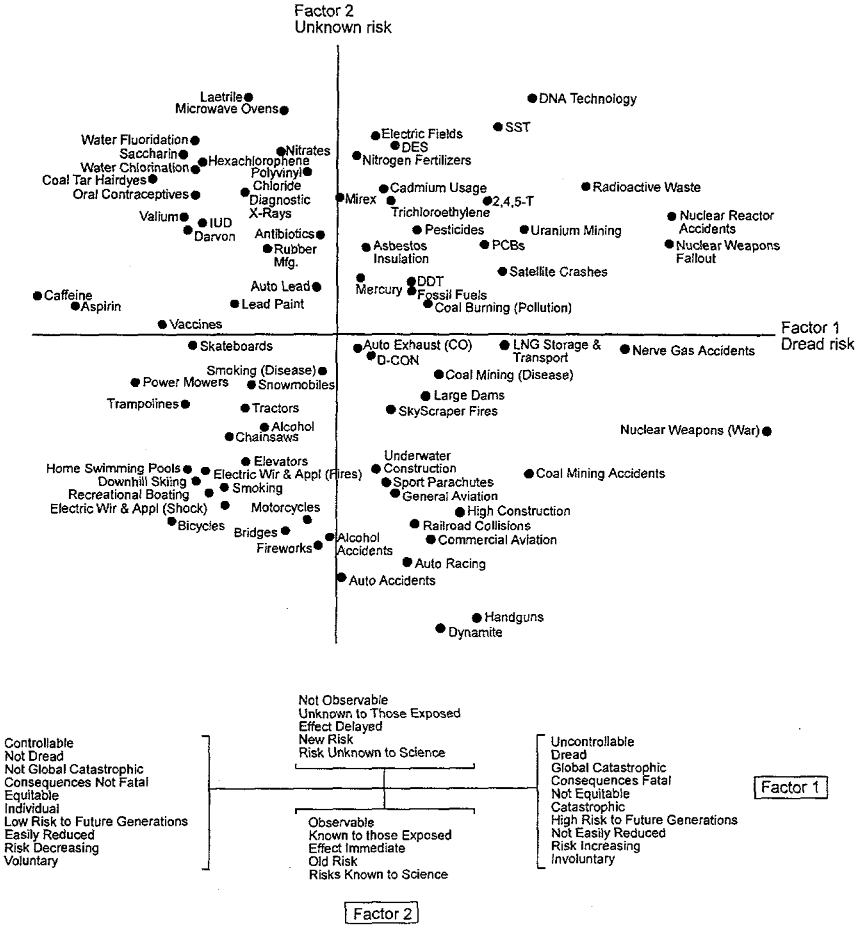


**Fig. 1.** Location of 81 hazards on Factors 1 and 2 derived from the interrelationships among 15 risk characteristics. Each factor is made up of a combination of characteristics, as indicated by the lower diagram (redrawn from Slovic, 1987).

perception for radiation. Different sources of radiation exposure are perceived in different ways. This was evident in the first psychometric study, summarized in Table 1. There we see that three groups of laypersons perceived nuclear power as having very high risk (rank 1, 1, and 8 out of 30 hazards) whereas a group of risk-assessment experts had a mean risk rating that put nuclear power 20th in the hierarchy. Note also that the three groups of laypersons judged medical x rays relatively low in risk (ranks 22, 17 and 24), whereas the experts placed it 7th. Thus, we see that two radiation technologies were perceived differently from one another and differently in the views of experts.

Table 1—*Ordering of perceived risks for 30 activities and technologies. The ordering is based on the geometric mean risk ratings within each group. Rank 1 represents the most risky activity or technology*

| Activity or Technology | League of Women Voters | College Students | Young Business Leaders | Experts |
|---|---|---|---|---|
| Nuclear power | 1 | 1 | 8 | 20 |
| Motor vehicles | 2 | 5 | 3 | 1 |
| Handguns | 3 | 2 | 1 | 4 |
| Smoking | 4 | 3 | 4 | 2 |
| Motorcycles | 5 | 6 | 2 | 6 |
| Alcoholic Beverages | 6 | 7 | 5 | 3 |
| General (private) aviation | 7 | 15 | 11 | 12 |
| Police work | 8 | 8 | 7 | 17 |
| Pesticides | 9 | 4 | 15 | 8 |
| Surgery | 10 | 11 | 9 | 5 |
| Fire fighting | 11 | 10 | 6 | 18 |
| Large construction | 12 | 14 | 13 | 13 |
| Hunting | 13 | 18 | 10 | 23 |
| Spray cans | 14 | 13 | 23 | 26 |
| Mountain climbing | 15 | 22 | 12 | 29 |
| Bicycles | 16 | 24 | 14 | 15 |
| Commercial aviation | 17 | 16 | 18 | 16 |
| Electric power (non-nuclear) | 18 | 19 | 19 | 9 |
| Swimming | 19 | 30 | 17 | 10 |
| Contraceptives | 20 | 9 | 22 | 11 |
| Skiing | 21 | 25 | 16 | 30 |
| X rays | 22 | 17 | 24 | 7 |
| High school & college football | 23 | 26 | 21 | 27 |
| Railroads | 24 | 23 | 20 | 19 |
| Food preservatives | 25 | 12 | 28 | 14 |
| Food coloring | 26 | 20 | 30 | 21 |
| Power mowers | 27 | 28 | 25 | 28 |
| Prescription antibiotics | 28 | 21 | 26 | 24 |
| Home appliances | 29 | 27 | 27 | 22 |
| Vaccinations | 30 | 29 | 29 | 25 |

Figure 1 further illustrates the differences in perception of various radiation hazards. Note that nuclear reactor accidents, radioactive waste, and fallout from nuclear weapons testing are located in the upper-right quadrant of the factor space, reflecting people's perceptions that these technologies are uncontrollable, dread, catastrophic, lethal and inequitable in their distribution of risks and benefits. Diagnostic x rays are perceived much more favorably on these scales, hence they fall in the upper-left quadrant of the space. Nuclear weapons fall in the lower-right quadrant, separating from nuclear-reactor accidents, nuclear waste, and fallout on the scales measuring knowledge, immediacy of effects, and observability of effects.

Although Table 1 and Figure 1 represent data from small and nonrepresentative samples collected a decade or more ago, recent surveys of the general public in the United States, Sweden and Canada show consistently that nuclear power and nuclear waste are perceived as extremely high in risk and low in benefit to society, whereas medical x rays are perceived as very beneficial and low in risk. Studies in Norway and Hungary have also obtained these results.

The powerful negative imagery evoked by nuclear power and radiation is discussed from a historical perspective by Weart (1988). Weart argues that modern thinking about radiation employs beliefs and symbols that have been associated for centuries with the concept of transmutation—the passage through destruction to rebirth. In the early decades of the 20th century, transmutation images became centered on radiation, which was associated with "uncanny rays that brought hideous death or miraculous new life; with mad scientists and their ambiguous monsters; with cosmic secrets of life and death;... and with weapons great enough to destroy the world..." (p. 42).

But this concept of transmutation has a duality that is hardly evident in the imagery associated with nuclear power and nuclear wastes. Why has the evil overwhelmed the good? The answer undoubtedly involves the bombing of Hiroshima and Nagasaki, which linked the dread images to reality.

Additional insights into the special quality of nuclear fear are provided by Erikson (1990), who draws attention to the broad, emerging theme of toxicity, both radioactive and chemical, that characterizes a "whole new species of trouble" associated with modern technological disasters. Erikson describes the exceptionally dread quality of technological accidents that expose people to radiation and chemicals in ways that "contaminate rather than merely damage;... pollute, befoul, and taint rather than just create wreckage;... penetrate human tissue indirectly rather than wound the surface by assaults of a more straightforward kind" (p. 120). Unlike natural disasters, these accidents are unbounded. Unlike conventional disaster plots, they have no end.

> "Invisible contaminants remain a part of the surroundings—absorbed into the grain of the landscape, the tissues of the body, and, worst of all, into the genetic material of the survivors. An 'all clear' is never sounded. The book of accounts is never closed." (p. 121)

Erikson's "contamination model" may explain, in part, the reaction of the public to exposures to carcinogens. Numerous studies have found that a high percentage (60 to 75 percent) of people believe that if a person is exposed to a chemical that can cause cancer, that person will probably get cancer some day. A similarly high percentage believe that "exposure to radiation will probably lead to cancer some day." The belief that *any* exposure to a carcinogen is likely to lead to cancer tends to coincide with the belief that it can never be too expensive to reduce such risks. Therefore, it is not surprising to find in an analysis by Tengs *et al.* (1995) of more than 500 life-saving interventions that radiation controls in industry were associated with the highest costs per year of life saved.

Table 2 summarizes the status of perceived risk for six radiation technologies, contrasting the views of technical experts with the views of the general public. In addition to nuclear power, nuclear waste, x rays, radon and nuclear weapons, food irradiation (Bord and O'Connor, 1990) and electric and magnetic fields (EMF) (a source of nonionizing radiation), are included in the table, although there is relatively less information about perceptions of these two sources. We see that there is typically disagreement between the experts and the public regarding the level of risk and its acceptability. To my knowledge there have been only two published studies thus far of perceptions of risk from electric and magnetic fields. Both of these studies, by Morgan *et al.* (1985) and MacGregor *et al.* (1994), found that perceived risks associated with fields from home appliances and electric blankets were relatively low, and that perceived risks associated with large power lines were relatively high. Both studies also showed that, when the respondents were given a briefing about research on health effects of electric fields (which said that many studies had been done but no adverse human health effects had yet been reliably demonstrated), their perceptions on subsequent retest shifted toward higher perceived risk. MacGregor *et al.* found that this briefing (in the form of a brochure) also led to increased dread (particularly regarding power-line risks), less perceived equity, and greater concern regarding effects of EMF on the nervous system, the immune system, cell growth and reproduction, chronic depression, and cancer.

## Lessons

What does this psychometric research tell us about the acceptance of risk from radiation? There seem to be several lessons:

First, although many technical experts have labeled public reactions as irrational or phobic, such accusations are clearly unjustified

Table 2—*Summary of perception and acceptance of risks from diverse sources of radiation exposure.*

| | Perceived risk | |
|---|---|---|
| | Technical experts | Public |
| Nuclear power/ nuclear waste | Moderate risk | Extreme risk |
| | Acceptable | Unacceptable |
| X rays | Low/moderate risk | Very low risk |
| | Acceptable | Acceptable |
| Radon | Moderate risk | Very low risk |
| | Needs action | Apathy |
| Nuclear weapons | Moderate to extreme risk | Extreme risk |
| | Tolerance | Tolerance |
| Food irradiation | Low risk | Moderate to high risk |
| | Acceptable | Acceptability questioned |
| Electric and magnetic fields | Low risk | Significant concerns beginning to develop |
| | Acceptable | Acceptability questioned |

(Drottz-Sjöberg and Persson, 1993). There is a logic to public perceptions and behaviors that has become apparent through research. For example, the acceptance afforded x rays suggests that acceptance of risk is conditioned by perceptions of direct benefits and by trust in the managers of the technology, in this case the medical profession. The managers of nuclear-power technologies are clearly less trusted and the benefits of this technology are not highly appreciated, hence their risks are less acceptable. High risks from nuclear weapons are tolerated because of their perceived necessity (and probably also because people lack knowledge about how to intervene in military security issues; they do have such knowledge and opportunities to intervene in the management of nuclear power).

The apathetic response to the risk from radon appears to result from the fact that it is of natural origin, occurring in a comfortable, familiar setting, with no one to blame. Moreover, it can never be totally eliminated.

## Risk Acceptance on the Mountaintop and in the Workplace

As shown above, psychometric surveys can give us insights into the determinants of perceived and acceptable risk from a wide variety of hazardous activities. But what about space flight in particular? Are astronauts adventurers, explorers, or workers, or all of these simultaneously? Certainly there are some missions that are more exploratory and more adventurous than others, a trip to Mars comes first to my mind as an example. In this perspective, we might look for guidance in the acceptance of risk from some of the most dangerous terrestrial activities—such as high-altitude mountain climbing. It is said that about one in ten Everest climbers dies in the attempt, and just a few weeks ago, eight climbers lost their lives on Everest in a severe storm. Everest climbers, and society, obviously accept a high level of known risk from a voluntary activity that is challenging and highly satisfying to the participants. To the extent that astronauts are adventurers and explorers voluntarily accepting known risks, the threshold of acceptability should be high—as it is for mountain climbers.

On the other hand, astronauts are also workers, and in the future more of their activities will be "routine"—maintaining a space station, for example. When we think of astronauts as workers, we may gain insight into acceptance of risk from a book that Dorothy Nelkin and Michael Brown published titled *Workers at Risk: Voices from the Workplace* (Nelkin and Brown, 1984).

### "It's Worth the Risk"

A number of people, mainly those in professional and skilled jobs, told us frankly that their work was "worth the risks." Aware of the hazards, they accept them as a trade-off for the personally gratifying benefits of their jobs. While often very careful to protect themselves, they measure the risks against the satisfaction of their work and the priorities of their careers. Fire fighters feel the risks are small compared to the satisfaction of saving lives. A deck hand is willing to take risks because she values her autonomy. Artists value the opportunities for creativity. A painter and a rose gardener love the aesthetic quality of their jobs.

*from Nelkin and Brown (1984, p. 97)*

Nelkin and Brown interviewed 75 workers from a wide variety of occupations, all of whom were exposed to rather dangerous chemicals. The book is a qualitative description of these workers' attempts to cope with the fact that their occupations put them in daily contact with dangerous substances. I think that this study definitely has relevance for the astronauts' situations. Nelkin and Brown observed that there were tremendously diverse reactions of workers to these chemical exposures, from very negative, hostile reactions among some workers to others who were really quite comfortable with the exposures, feeling that "It's worth the risk" (see box). They found that people in highly professional and skilled jobs (like astronauts) tended to feel that their work was worth the risks. Such individuals found the benefits high (again we see the relationship between perceived benefit and acceptance of risk), and the work very satisfying. They tended to downplay or deny the risk and really were not dwelling on it as did those who did not like their employment. Nevertheless, despite the fact that some people were very comfortable with the risks of their job, the overall message that Nelkin and Brown took from this extensive series of interviews was that workplace hazard is a serious concern to those at risk.

Nelkin and Brown (1984) concluded:

> "Hearing these voices, we believe they carry a critical message—that the pervasive presence of chemical risks in the workplace has profound human costs in terms of anxiety as well as of illness. With the proliferation of chemicals in so many occupations, such concerns are likely to have an increasing effect on collective bargaining, on compensation claims, and on the general morale of the work force. Thus the voices of workers, their identification of problems, their insights, and their views must be heard. They are critical to the creation of a more humane working environment." (p. 183)

I certainly believe that we need to take this perspective with regard to our astronauts as well, and to listen to their concerns about safety.

## Some Concluding Remarks About Acceptance of Radiation Risks in Space

There is no magic formula that leads us to a precise level of acceptable risk from exposure to radiation in space. Acceptable risk levels evolve through a process of negotiation that must integrate a large number of social, technical and economic factors. The research described above indicates many of the factors that are important in this context. Some of them lead to a high degree of tolerance for radiation risk; others to a low degree of tolerance.

## The Nature of the Hazard Implies a High Degree of Tolerance or Acceptance

Just because the hazard is radiation doesn't mean that exposure cannot be tolerated. We have seen that public reaction to radiation exposure varies widely, depending upon the context of that exposure (see Table 2). Radiation in space is a natural phenomenon and we find that people are much more tolerant of voluntary natural exposures than to exposures imposed upon them by industry or some other human activity. Second, this voluntary exposure cannot be totally eliminated, much as is the case with radon. Third, the risk is latent, unobservable, and small compared to the more immediate risk of accident or failure to accomplish the mission objectives. The chronic, latent, unobservable property of radiation risk means that there will be less pressure to minimize it, in contrast to the reaction after a major accident (*e.g.*, the Challenger disaster).

The social context also fosters a high tolerance for risk in space because the work is exciting, challenging, socially visible, satisfying and valuable, much as Nelkin and Brown's firefighters who, when interviewed, said that they don't care about the risks from chemical exposures in fires because they are saving people's lives. In addition, I would assume that astronauts have a lot of confidence in the overall system in which they work and identify with NASA's organizational goals and this, too, leads to tolerance for risk. Astronauts are skilled professionals. They are also self-confident individuals, who tend to be listened to and cared about and have been successful takers of calculated risks throughout their careers. So, high levels of risk from radiation in space could be justified and probably would be accepted by all involved.

But we have to also be cognizant of the fact that the values of the astronauts may change over time and as their active flight careers wind down, they might develop a different perspective on the risks from the radiation to which they've been exposed. Society's values may change as well. We have seen occupational risk levels declining steadily over time due to pressure to make things safer. Thus the value systems that are important to the social negotiation of acceptable risk are not stable. As the number of persons exposed to risk increases, we find that tolerance for risk tends to decrease (Starr, 1969). Finally, any noticeable above-normal incidence of cancer among former astronauts could cause problems not only for the astronauts but in terms of the stigmatization of the profession and criticism of NASA's protection of its astronauts. And one might expect that astronauts, being rather fit individuals, might have a lower incidence of cardiovascular disease, which means that their base level of cancer might be high and that any additional cancer burden from radiation could lead to a noticeably higher degree of cancer among older astronauts. These are just a few of the complexities in terms of perception of risk which are relevant to the social negotiation of acceptable risk and I hope that when we hear the perspectives of the astronauts later this afternoon we can perhaps return to some of these issues. Thank you.

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# General Discussion

AMY KRONENBERG: I'm Amy Kronenberg. I'm at the Lawrence Berkeley Laboratory. I really enjoyed the presentations and the session. I'm not sure to whom I should address this question, but there was an article in last Sunday's *New York Times* magazine section about the possibility of private missions to Mars. One of the factors that this article, and your example of climbing Mt. Everest, brought to mind is that the choice of an occupation or a task as an explorer may be perceived very differently based on the cost, the literal cost, to society as a whole. The choice of an individual to go on an Everest expedition financed privately may be seen differently than the cost of a space flight funded publicly versus the cost of the space flight funded privately. So the risk perception might be different, as well as the acceptability of the risk. Would you like to comment on that?

PAUL SLOVIC: That is clearly a relevant factor as a general issue. We even see that there are pressures within the mountaineering profession to see this as something that the public is involved in. That is, if rescuers have to risk their lives and spend a lot of money to rescue people, then that changes the picture and maybe we should regulate mountain climbing more strictly. Those are real pressures in that direction. But I think also that the radiation hazard is not so visible. I mean in climbing, the accidents are visible and dramatic and everyone gets excited about them. In contrast, we're talking here about something very subtle, hidden, unobservable and I don't know that we're going to, at least for a long time, be aware of some of the differences in the levels of risk that we are talking about so I don't know that those pressures would necessarily surface in the same way.

TERRY JOHNSON: I'm Terry Johnson from George Washington University. It seems to me that the risks to astronauts of doses in the range of 40 rem lifetime would be in the category that, according to Mr. Whipple, shouldn't be quantified. That is to say, they are minuscule compared to the overall risks that astronauts, mountain climbers, deep sea divers, etc., take. And yet they can hamper the careers of the individuals. Wouldn't it be sensible for the NCRP, instead of proposing a limit, to produce a training document that could be used to fully inform the astronauts of the radiation risks involved in space travel at the time they embark on their space careers? Then we could forget the issue of proposing upper limits.

CHRIS WHIPPLE: To respond to the first comment, I don't think that's a situation where there is an either/or choice between these two points. Within the context of risk that I know about, a dose of 40 rem would represent about a two percent added lifetime risk. That's a big risk. It's by no means trivial! It would be difficult to find a risk of that magnitude being accepted in any other institutional activity.

TERRY JOHNSON: In discussing one of the risk models earlier, someone asked how you demonstrate or validate the risk. The same thing could be said about the 40 rem lifetime risk. The number cannot be validated, not for the situation where the source is low-LET and the dose is gradually accumulated. There simply is no human experiment that's ever been performed that really quantifies the risk. We are extrapolating down from data developed for doses of about 20 rem involving, in some cases, high-LET short-term exposures. For protracted exposures involving low-LET radiation, we really cannot demonstrate risk at much below 10 Sv or something like that. We certainly cannot quantify the risks of a dose of 40 rem.

WARREN SINCLAIR: I'm sure Mr. Johnson did not mean to say 10 Sv. The latest data for the Japanese World War II survivors, which is to be published shortly, goes down to 0.05 Sv. We allow a factor of two to compensate for the dose rate effect, but we're in the ball park of fairly small numbers. And we have risks for thyroid cancer, etc., in the 0.1 Sv range. Furthermore, when you're in a situation where limits are imposed by the statistics of the information, what you have to do is use models that have been shown to be applicable to situations where you do have information. The models that fit the Japanese response data are very good. I cannot see any reason that they cannot be extrapolated downward. It's the best we can do.

LARRY TOWNSEND: I'm Larry Townsend from the University of Tennessee. I want to offer several comments. A couple of times this morning I have heard something about certain radiation risks being negligible. All of us must keep in mind that on the scale of a space mission, itself, radiation may not be a big factor. But once you are back, you will carry a residual risk due to the radiation exposure. Although perhaps there was a 10 percent probability of the solid rocket booster malfunctioning during lift-off, once you have returned from the mission those probabilities disappear. The radiation risk, however, remains.

The second comment I'd like to make is to cite an element that I believe has been forgotten—that is, the range of perceptions of the various groups involved in these activities. Even though the astronauts have been told that they are in a risky business, they may be like test pilots and believe that they are invulnerable, If something happens to them, however, their families are going to care. Another group to consider is the public. The perceptions they have relative to these types of activities is largely molded by the news media. When an F-14 crashes and crew members die, the people who are involved in flying such planes will tell you that acceptance of the associated risks is just part of the job. The point is, we need to look at the perceptions of these various groups from a broader context, not only with regard to the astronauts themselves, but also with regard to their families and members of the public. I would be willing to bet that in most cases their families don't perceive the risks in the same context or magnitude as the astronauts.

STAN CURTIS: I'm Stan Curtis from the Fred Hutchinson Cancer Research Center. This is a question to both Dr. Whipple and Dr. Slovic. It came to mind as I was listening to Dr. Slovic that we have had discussions about considering two different astronaut groups. One would be the ones who would go up and construct the space station, in which they might be considered to fall in what might be called the "worker" category. And then there is a second group, those who might undertake a return trip to the moon or a mission to Mars. These people might be considered to fall in what might be called the "explorer" category. My question is whether we should consider developing and applying two different levels of acceptable risk to these two groups? Would either of the last two speakers comment on this?

PAUL SLOVIC: I think that there is a sense in which it would be legitimate to make that distinction because people themselves might make a distinction between routine work and exploration. As part of this social negotiation we could say that, if you're really exploring, you should be allowed to bear a higher level of risk. But then we get into definitions. People who are building a space station would also be considered explorers by many. If there were a clear distinction between routine work versus explorer activities, then I think it fits with everything else we do in society where we have different tolerances as a function of the value and the benefits and so forth. But we'll probably have to think hard about this distinction.

CHRIS WHIPPLE: This is a good comment. It shows that one must look at the radiation risks to astronauts from any number of perspectives. They're workers, they're explorers, and they're individuals capable of making decisions on their own behalf. I think that, while the suggested distinction is good, I would find it difficult to explain to somebody why the two groups should have different dose limits. I am not sure that it would make sense. The whole subject is sufficiently arbitrary and judgmental that, to split hairs, and say: "You're on a routine, boring bus driver kind of a mission, as opposed to the glamor of space exploration," is not something that I believe it would make sense to do.

HARRY HOLLOWAY: I'm Harry Holloway, former Associate Administrator for Life and Microgravity Sciences, NASA. I want to correct one statement that has been made. There is a whole set of items associated with long-term deep space travel that would produce permanent changes in the human body. Examples are loss of bone and loss of muscle, neither one of which is entirely healable or correctable. There are also prolonged changes in CNS functions immediately after returning from a mission. In the sense that radiation can produce long-term effects, exposures to toxins in the spacecraft environment will produce the same kinds of biochemical changes. In a similar manner, injuries such as severe burns or the loss of a limb, that cause damage to the body, are not transient in nature. I think you need to examine space travel as a totality, that is, you need to view it in the context of an event that has associated with it a number of different stresses, not a single stress that will be residual.

WALLACE FRIEDBERG: I'm Wallace Friedberg from the Federal Aviation Administration. I believe any thought that the astronauts could tolerate the doses they will receive in the space environment would go out the window if some of them are inadvertently exposed to a large solar particle event. This would especially be true if later it was found that the mission planners failed to account for the stage of the solar cycle in which the mission was scheduled and the associated probabilities of such an event.

TERRY JOHNSON: What Mr. Friedberg is referring to is a life threatening event, one that could incapacitate the entire crew. In this case, the issue of whether their limit was 40 rem or something else is going to be irrelevant. That is to say, if the dose were up where we have good evidence from the Hiroshima/Nagasaki data to say that it will definitely lead to an increased risk—say, up around 100 rem. For short term exposures in the 50 rem range, however, there is extremely slim evidence that there is any increased risk of any form of cancer or other delayed effects. For protracted exposures, the risk becomes diminishingly small.

Having said this, I would like to comment on several other items. Back to the comments of the former NASA Administrator, I believe that the decision whether astronauts will fly is made at the beginning before they accept any risk. If there is a boundary placed on their careers—that they cannot fly after receiving 40 rem—that's as much as saying that a delayed two percent risk of fatal cancer is more important than the 10 percent risk just from being an astronaut. To me, that does not make sense. With respect to sexual discrimination, the Supreme Court has already ruled on the matter. It's illegal in this country to propose any form of protection that is specific to women based upon the risks in their environment. The issue in the Johnson Controls decision pertained to protecting a pregnant woman who was being subjected to a lead hazard. Radiation was not the hazard, and the effect under consideration was not increased carcinoma, for example, breast cancer. But the court decision did not reference all of that. It just said that it's illegal in our society to propose protection for women in the workplace that does not apply to men. Nothing can be done that will limit their careers, their opportunities, their promotions, their overtime, or anything like that.

BOB YOUNG: I'm Bob Young from New World Images. I thought that the comments of Dr. Townsend were extremely cogent and I wanted to reflect on the fact that we can all agree that risk perception is different depending on who the perceiver is. This brings me to a question to pose to Paul Slovic, and perhaps Harry Holloway. That is whether some of these matters might be addressed by simply asking the astronauts to sign a consent form that fully discloses all their risks and the associated implications as best we know them. Is there any merit in this? Is it already being done?

DADE MOELLER: Rather than addressing that question now, I would suggest that we hold it for the panel session this afternoon. If there is no objection, we will now recess for the lunch period. We will resume the program promptly at 1:45 p.m. Thank you.

# Philosophy on Astronaut Protection: A Physician's Perspective

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## Abstract

The National Aeronautics and Space Administration has a responsibility to assure that proper ethical standards are applied in establishing and applying limits for the control of radiation doses to the astronauts. Such a responsibility obviously includes assuring that the astronauts are properly informed of the hazards associated with individual missions and that they agree to accept the associated risks. The responsibility, however, does not end there. It includes a need to discuss how to initiate a discourse for developing the related ethical standards and how to determine who should be involved in their establishment. To assure that such a discourse can be developed, there is a need to determine how to foster proper communications on matters that encompass the realms of policy, science, politics, and ethics. There is also a need to mesh public perceptions with those of the scientific and technical community. This will be a monumental undertaking.

## Introduction

Although my assignment is to discuss the perspective of physicians, in general, my remarks will obviously reflect many observations that are personal in nature. In this regard, two of my previous roles—serving as the first chair of the Aerospace Medicine Committee, and subsequently as Associate Administrator for the Life and Microgravity Sciences Office within NASA—will obviously influence what I have to say and, most importantly, the issues that I will raise. As an approach to this discussion, I am going to assume that you are the suppliers and that I am one of your customers. In that sense, I will share with you the types of information I need and the issues on which I need the help of your insights, understanding, and guidance. In several cases, the types of information required will be illustrated through the presentation of a series of questions.

## The Existing Database

At the present time, NASA has a database on about 220 astronauts, going back to the days of the Apollo program and continuing to the present. This includes all the astronauts for whom relatively good exposure data are available. For purposes of evaluation of the associated health impacts, we have adopted a case control approach. That is to say, we have three controls for each astronaut who has flown. These have been drawn from people who match the astronauts on a demographic basis, with oversight being provided by a council of epidemiologists. As most epidemiologists will recognize, this cannot be truly considered a case control study because of a variety of constraints. Nonetheless, our analyses of the available data fail to show any increased risk of cancer or oncologic disease among this astronaut population.

One interesting outcome of this study, however, is that astronauts have a higher rate of deaths due to accidents. This is at a highly significant level primarily due to the fire that occurred in Apollo One and the subsequent accident involving the Challenger space shuttle. In addition, there have been deaths among the astronaut group due to automobile and airplane accidents. In terms of radiation exposures, these analyses show that the largest radiation exposures for the astronauts are those associated with medical procedures involving radionuclides and x radiation.

One of the questions that has been raised is whether the radiation exposures associated with these medical procedures are ethical. Specifically, the questions that I, as a customer, need to have answered are:

- Are we observing proper ethical standards in asking that individual astronauts agree to take part in medical experiments?
- Is it proper to consider astronauts as radiation workers for purposes of establishing radiation dose limits?
- Have we selected the correct population of controls in our evaluations of the effects of radiation on the astronauts?

- Are our processes for informing the astronauts about their risks adequate, proper, and ethical?
- Is our process of informed consent acceptable and is it being properly followed?

One factor that must be recognized is that the process of obtaining informed consent has a number of ramifications. Simply because an astronaut has agreed to undergo a certain type of test is not, unto itself, a license to have him/her do it. Another consideration, in my opinion, is the fact that the United States' space program is sponsored by the public—that is, through taxes. This brings to the front the question whether the public, at present, is being provided an ample opportunity for input into the United States' space program.

## Communicating With The Public

The decision on whether the astronauts should be permitted to accept a given risk involves technical as well as policy and political considerations. From a technical standpoint, it is my belief that NASA as a customer should not assume that estimates of the risks associated with various aspects of a given space flight are accurate. If the proper decisions are to be made, we need to examine the accuracy and validity of the various inputs into the estimate, and to fully understand the process through which the risk estimates were generated.

Once this has been accomplished, we also need to be able to communicate this information in a clear and succinct manner to members of the Congress as well as the public. It would be extremely helpful if we could communicate in an understandable manner with the average wage-earner who, through his/her taxes, is making the space program possible. If this is to be accomplished, there is an urgent need to develop the statistical, as well as linguistic, tools that will allow us to discuss risk, and most specifically the risks associated with the space program, in an acceptable manner. As plans move ahead for construction of the International Space Station, and the undertaking of interplanetary space travel, we need to be able to explain what our dose limits are, how they were developed, and how we will make the measurements necessary to ensure that the limits are not being exceeded.

## Technical Considerations and Research Needs

In terms of the proposed trip to Mars, which could take several years to complete, there will be a need not only to examine the risks of cosmic radiation and solar particle events, but also to decide whether the journey should take place during a period of solar maximum or solar minimum. For missions of this duration, concerns about providing adequate protection against radiation will be paramount. Questions that need to be addressed include:

- Are the tools currently available for controlling radiation exposures adequate?
- Are there additional steps that could be developed to moderate the effects of radiation at the biological/molecular level?
- Are there steps that can be taken in the pharmacological realm?

There may be some novel approaches that can be taken in the development of radiation shields, for example, through the use of so-called nonlinear materials such as carbon filaments. Better protection might also be achieved through the design of spacecraft in which increased advantages can be taken of the use of water as a shield. Back to the need to communicate, one could ask whether members of the public should be informed about these areas of informational and/or data shortages, how we plan to develop the required data, and how it will be used to solve these problems? Also important are estimates of the associated costs and whether such expenditures are justified? *It is on the specification of these risks and how they are to be managed that we are most in need of your guidance.*

## Other Areas of Uncertainty and Opportunity

Although much is known about the effects of radiation, particularly those of an acute nature, many questions remain in terms of the long-term chronic effects. Is our information on potential injuries to the immunological system adequate? These are secondary to the effects on our capacity to produce blood. If, as I have been told, it is correct that the radiation exposures associated with a trip to Mars will be sufficient to pass through 22 percent of the cells of the body, what will be the associated consequences on the central nervous system? And are there other subacute effects that should be of concern? A definitive answer to this question is essential if interplanetary journeys of this duration are to receive widespread support from members of the public. An answer to this question is also necessary if NASA is to develop a procedure for coping with the associated ethical issues.

As pointed out by Dr. Slovic, there is also a need to develop a better understanding of the social and psychological aspects of risk. This includes the development of mechanisms through which we can relate these aspects to the mathematical and statistical concepts that grow out of the analyses developed by the great mathematician, Pascal. Also needing to be addressed is how these elements are to be married or combined so that we can communicate and make clear distinctions between the two—if, indeed, that is what is required.

Entering into the realm of these types of discussions is a range of questions that need to be addressed. Examples include:

- Who should be involved in making these types of decisions?
- If outside experts are needed, how should they be identified?
- Once such experts have been identified, what should be the criteria for deciding which are to be selected to take part in addressing a specific question?
- What and how will the public be provided an opportunity to participate?

If the public is to be involved in such decisions in a meaningful way—as the last question implies—it will mean that NASA must reach out and encourage youngsters to become interested in such problems. This age group represents the future and procedures must be developed to involve them at an early stage in their lives. This will include the necessity of developing methods for stimulating young people to seek the type of education that will qualify them to assist in solving such problems. Experience has demonstrated that young people, at one phase or another, are interested primarily in two things—dinosaurs and space. Both of these represent doors that can open the overall realm of technology to them. A side benefit that must not go unrecognized is that, as young people are taught about the risks in space, they will also learn about the risks here on earth. This is the type of guidance we need. Discussions of problems, such as the risks of radiation in space, can provide a basis for addressing more widespread problems of this nature. The outcome can provide benefits in many aspects of our lives not only now but in the future.

## Commentary and Conclusions

It is incumbent upon us as scientists to address issues of radiation doses in space in a serious manner, and to develop techniques for communicating the resulting information in a meaningful and effective manner both to our fellow scientists and the public. Our ultimate goal is to provide the safest possible environment for our astronauts. An essential part of this effort is to assure that acceptable ethical standards are applied in establishing and applying the relevant dose limits. This includes informing the astronauts of the hazards associated with individual missions and using proper procedures to confirm that they have willingly accepted the associated risks. This involves the need to foster proper communications on matters that encompass the realms of policy, science, politics, and ethics. It also involves a need to mesh public perceptions with those of the scientific and technical community. This will be a monumental undertaking but the benefits are clearly worth the effort.

# Philosophy on Astronaut Protection: Perspective of an Astronaut

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## Abstract

There are significant differences in the risks during the launch of a spacecraft, its journey, and its subsequent return to earth, as contrasted to the risks of latent cancers that may develop as a result of the associated radiation exposures. Once the spacecraft has landed, following a successful mission, the risks of accidental death are over. The risks of latent cancers, however, will remain with the astronauts for the rest of their lives. The same may be true for many of the effects of the space environment, including microgravity. Compounding the problem with respect to radiation are the large uncertainties accompanying the estimates of the associated latent cancer risks. In addition to radiation doses received as a result of being exposed in space, astronauts have received significant doses of radiation in conjunction with medical examinations and experiments conducted to obtain data on the effects of the space environment on humans. The experiments were considered to be a part of the "job" of being an astronaut, and the resulting doses were included in the medical records. Following this approach, the accompanying doses were counted against the career limits being imposed on each astronaut. As a result, volunteering for such experiments could cause an earlier termination of the career of an astronaut than would otherwise have occurred and add to the total radiation exposure, thereby increasing one's risk of subsequent illness. Through cooperative efforts, these doses have been significantly reduced in recent years. In fact, one of the outcomes of

these efforts has been the incorporation of the ALARA concept into the radiation protection program for the astronauts. The fact that a space mission has a range of risks, including some that are relatively large, is no justification for failing to reduce the accompanying radiation risk.

## Introduction

Let me begin by expressing the same disclaimer as Dr. Holloway, namely that the comments I am offering reflect my opinions and perhaps those of a few other people in the astronaut office. They do not reflect the official views of the National Aeronautics and Space Administration. In fact, you may well want to keep in mind that I am your typical paranoid and hyperchondriacal physician. As a result, I tend to be more excitable about certain medically related issues than the average member of the astronaut corps.

As background for my comments, let me also say a few things about risk and how it is viewed by some of us within the astronaut office. First, there are technical areas that one can consider, such as the risk of a catastrophic failure of the main engine. Estimates of risks of this type can be made on the basis of engineering tests and related data. For all practical purposes, the resulting estimates can be assumed to be objective and non-reflective of personal biases. Certain other sources of risk, however, do not fit into this category. Radiation is one of these. The associated risks involve both a large amount of uncertainty as well as what I will call "emotional overlay." The reasons for this are several, one being that those who have been exposed and subsequently develop an illness or disease may view it as a personal failure. Also to be noted is that, while all of us recognize that many of our daily activities carry risk, the fact that a risk has been officially sanctioned and analyzed does not necessarily mean that it's acceptable.

## Risks and Risk Perspectives

Although many of us make choices that influence the risks to which we are subjected, each of us has a different degree of comfort with different risks. The extent of the comfort, for example, may be influenced by our technical background, our personal experiences, and our personal biases. During the past 15 y, I have spent a lot of time working with pilots and, as a result, I am very comfortable with airplanes and flying. On the other hand, as a result of my technical training I am probably much more critical and much more attuned than the average person to the risks of flying. On the emotional side, I lost a very good friend in a commuter aircraft accident and so I have a somewhat greater than average uneasiness about commuter planes. I say this even though I know that such planes are certified, and the pilots are licensed. Although I realize this is not a rational decision, I cite it as an example of the personal biases that each of us has and which influence our points of view on risk.

One of the issues brought out this morning is that astronauts are subjected to a wide range of substantial risks. However, just because people are willing to accept higher risks does not mean that we should collectively permit them to do so. We should always seek to minimize the risk. Risk may be difficult to quantify, as uncertainties do exist even in the engineering world. Five days before my second flight, which was to involve orbiting the earth for 14 d, the crew was in quarantine and a small group of engineers came in and told us that "given the way the shuttle was to be oriented in space for this particular mission, the risk from catastrophic failure due to a hit by space debris or a micro-meteorite was one in thirty." In short, we had just been told that we had a chance of one in thirty of undergoing a catastrophic event. What were we supposed to do? Who, for example, among you would have been willing to take a risk like that?

The engineers then left and, noting our dismay, they returned the next day and informed us that "we miscalculated; the risk is really about one in five hundred." Our reaction was simply to sit there, look at each other, and say, "What did they find out yesterday that they did not know prior to making their first estimate?" In essence, we were initially told that a risk that we previously had not considered all that important, could be one of the dominating risks of this particular flight. When we expressed concern, the response was to reanalyze the situation and come up with a lower (more acceptable) risk. This compounded the situation and left us at a loss as what we were supposed to do with the information, especially at that point in time. Needless to say, these concerns remained with us throughout the flight. It was a difficult situation and it subsequently became a major issue within NASA.

## Risks From Radiation

Now to address the risks associated with radiation. First, I believe it is important to point out that the risks of radiation exposures are different than any of the others that I have mentioned. Once your flight on the commuter plane is over, your risk of being killed on that particular journey is zero. Similarly, once you have completed a successful shuttle flight and returned to earth, your risk of dying from an accident during that mission is also zero. In the case of the shuttle flight, however, the risk of illness and disease due to the accompanying radiation exposure follows you the rest of your life. Adding to the problem is uncertainty. It is difficult to quantify the risks associated with radiation doses in the ranges that astronauts have experienced to date. Once you receive a dose, there's no turning back. Although much more of an unknown than some of the other risks that astronauts face, it is nonetheless minor in magnitude compared to many of the other risks. As a result, it is not surprising to note that radiation is not the number one concern on the minds of astronauts when they are asked to fly on a shuttle mission. This is especially true during the first eight and a half minutes after lift-off. At that point, however, you can begin to worry about risks other than those accompanying the launch. Increasing the concern about the potential ill effects of radiation is the previously mentioned fact that the potential occurrence of these effects remains with you even after the mission has been completed.

As noted this morning, the radiation dose limits currently being applied in the shuttle program are estimated to carry with them a three percent chance of developing a fatal cancer. Such a chance may not sound like a big deal unless you're the one who develops a cancer. Then it matters a lot! Consequently, there is much debate on where each of us should draw the line in accepting this type of risk. One approach that has been suggested is to seek the informed consent of the individual astronauts. This is difficult since it is like asking someone who smokes cigarettes to sign a consent form that they understand the associated ill effects. Some 30 y later, when they are having trouble breathing because of emphysema or lung cancer, you can be sure that they will say that they did not understand the nature or the magnitude of the risks they had agreed to accept. Also, just because someone is willing to take a risk doesn't mean they should be permitted to.

## Radiation Doses to Astronauts

Under normal circumstances, the radiation doses received by astronauts during short, shuttle space missions are not a major concern. Typical doses during shuttle missions have been very low. In fact, they have been so low that few, if any of us, have worried about them.

At the time of vehicle launch, each astronaut is provided with a personal dosimeter which is incorporated into the launch and entry suit. After the first few hours in orbit, you take off the suit and place it in a locker or behind a retention net. Under normal circumstances, the astronauts pay little attention to their dosimeters. Occasionally, however, when the possibility of radiation exposure is viewed as something more serious than that on the average mission, the crew will become more vigilant.

This is particularly true when astronauts engage in extravehicular activity (EVA). Under these circumstances, they are much more careful about where they put their dosimeters, they are much more careful in carrying them with them, and they pay attention to the doses they are accumulating.

The Hubble space telescope crew was more vigilant in carrying their dosimeters. Though of low inclination, this was one of the highest altitude flights to date and the accompanying radiation doses were anticipated to be higher than previously experienced. The fact that all the film from the mission was fogged was a graphic and visible reminder that the space environment is not benign. During my first flight, we launched the Galileo space probe. This probe, as some of you know, carried with it a plutonium energy source. In fact, there was considerable discussion in the media about this flight, largely stimulated by a small number of dissidents who wanted to scrub the flight because they were worried that an accident during launch could potentially contaminate the state of Florida. Although the plutonium source was positioned far from any of us, and it was removed from the spacecraft and placed into orbit within six and a half hours after lift-off, you can rest assured that each of us kept careful track of our dosimeters! And when we did our EVA training for potential contingencies, we paid close attention to the location of the radiation source in the payload bay.

## Solar Particle Events

Another potential source of radiation exposures in space are solar particle events (SPE). During one flight several years ago, the group at NASA who monitors radiation dose rates while missions are underway noted a SPE in progress. At the time the event was reported, the crew was about 16 hours from returning to earth. In fact, they were preparing for bed the night before landing. Within the group at Mission Control, however, there was considerable debate on what to do. Questions that arose included: "Should we tell the crew there is an active on-board dosimeter? Should we wake them and request that they read what it says? If we do, should we tell them that the readings it provides are not all that reliable? In short, how much and what types of information should we share with them?"

In the end, the decision was made not to call attention to the event. During the debriefing following the landing, however, the crew was told that it was possible that they had received as much as 65 mSv—ten times what any previous crew had received. Fortunately, a few days later it was found that the actual exposures were about one tenth this amount, namely about 6 mSv. In hindsight, the experience proved instructive and luckily the doses were not as high as initially anticipated. It did remind us, however, that the space radiation environment can be a major concern.

## Other Radiation Sources

Having discussed these sources, let me now turn my attention to radiation doses astronauts receive as a result of medical diagnostic and therapeutic procedures, and through serving as subjects for medical experiments. The manner in which this aspect of the program has been handled has been somewhat of a rocky road. As plans for future space missions—for example, the establishment of the space station and the conduct of interplanetary missions—are developed, these exposures may become less important. Nonetheless, there are valuable lessons to be learned from past experiences with the contributions from medical and experimental sources.

This is especially true in the case of exposures received by astronauts as a result of the administration of radionuclides and the conduct of x-ray fluoroscopic examinations in conjunction with medical investigations. The ethics of committing an individual to a medical experiment involving radiation exposure is as important as the design of the experiment and the delivered dose. There may be a tendency to permit exposures under such circumstances because the radiation risk seems minor compared to the other risks of the mission. This rationale is unacceptable. Individuals in dangerous occupations should not be subjected to higher risks as medical subjects than anyone else—even if the exposures involve doses commonly encountered in clinical care. While hopefully the experiments will provide data having potential benefits to future astronauts, or maybe for future earthly populations if the experiment has some ground-based payback, so far as the individuals receiving the exposures are concerned, the benefits are non-existent.

Also of importance in such considerations is the fact that astronaut subjects, even some with medical backgrounds, may not really understand the risks involved in radiation exposures. As a result, it is up to the radiation experts and to the Institutional Review Board to ensure that the accompanying radiation doses to the astronauts are properly evaluated and controlled. It is also a responsibility of these groups to ensure that all such doses are maintained ALARA, that is, that every effort is made to keep them "as low as reasonably achievable." That such efforts can be successful is exemplified by the reductions in doses that have been accomplished in two similar missions that took place over the past several years. In both cases, the scientific experiments that were conducted and the associated medical experiments involving the astronauts were very similar. Primarily through the urgings of the crew, the doses on the second flight were significantly less than those received on the first flight. These reductions were accomplished through several changes—the substitution of a stable isotope for a radioisotope; the use of smaller quantities of radionuclides in several of the medical experiments; and changes in the follow-up fluoroscopic procedures. Overall, for the second crew there was a 50 percent reduction in the doses resulting from the administration of radionuclides and an 84 percent reduction in the doses received from fluoroscopy.

## Doses in the Space Station

With the development of the space station, and the longer time periods that astronauts will be spending in orbit, certain of the perspectives described above will undoubtedly undergo change. The projected daily dose to a crew on board the International Space Station at 51.6 degrees inclination and 210 nautical miles altitude is 0.4 to 1 mSv. During a six month tour on this station an astronaut may receive 0.18 Sv. However, the dose can be considerably higher. For example, during a six hour period on October 19, 1989, the crew on the Russian Mir Space Station received about 0.15 Sv as a result of an SPE. I was in orbit on board Atlantis at the same time; however, I was at 34 degrees inclination and 160 nautical miles altitude, versus the 51 degrees and 210 nautical miles of the Mir Station. As a result, my total dose was only 0.8 mSv! The higher dose to the Mir crew was, of course, a result of their different altitude and inclination. Although this was an unusual event, we should anticipate that similar events will occur in the future. In a few years, when the International Space Station is in orbit, our annual limits and our career limits will become more meaningful and our exposure levels may approach those that have been experienced in the Mir station. Our risks will also be significantly increased.

## Current Dose Limits

As I mentioned previously, I have been with NASA about 15 y. When I joined the program, the career limit for astronauts was 4 Sv. To me, this is extraordinarily high. In fact, I doubt if anyone in this room, who is between 30 and 40 y of age, would feel comfortable receiving a dose of that magnitude, even over a 1 y period. To help us monitor our doses in future missions, the astronaut corps has asked that the space station be equipped with a monitoring instrument that will provide dose readings on a real-time basis. We have also requested that it be wired with a caution and warning signal so that, if a predetermined dose or dose rate is exceeded, we will receive immediate and direct notification. Such an instrument will also be useful in locating the zones of lowest radiation dose rates within the station. The International Space Station will not be provided with so-called "safe havens." That is, there will be no special areas that are shielded to protect the astronauts in case of a major SPE.

## Commentary and Conclusions

In conclusion, it is clear that astronauts accept risks that are significantly higher than those received by people in other occupations. This includes a willingness to incur higher radiation doses than would be acceptable to many people on the ground. I do not believe, however, that this means that we should accept any level of radiation risk simply because our other risks are so high. We clearly have choices and one of these is to strive to do our best to maintain the doses to the astronauts as low as reasonable achievable. This includes giving careful attention to the possible benefits of additional shielding and the choices related to the possible provision of safe havens within the space vehicle. Something as simple as providing shielding for sleep stations might reduce overall doses by 20 to 30 percent. Such savings can be significant over the long term. Similar considerations should continue to be directed to reducing the doses from medical experiments.

In spite of advances in medical science, we still do not understand the full range of risks that can result from radiation exposures. As a result, it is important that those of you who are experts in the field continue to provide us the latest information on, and the latest estimates of, the risks associated with radiation exposures. It is also important that you continue to provide us guidance on the most up-to-date techniques for reducing and minimizing the accompanying doses. Thank you.

# Some Comments on Space Flight and Radiation Limits

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## Abstract

Setting limits on human exposure to space-related radiation involves two very different processes—the appropriate hard science, and certain emotional aspects and expectations of the groups involved. These groups include the general public and their elected politicians, the astronauts and flight crews, and NASA managers, each group with different expectations and concerns. Public and political views of human space flight and human radiation exposures are often poorly informed and are often based on emotional reactions to current events which may be distorted by "experts" and the media.

Career astronauts' and cosmonauts' views are much more realistic about the risks involved and there is a willingness on their part to accept increased necessary risks. However, there is concern on their part about career-threatening dose limits, the potential for overexposures, and the health effects from *all* sources of radiation. There is special concern over radiation from medical studies. This last concern continues to raise the question of "voluntary" participation in studies involving radiation exposure. There is great diversity in spaceflight crews and their expectations; and "official" Astronaut Office positions will reflect strong management direction.

NASA management has its own priorities and concerns and this fact will be reflected in their crucial influence on radiation limits. NASA, and especially spaceflight crews, might be best served by exposure limits which

address *all* sources of spaceflight radiation and *all* potential effects from such exposure.

## Introduction

This symposium has been called to provide guidance on an important aspect of human space exploration—acceptable limits of ionizing radiation exposure. Space exploration, and the radiation dose limits the National Council on Radiation Protection and Measurements has been asked to revise, depend upon two very different processes: (1) hard science and technology and (2) certain aspects of human emotion. Unlike the early days of space flight when the major emphasis was on hard survival data, you are now being called on to reconcile reality with the expectations of several very different groups or populations. These groups include the public, their government representatives, the NASA Astronaut Office, payload specialists, NASA managers, and perhaps most importantly, the NCRP. The following personal comments are based on four-plus decades of observation of, and active participation in, advanced aerospace efforts, including space flights.

## Expectations of Space Flight

Typical expectations of space flight, which often have a mythic quality for many, vary greatly with the groups involved.

No nonprofit effort as large as the NASA Space Program can exist without government support. Without public support, no politician can afford to vote funds, year after year, for a program that is poorly understood at best. From experience with the public's reactions to nuclear power, the NCRP is aware of the potentially explosive nature of emotional reactions to radiation exposure. Several industries have been killed or are stillborn by emotional reaction to a perceived threat of radiation exposure. This public can also be easily misled to an overestimation of danger by scientists with a biased view who are in respected positions and also have access to the current media. An international furor over "mad cow disease" is a current example (Green, 1966).

The *Challenger* disaster demonstrated that support for the Human Space Program also rests on volatile emotional ground. In that case, the faith of the public, many astronauts, and government had been badly misled by safety propaganda. For the public and government, the myth of Shuttle safety was shattered and support for human space flight threatened by a demonstration that space flight is dangerous (McConnel, 1987; Trento, 1987). Compounding the problem was that the *Challenger* disaster occurred at a time when the public had come to expect more and more safety in many areas, including occupational health and safety.

## A View of an Astronaut

In every age, the relatively tiny, but essential population of explorers, in this case the astronauts, usually stand at the other end of the emotional spectrum as regards the dangers of their effort. My observations have been that most astronauts realize that exploration, and especially space exploration, has and always will have increased risk. This risk, which is dealt with in a variety of individual ways, is usually not of as much concern to the astronaut as is the possibility of "screwing up" a task or mission. Equally or more emotionally threatening to the astronaut is the possibility of having a career cut short by an unexpected physical defect or, even worse, by an unnecessary event such as a misapplied or too stringent regulation.

It is in this last area that radiation, and especially radiation limits, may become threats to the astronaut explorers. Some of this group still need their emotional highs of increased danger and high-profile exposure. Nonetheless, they usually take time to assess and prepare for such danger and exposure. If there is the probability of a dangerous event, say a large radiation dose from a solar particle event (SPE), astronauts want and need the best data possible to maximize both their emotional and actual security. They need probabilities, knowledge of *all* aspects of the associated health effects, and any knowledge which could improve their odds of survival or decrease their probability of injury.

As to how this population views exposure limits, it should be well understood that it makes no difference to an astronaut how the sum total of radiation is accumulated, whether it is from galactic cosmic radiation, SPE's, or more likely excess exposure to radioactive tracers in medical experiments.[1] This last source of exposure has been a matter of significant concern in the Astronaut Office, for the dosages were frequently inconsistently reported and often seemed large for the scientific value of the results obtained. Another occasional source of potential exposure are the Shuttle payloads such as satellites with nuclear power generators. It should also be noted that astronauts are concerned about any and all effects of radiation, not just carcinogenesis. In fact, the order of concern might rank as follows: (1) any acute radiation effect which could affect a

[1]*Most radiation exposure for astronauts actually occurs on earth during training* and baseline data sessions postflight.

mission whether exposure involved one or all of the crew, (2) any effect which would threaten careers, and lastly, (3) delayed carcinogenesis.

There has been a dramatic change in the population of the Astronaut Office from a small homogenous group of experienced American male test pilots to more than a hundred males and females over a wide range of ages, many of whom are still begetting children and who represent a major increase in diversity of background, nationality, expectations, and emotional makeup. The population of Shuttle crews is made more complex by an increasing number of noncareer, often international, payload specialists who expect to make one or two flights for purposes of their own or their colleagues, usually to conduct specific experiments or studies in space. Career cosmonauts are now frequent Shuttle crew members, and Russian exposure limits must be of concern to them, and to astronauts who participate on Russian flights.

## Dose Limits and Medical Experiments

There are other more subtle differences that affect astronaut expectations, even during the course of a career. By way of a personal example, prior to joining NASA and before my wife and I reached our planned number of children, I would not participate in any radioactive tracer study[2], but later readily participated in a very large number—until it became obvious that the combination of research studies and a more stringent radiation limit might terminate my career. My first decision was determined by an over-riding concern for genetic damage and the same concern is probably still present in some of the current astronauts. In short, there is no representative astronaut as regards to radiation exposure limits. This fact was tacitly recognized when the NCRP set different limits for age and sex (NCRP, 1989).

Any determination of radiation dose limits is usually based on the concept that individuals are both informed and free to choose to participate, or not, in experiments having significant associated radiation exposures. There has been a great deal of *sturm und drang* over astronaut participation in medical studies and experiments, many of which involved radioactive tracers or other exposure to radiation. The following is my understanding of volunteerism for human research by astronauts. Participation was voluntary (though 'expected') until 1972 when NASA (1972) stated "a text pilot or astronaut ordinarily would fall within this

[2]This was before the long-term results from atomic-bomb survivors and other data on genetic effects were well known.

exception," *i.e.*, would be expected to participate. There was a subsequent move to make participation part of the employment contract, but this attempt was not successful. A recent policy directive stipulates (NASA, 1996) that any flight crew that withdraws from designated flight experiments on Spacelab missions will be replaced. Also relevant to this issue is a series of directives issued by the Johnson Space Center (NASA,1973-1995).

Regardless of policy, the reality was, and I suspect will remain, that a quick way to terminate an astronaut career is to be deemed "uncooperative," a term increasingly applied to nonparticipation in medical experiments. Commanders and pilots were properly exempted from medical experiments[3], but only those astronauts who were solidly established were really free to choose whether to participate in flight-related studies. Others were usually only too glad to "volunteer." This last trend reached a peak among the payload specialists who were often selected after a long period of competitive training. Indeed, it appeared that they would "volunteer" for anything which might give them a competitive edge in the reviews by their non-NASA selection committees.

Another problem for most of the astronauts was lack of readily available and consistent sources of information on radiation and its health effects. While radiation experts were present and active in NASA, information available from them usually did not answer many of the personal questions astronauts in our office had on this subject area.

The retired astronaut population is a unique resource for following late effects of radiation exposure and a voluntary yearly physical examination is available to follow the general health of former astronauts. While there is no doubt that a major event such as a malignant carcinoma would be documented, the current examination program cannot detect many of the more subtle, but significant, effects. The limited scope of this examination is not a question of resource, but is apparently local policy.

## Other Considerations

A major portion of the Astronaut Office accepted the fact that space flight has, and will continue to have, greater risks than the average population openly accepts. Career astronauts may be threatened by radiation dose limits, since these limits include non-space radiation exposure which, for many, must be tacitly accepted as part of the job. There is a

[3]This group often voluntarily participated.

large diversity in astronaut and payload specialists' expectations which can range from demand for minimum risk by a person who wants to accelerate their career by a space flight or two, to the test pilots and other who recognize and accept necessary hazards which include potential and unpredictable space-radiation exposure during flight.

It is essential to note that an "official" representative of the Astronaut Office will express, at best, the consensus of office administration or, more likely, that of non-astronaut JSC administrators. The halcyon days of astronauts chatting with presidents on picnics or talking with national reporters over a beer has matured into a political structure that is more sensitive to prevailing management perceptions of correctness than to astronaut views of an unresolved issue.

It is the NASA managers who have the resources, wield the power, and exercise the responsibilities for implementation of NASA's Space Programs and these managers have their own unique objectives influenced by job needs and personal emotion. This group is subject to many potential conflicts: (1) resources versus program goals, (2) personal goals versus program goals, and above all, (3) program realities versus expectations and the goals of higher level managers, a relatively small group of politicians who control the budget, the media, and public expectations. Managers need, but do not always want, the best advice as demonstrated by the last launch of *Challenger* (McConnel, 1987; Trento, 1987). However, these managers will have the final say on many features of the guidelines currently under discussion, and while some features of the guidelines may be appropriately directed by these managers, the science involved should not be.

## Commentary and Conclusions

Two comments on technological and operational issues appear to be appropriate: (1) The more knowledge that NCRP has of spacecraft operations, the more options the Council will have to recommend protection options. While many aspects of a flight cannot be altered, many can. For example, sometimes alteration in spacecraft orientation or configuration, or reconfiguration of spacecraft contents, or adjustments in location and position of crew are possible. Such changes might significantly alter the accompanying radiation doses at little or no cost to the mission. (2) In terms of safety, care must be taken not to overemphasize one safety aspect at the expense of another because resources are very limited for human space exploration. It is possible, for example, that increased resources for ground studies or flight hardware concerned with radiation could adversely affect a higher risk area, such as engine propulsion, thereby producing a net loss in overall safety.

Finally, the proper business of human space flight is human exploration, an expanding physical presence of human beings in the solar system and beyond. However, this expansion has been on hold since Apollo.

Space exploration, like all historic exploration, involves a significant increase in personal danger and the questions asked should focus on how large is the danger, and is the risk worth taking for the potential benefit to the human race. Individual wants and needs often must be secondary if progress is to be made. The surest way to indefinitely prolong the present lack of progress in human space exploration is to demand absolute safety and total understanding of all phenomena involved. Conversely, where there are unresolved potentially hazardous effects such as galactic cosmic radiation, efforts should be made to quantify these effects during this hiatus in human-exploration activity. History provides numerous examples of individuals who, by understanding the problem, skillfully used minimal, apparently risky, procedures to succeed while more conservative approaches failed. For example, the single-pilot, single-engine Lindbergh with a fuel overload succeeded over the multiple crews and engines of others.

My only concern with the ongoing revision of the recommendations for dose limits for space travel is that the NCRP has become increasingly focused on restricted aspects of the radiation problem, namely, carcinogenesis and the current emotional demands of various concerned groups. I believe it would be useful for the Astronaut Office and also the Johnson Space Center to address all aspects of astronaut radiation exposure. It would also benefit the general public and Space Program for some knowledgeable group to address, in the simplest way possible, the realities of space radiation versus letting some media person, or self-styled expert, add to the overburden of space-radiation emotions already carried by the public.

If the NCRP continues in the tradition of past guidance, I am sure that the outcome of the current revision of dose limits will be another example for others to emulate.

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# General Discussion

CHARLES MEINHOLD: I thought Dr. Holloway gave an excellent presentation. In fact, your comments changed the tenor of our discussion somewhat. I'm glad you did that. It is important for all of us to realize that it is not just the astronauts who should be involved in setting dose limits in space. It is also a responsibility of NASA, as their employer, not only because NASA controls the funds but also because such a responsibility is what the employer/employee relationship embodies. It is a NASA responsibility to understand the needs of its astronauts, a primary goal being to be a good protector of their health and safety. The NCRP also has a role in this process, one of the most important being to make recommendations. Although the NCRP has no regulatory responsibility, we definitely have an obligation to provide the best possible guidance we can.

HARRY HOLLOWAY: For NASA to fulfill its role, we also need to understand. You, the NCRP, must work at making us smart. Sometimes we start off at a pretty low level!

JOHN GARRICK: I was struck by the points you made about the importance of communicating and helping the public to understand risk. I think people would be surprised to learn how little effort has gone into work in this subject area in terms of trying to mesh the public view and conception of risk with the scientific probabilistic view. These are really two different worlds and it's very difficult to bring them together. Some one needs to take on the task of trying to see if these views can be integrated. Communication, however, will be difficult since the two groups are speaking entirely different languages.

HARRY HOLLOWAY: Thank you for expressing it in such an excellent manner. I would add only one thing to expand your point. C.P. Snow talked about two cultures and I think he may have got it a little wrong, at least wrong for this country. The two cultures are really people who go to graduate school and understand these concepts, and the remaining members of the population who are being totally closed out. No one should ever lose sight of where the money comes from!

TOM BORAK: Tom Borak from Colorado State University. Earlier today we heard some discussion about the possibility of applying different dose limits to astronauts involved in different aspects of space missions. In one case, you're going to be an explorer and, in another case, you're a cosmic bus driver. What do you think about applying different risk limits to these different types of activities?

ELLEN BAKER: I guess I don't believe in having separate standards. I think we ought to decide on a standard that is designed to protect the health and safety of the crew, and then stick with it. I would not say that one crew is more valuable than another. I would also not feel right in saying that the crew going to Mars can receive higher doses and, if they die young of cancer, that's the price they'll have to pay! I would urge that we exhaust all possible options for ensuring a low dose in a mission like that.

WARREN SINCLAIR: You may have heard of the term, ALARA, which means "as low as reasonably achievable." It sounds as though your crew did their own ALARA assessment between the first and second of the two missions you described in your talk. As a result, you were able to reduce the exposure somewhat. On this basis, I gather that ALARA is a fairly lively program in NASA. I offer these comments because I understand that the Russians are applying the ALARA concept very consciously. The Russians have told me, for example, that they move the crew whenever their spacecraft passes through the South Atlantic anomaly. Were you aware of this in your contacts with the Russians?

ELLEN BAKER: Yes, I was. In fact, those issues have come up for the American astronauts on board the Mir. That's where I first became familiar with the Russian efforts. By selecting preferred low-dose locations within the spacecraft, particularly for occupancy during the sleeping period, you can reduce your dose. People at NASA are definitely evaluating such approaches. Within the medical community, the concept of ALARA is fairly well known and its application is well accepted.

AMY KRONENBERG: There was some discussion this morning about placing risks in context. In this regard, there are other environmental exposure risks in space flight besides radiation, particularly in view of the closed confines of a spacecraft. Are these other exposures considered with a similar dread factor among the crew members? I'm aware, for example, of carbon dioxide exposure as one issue and there have certainly been other chemical exposure issues. How do you view these other exposures?

ELLEN BAKER: Radiation probably is the one issue that people are most familiar with and think more about than some of the other things you mentioned. The chemical exposures and the off-gassing are probably not as well understood and as well publicized, so to speak. Based on my observations, I would agree that radiation is something that people are more attuned to.

TERRY JOHNSON: I believe you said that the astronauts on one flight, which you were not on, received a dose of about 20 rem. Did I understand you correctly?

ELLEN BAKER: Yes, that was the dose received by the Mir crew during the solar event in 1989.

TERRY JOHNSON: If there were opportunities for astronauts to take more than one mission assignment, would it be reasonable for NASA to specify that men could flight twice and women could fly only once? Or would you oppose such a procedure?

ELLEN BAKER: There is no disputing that men and women are different. As a result, there are going to be differences in radiation risk, due to gender. In my case, I have a family history of cancer that I would not like to combine with the risk of radiation exposure. To avoid differentiating between men and women, NASA could set the limit at the lowest common denominator, that is to say, they could make the career limit for all astronauts what it is for women. Following that approach everyone would be equal. How you deal with the numbers and what you decide to do is probably more of a legal issue. The problem of astronauts bumping up against career limits has not been a problem in the past, but it may occur within the next several years. A similar question has arisen relative to making assignments for extravehicular activity. There has been some dispute and discussion over whether women need a longer prebreathe period. We have elected to use a prebreathe period that is suitable for both men and women so that there are no differences. The issue you raise is not a new one.

TERRY JOHNSON: So you're saying that, in general, you believe the issue should be resolved in a way that men and women are treated equally?

ELLEN BAKER: I said that that was one option. I don't know how it will be resolved. That's above my level of decision. But I won't dispute that there are different risks for men and women. I think that's clear.

PAT MULLIGAN - NOAA: I'd like to comment on the proton event that you discussed, the one that occurred in 1989 while the crew was sleeping. I remember it well because, as I recall, I was on duty that night. This event was different than most. Typically, such events are accompanied by a very severe geomagnetic storm. This one was not. As a result, the

Earth's magnetic field provided considerable shielding against the protons. This information is important in terms of keeping this event in context. Had the event been accompanied by a magnetic storm, however, the exposures on the Mir and the shuttle could both have been considerably higher.

ALOKE CHATTERJEE: In your experience, have you come across any situation where the equipment has failed because of radiation damage?

ELLEN BAKER: I'm not the ultimate authority on this. We've had a couple of computer failures that we have been unable to reproduce and diagnose. The diagnosis of exclusion has been that the failures were due to a cosmic ray hit. Sometimes, we bring the equipment back and it works fine. We've not been able to reproduce these failures on the ground, even with detailed examinations of the software and hardware. So it's possible that some of these failures could have resulted from radiation hits.

# Panel Discussion

HARRY HOLLOWAY: I want to comment on the question of chemical exposures that may involve the astronauts. This might be the exception that proves the rule. The question was whether people were as sensitive to chemical exposures in the spacecraft as they are to radiation exposures. At one time we thought we had problems with benzene as a contaminant. In the case of the Russian Mir Station, it was probably xylene, not benzene. That issue is still being explored. In any event, as soon as the possible presence of benzene was mentioned, there was an immediate response. This was undoubtedly due to the fact that many people associate benzene with liver cancer. This demonstrates, once again, the different ways in which various stresses are perceived.

Having said this, I would like to address a question to Dr. Thornton. Do you believe that our efforts within NASA in evaluating the risks of radiation exposures in space, and taking steps to counteract these exposures, have been adequate?

WILLIAM THORNTON: Although my basic answer is "yes," I want to comment further. My overall impression was that at the Johnson Space Center the general response was to react to new information and/or developments in the field of radiation protection in the form of explosions and panics, rather than pursuing them on an orderly basis. Perhaps Dr. Baker will want to comment on this. I also gained the impression that, from time to time, the astronauts would be told about changes in the dose limits, or they would be informed about some "new discovery" about the health effects of radiation, without being provided adequate supporting information. These types of events caused a lot of furor among the astronauts. Efforts might have been taken to better handle these types of situations.

ELLEN BAKER: I guess I would agree with that. The major decisions within NASA revolved around the doses received in medical experiments rather than those received in flight. To some degree, this was stimulated by the fact that we had a lot more ability to control the doses associated with the experiments. Consequently, the focal point of discussion, at least within the shuttle program, has been on the doses from the experiments. As I said earlier, however, I believe that this will change now that the astronauts are undergoing longer term missions and are receiving higher doses as part of being exposed to the space environment.

WILLIAM THORNTON: I would like to address a question to Dr. Holloway. When I came on board, many of the medical experiments were voluntary and the astronauts could and frequently declined to participate. Since I left NASA, I understand that this has changed. In fact, I am told that candidates for the astronaut corps no longer have this option, that is, they are now told that participation in such experiments is considered part of their contract. Could you elaborate on this?

HARRY HOLLOWAY: Our current standard is that a person may decline to volunteer, or may withdraw from, any experiment at any time. Ellen Baker and Sonny Carter (who was later killed in an airplane crash) were two of the leaders in establishing this policy. If a mission is being flown for the purpose of conducting a specific experiment, and one of the crew early on says: "I'm not going to take part in that experiment," the NASA staff has the option of seeking another astronaut for that flight. This may not be done, however, if the experiment is not part of a core study. About 24 months ago, NASA agreed to participate in the "common rule" that was established by NIH and now applies throughout the U.S. government. Initially, however, the regulations within NASA did not always reflect this rule in as much depth as would have been appropriate. Today, the policy is to work very hard to minimize every risk. This philosophy is now a very active part of the structure.

CHRIS WHIPPLE: This afternoon's session has been very instructive. Although not everyone's opinions are identical, there appears to be some reasonable complementarity. One point that I believe came through loud and clear, and Harry made it at the beginning of his talk, is that whatever basis NASA adopts for establishing radiation exposure limits has to be ethically defensible—not only to members of the public but, most importantly, to the astronauts themselves. Dr. Baker made the additional point that she thought it was not appropriate to use occupational groups with high risks as a basis for setting dose limits for the astronauts—as was recommended in the 1989 NCRP report. Some of the comments made by Paul Slovic in distinguishing between radiation and accident risks carry, at least for me, considerable weight. I think we clearly need to think about a more appropriate basis for comparison. There is no one right answer; we need multiple perspectives. The risk from accidents is not necessarily the best one we could find.

Another impression that I gained from this afternoon's session—something that I did not previously appreciate—was the large amount of radiation exposure that the astronauts receive in being screened for fitness for duty and in participating in medical experiments Although NASA may now be managing these two types of exposures within a coherent framework, I'm not sure that the NCRP recommendations, as expressed in its 1989 report, use the same approach. It would be wise to apply the ALARA criterion with equal vigor in the control of these exposures as is done in controlling the doses from the space environment. This is especially true in view of Dr. Baker's observation that there may be technically more opportunities for controlling the medical exposures than those associated with the space environment.

JOHN GARRICK: One of my observations as a practitioner of risk assessment is the absolute importance of developing an operations perspective during the formulation of your risk model. Both speakers this afternoon reminded me of this in commenting on how the astronaut crew has become increasingly involved in the risk management process. In attempting to assess the risk for a specific mission, it is important for the people who are building the models to keep their fundamental goal in mind, that is, to answer the question, "What is the risk?" This is not a designer's perspective as much as it is an operations perspective. If your risk assessment is to be of any value, it must provide the crew and the operations people additional knowledge on what to do when things start going outside the norm. As I mentioned this morning, one of the central underpins of risk assessment is the development of scenarios. In this regard, I recall the first time that I was asked to review some of ways that NASA performs safety analyses. I was struck by the absence of input by either the operations staff or the crew. I say this because there is no way that we could have built a nuclear power plant risk model without heavy involvement of the senior reactor operators. They understand better than anyone else the specific circumstances of their specific plant, at their specific site, and what a given symptom really means. Even though you can obtain input from designers and other experts, if you want to really get a handle on the opportunities for mitigation—for corrective action—then it's absolutely essential to understand the symptoms and what they mean. That point has been driven home even more today.

Another factor that I discussed in my talk was the importance of ranking contributors to risk. I went on to say that radiation was most likely not a major issue from a risk perspective. I now realize that I need to clarify that point. In making that statement, I did not mean to imply that radiation should not be considered. On the contrary, the only time you can reach that conclusion is if indeed you have considered and evaluated its associated risks. The main point is that the development of risk assessment models provides an opportunity to put issues in context, that is, to provide perspective relative to the various contributors.

In considering the contribution of radiation to risk, it is also important to recognize that some contributors have much more emotional content than others. Clearly, there is a disease in this country, perhaps more than in any other country of the world. That disease is "radiation phobia." We should fear anything nuclear! All of us involved in the risk assessment field must deal with this. In particular, we need to recognize that much of what we do in dealing with radiation is done not because it is of equal importance to many other issues that may not be receiving as much attention. Rather, it is done because there is the perception, there is the fear, and there is the anxiety, and all the other things associated with it, that we must somehow deal with.

CHARLES MEINHOLD: As Dr. Holloway mentioned, one of the problems being faced by NASA administrators is the ethics question. In this regard, perhaps it would be helpful for me to review how the ICRP and the NCRP decided that a risk of three percent was acceptable. In the case of the ICRP, the basic approach was to compare the risks to radiation workers to those of people employed in other occupations. One of the first questions that arose, in making such comparisons, was whether it was proper to use mean values of the death rates within various industries. The ICRP quickly concluded that such an approach was not proper because the radiation dose limits represented the risk to workers exposed at the maximum level, not the mean. After examining the risks in a number of industries, the ICRP concluded that an acceptable limit on the tolerability of fatal injuries was $10^{-3}$ per year. On the basis of an assumed working span of 50 y, this translates into a lifetime risk of about five percent, somewhat higher than three percent. This is a matter that you may want to think about.

The NCRP, as exemplified by the information presented in Report No. 116, took a similar approach. That is, the NCRP decided not to look at the average within a safe industry and apply some limit based on that, but rather to look at the top end of industries. In this regard, it is important to keep in mind that the discussion was not directed to the limits for which various radiation systems were being designed. Rather, the discussion was directed to risk imposed on the person receiving the maximum dose. One of the questions that now needs to be addressed is whether this is the approach and/or philosophy that should be used in developing dose limits for astronauts. That is to say, will the goal be to set a limit which we do not expect any individual astronaut to reach but which will serve as the boundary condition on whatever might happen for any given astronaut for any given situation? Following this approach, one way to look at the issue is to emphasize that it is a limit on doses to the astronauts, not a goal in the design of specific spacecraft or the planning of a specific mission. Again, this is a matter on which you may want to give additional thought.

WILLIAM THORNTON: My experience indicates that any true exploratory program involves risk. Part of this experience also tells me that there are certain circumstances or goals that justify increased risk. This is true of the space program. Since resources and risk are related, an atmosphere of limited resources may well imply the need to accept increased risk. If accepting a certain level of increased risk means the difference in accomplishing a successful trip to Mars in my son's or grandson's lifetime, I would be perfectly willing for either one of them to be exposed to increased risk if he wanted to be and was willing to voluntarily accept the higher risk. To me, the acceptance of risk is part of the price of progress. Based on this philosophy and depending on the situation, you may not want to have an absolute limit on the dose from radiation. It's a trade-off between the possibility of increased damage to your health versus the benefits of the mission.

ELLEN BAKER: My philosophy is somewhat different. Just because there are people who are willing to accept a given level of risk does not necessarily mean that we should let them do so. I suppose it depends on what the limits are, but I believe in similar protection for similar endeavors. I still believe that we have a lot of work to do to reduce the risk and to reduce the exposure in the types of upcoming missions that are being discussed. This is especially true in terms of the proposed mission to Mars. I am not prepared to throw in the towel and say that those folks going to Mars will just have to be exposed to a lot of radiation.

UNIDENTIFIED: I want to raise a question regarding the comments by Professor Meinhold. What did you mean by a five to six percent increase in fatal cancer over my life? Is that five percent risk going to occur in 1 y? Or will it have a higher probability of occurring near the end of my life? How do I communicate this to someone who has been exposed?

CHARLES MEINHOLD: What makes the five percent probably acceptable is that it all happens when you are, on average, 68 y old. The average length of life lost would be something on the order of 15 y. The easy way to look at this is that the average member of the United States' public has a 20 percent chance of dying of cancer. This is the "normal" probability, that is to say, without exposure to radiation in excess of natural background. The astronaut who accepts a radiation dose limit based on an annual risk of $10^{-3}$ will have, as a result, an estimated additional five percent chance of dying from cancer. This means, in his/her case, that the total risk of fatal cancer will be 25 percent, versus 20 percent.

UNIDENTIFIED: I would like to direct this question to Professor Meinhold. When you say that the astronaut would have a 25 percent chance of developing cancer, what do you mean? Skin cancer? Uterine cancer? Malignant myeloma? What does it mean?

CHARLES MEINHOLD: The 25 percent expresses the development of a cancer that would cause you to die with about a 15 y loss of life. It's sometimes called the fatal cancer probability. That's what it means.

PAUL SLOVIC: The response by Professor Meinhold touches on what Chris Whipple was alluding to in terms of the comparisons we make. I think the approach of comparing the risks of radiation to the deaths caused by accidents in various other occupations deserves some real analysis and questioning. Just because the death rates in certain industries, for example, agriculture and mining, are high does not mean that this represents an acceptable level of risk. That may or may not be the case. It is also not clear that this same level of risk, involving accidents and deaths that are clearly visible, would apply to something like radiation, where the consequences are often not apparent. If we took a poll of workers in various industries and asked what risks they would consider to be tolerable or acceptable, what would they say about these types of comparisons?

CHARLES MEINHOLD: Let me react briefly to that. What you are saying is absolutely true but what is not clear is which way the workers would go. As Dr. Baker pointed out, when she returns home from a mission, she's still alive but she has to face the radiation risk forever. The same is true for truck drivers who have an annual risk of about $10^{-4}$. If they make it to age 65, they're in great shape, all other things being equal, whereas the radiation worker still faces a risk. There is absolutely no doubt that these risks are not equivalent, but I am not sure which way it goes. Whether it's better or worse—that the risk is not immediate but protracted—I don't know the answer. This is, in essence, one of the ethical issues we face. Perhaps others will have comments to offer.

CHRIS WHIPPLE: As a first comment, I want to relate back to Warren Sinclair's talk this morning. Imbedded in his presentation were two important ethical principles that all of us accept, perhaps implicitly. The first is that whatever we do has to be adaptive to changes in the science. The table that Dr. Sinclair presented in his talk was different than that published in the 1989 NCRP Report because the scientific consensus on radiation risk has changed. The second point that he made is that we must be adaptive to changes in what risks society creates and accepts. If one checks the numbers, the accident rates in essentially all industries have been decreasing and life, in general, is becoming safer. As a result, the willingness to impose a risk of a fixed magnitude is decreasing with time. That is to say, our expectations on the degree of protection people should be provided has shifted. As presented by Dr. Sinclair, those principles were implicit. I think they should be made explicit.

Now for my second comment. In his earlier remarks, Charles Meinhold raised the question as to how one establishes ethical criteria. One approach to answering that question would be to have an ethical process for setting a standard. Although the astronauts are obviously a very busy group, I cannot imagine a group better able to play a major role in participating in that process. They are scientifically trained, some of them are medically trained, they understand the risks, and any limit that is established will affect them personally. They want to fly but they don't want to expose themselves to unreasonable risks. So I think that it would be entirely appropriate to permit them to take part in establishing limits on the amounts of radiation exposure they are allowed to receive. At the same time, however, I believe that the process would need to be managed in a way that the astronauts will be free to say, "That's simply too high," without being booted out of the program. Above all, you must not let people shop standards and bid for high risks. That part of the process must be controlled. The development of a process in which the astronauts participate and are happy would be one that I would define as ethical, particularly since the resulting standard would be one that was voluntarily agreed to by the people who will bear the risk.

JOHN WILSON: I'm John Wilson from the NASA Langley Research Center. One of the things that I have not heard discussed today is the relationship between the risks of radiation versus those from other aspects of the mission. Obviously, if you increase the protection against radiation—for example, by installing increased shielding and weight within the spacecraft—you may increase the mechanical risks of the mission. Adding additional shielding may also increase the complexity of the spacecraft. How do you play one of these factors against the others? Are there risk models that permit you to do this?

JOHN GARRICK: What you are referring to, in essence, is the conduct of a "total scope risk assessment." This process includes making an effort to understand what the risks are, taking steps to put them into perspective, and determining the trade-offs. Risk assessment is really an attempt to understand the probability of occurrence of certain kinds of events that you have chosen to be a measure of risk. If you conduct a broad based risk analysis, and don't have too much to go on, then of course the results will be very broad in terms of uncertainty. As you increase your understanding of the mission—this includes the space vehicle, the crew, and the operations—then the curve tightens up in terms of uncertainty. At this point, you will have two curves that represent your expression of risk based on two analyses at two different points in time, each reflecting a different state of knowledge. Nothing has changed in terms of the crew, the hardware, etc.; it is just that you now have better knowledge of the subject. The next step might be to make a change in the design, hoping to reduce the risk. But you must also, in your analysis, allow for the fact that the changes may have opened the door for increasing the risk. The likelihood may be small, but it is there. While the incorporation of an escape mechanism for the crew during launch may appear on the surface to represent a reduction in risk, this change will introduce things into the vehicle that were not there before, and about which you may not have as much information as for the other components of the system. So analyses of trade-offs are absolutely essential. Specific questions that must be addressed include: What do we get from an extra safety system? What do we compromise in the way of performance—in the way of possible accident scenarios that we did not have before? The only hope is that those scenarios, while they exist now and did not exist before, will be sufficiently small contributors to risk that the overall result will be an increase in safety.

One additional comment. Several people today said that radiation is unique because it is the only phenomenon that we deal with that has a residual risk. I can't accept that. We know a lot about radiation; in fact, one of our problems is that we know too much about it. We can measure it at levels decades below those that might represent a serious threat. There are many other residual effects present in space flights for which our detection and measurement capabilities are nowhere near as sensitive. I am not convinced that, upon returning from a mission, the only thing that you will have to worry about is the latent effect of radiation. As a matter of fact, I suspect—as Dr. Holloway so elegantly stated this morning—that there are many other things that we may need to worry about. Some of these may even overshadow the effects from radiation.

HARRY HOLLOWAY: I want to respond to one comment made by Dr. Garrick. That pertains to his statement that, when you make a design change, you can estimate the overall new probabilities of risk. In the "real world" of space flight, this may not necessarily be the case. For one mission, we had planned a particular experiment in which radionuclide tracers were to be used. Based on consultations with physicians at several universities, we decided the accompanying risk was too high. As a result, we replaced the proposed experiment with a clinical procedure that had been routinely used hundreds of thousands of times and had an exceptionally low level of risk.

On the surface, this change appeared not to be important and certainly it was not anticipated that it would alter the risk in any radical way. Under conditions of the mission, however, it was necessary for us to administer in quick succession—seconds apart—two substances, that are normally administered some minutes apart. The net result was that the two substances interacted and apparently created a unique antigen complex which produced the tendency toward anaphylaxis! Space travel is dangerous. Learning the things we need to know to be able to travel there is not easy. In this case, a change in the design of an experiment—to reduce the risk—actually resulted in an increase in risk. The helping hand strikes again!

JOHN GARRICK: Harry, this might be chasing a detail. But I thought you went through multiple simulations on the ground prior to each mission and that you would have picked up something like this prior to the launch.

HARRY HOLLOWAY: The problem is that a person can have anaphylaxis on the ground and die before they ever get into space. And they are just as dead. That's exactly one of the things that happened in this context. So my point is that the dangers that are part of the space program can occur during training or in preparation, as well as during the mission itself. Rare events have a nasty habit of not occurring when you first do the simulation; they occur exactly at the worst possible time.

UNIDENTIFIED: In his comments, Professor Meinhold stated that the average radiation induced cancer results in a loss of life of approximately 15 y. If I were an astronaut and thought that the three or five percent increase in risk of a fatal cancer would result in only a few days of life lost, I would not be concerned. But 15 y sounds high. Have similar numbers been calculated for other types of events, such as the failure of a mission in which people are killed?

JOHN GARRICK: The aggregation of different threats, those that come from chronic exposures versus those that come from accidents, is a part of the risk assessment exercise. The construction of models that take into account both kinds of threats is certainly within the maturity level, if you wish, of risk assessment. Although not a routine part of the exercise, it is not beyond the technology.

EARL FERGUSON: I have a number of comments. One relates to occupational and environmental monitoring within the spacecraft. NASA has a very active program for closely monitoring the air and water quality, as well as the radiation levels. In the case of the Mir, we are able to obtain grab samples of air, only, and we cannot analyze them in real time. We are working to improve these capabilities.

My second comment relates to the longitudinal study of the health of the astronauts, previously cited by Dr. Holloway. Our data show that about two-thirds of the lifetime radiation exposures for the 220 people in this group have resulted from physical examinations and medical studies. Only about one-fourth of their exposures have resulted from radiation in space. About eight percent have come from medically administered radionuclides. Also to be considered is that the astronauts who participated in the early portions of the space program were more extensively studied. Such studies included many medical exposures that were subsequently discontinued. As a result, the exposure data are skewed with the highest exposures occurring among the earlier group. In addition, the time spent in space for astronauts in the past has been quite low compared to what we anticipate in the very near future. One of our challenges is to learn how to deal with these changes.

The third subject that I want to address is the ethics of human experimentation. As a result of various reviews, we've revised the applicable NASA management instructions and regulations. There is now a subject advocate who is part of the institutional review board (IRB) process so that the questions that are raised can be answered by an independent individual. In addition, we are studying the cumulative risks of the exposures that have resulted from various medical experiments. Sometimes many, many experiments were done on the same person, or the same group of people. That is quite different than in the external community. We now have an advisory group that is helping us develop guidance on clinical and ethical best practices in space medicine. As part of this process, we are reviewing all the medical procedures that have been done and the relevant medical standards. One goal will be to justify the tests that are done. This will include an assessment of the benefits of each study and deciding which can be discontinued. The emphasis will be on decreasing radiation exposures or exposures to other risks.

Finally, I want to comment on the future. We are planning to return to the moon within the next decade, and we are developing a road map to Mars, the goal being to undertake such a mission in the year, 2018. There will be many problems associated with the latter journey. These include the design of special radiation shields, as well as the development of a medical road map to help us figure out how to obtain the data we need to combat the effects of radiation and weightlessness. We are especially interested in guidance on the types of research that need to be done. To be helpful, this guidance will be needed fairly quickly. We hope you will be able to assist us in solving some of these problems.

HARRY HOLLOWAY: No longer being with NASA, I want to make a couple of additional points. The effort to solve the types of problems being discussed here today represents the most underfunded program in NASA. I've made that statement publicly before and I will make it again now. Such a situation does not match up to the overall structure and delivery time.

Another point—contrary to what you heard at this meeting, the 2018 time frame for the Mars mission was specifically selected to fly the mission at solar minimum. Based on what has been discussed today, one could ask whether that is a proper choice? We need to hear something on that fairly soon.

STAN CURTIS: First a comment on what Dr. Holloway just said. Our solar physicist colleagues are not prepared at the present time to tell us exactly, even within a few years, what phase the solar cycle will be in at that time. It could be at solar minimum or it could be half way through the cycle. Although the cycles have been called 11 y cycles, they are not always of this duration. Sometimes they are 9 y; sometimes 12. It's not easy at this point to say when, some 20 y or so into the future, a particular solar minimum or solar maximum will occur.

Having said that, I want to get back to a question that came up earlier. That pertains to the ethics of setting the dose limits for space travel. The NCRP has suggested that we use—let me call them—the intermediate risk industries as our guide. I agree with the suggestion that we ask the astronauts to tell us what they consider to be a reasonable limit. That would appear to be the ethical approach. Are there members of the panel who would like to comment on the use of the so-called intermediate risk industries as a guide for setting a risk limit? What are our alternatives?

HARRY HOLLOWAY: Let me suggest an alternative—one that ought to offend everybody! What about requesting input from focus groups composed of congressional staffs that represent the people? What about focus groups derived from community populations, ones that would include people with space interests and those without? Are these reasonable ways to seek inputs for resolving this sort of issue? What are the ethical objections to these kinds of surveys and that kind of outreach?

JOHN GARRICK: I have a practical, as opposed to an ethical, objection to that suggestion. This stems from the fact that this is the most radiophobic society on earth. Most members of the public would call for a dose limit of zero! That, in essence, would end the space program.

On another item, it appears to me that many of the risks from radiation are theoretical in nature. So far as I know, there are no human studies that demonstrate any delayed carcinogenesis unless the radiation dose is in excess of 40 rem. In the case of the Hiroshima/Nagasaki studies, the risks became statistically apparent at around 50 rem and this was for a dose that was delivered instantaneously. This being the case, setting the career limit for the astronauts at 40 rem appears to me to be in and of itself a theoretical thing. I think this point should be made clear to the astronauts. In terms of involving the astronauts in the decision of where the risk limit should be, the logical extension is to permit each astronaut to make a personal decision about a given risk for a given mission. While somebody commented that some astronauts would charge into a dose that was $LD_{90}$—at least that's what I thought they said, perhaps they meant $LD_{50}$—I believe that may be true for some astronauts but it's hard to imagine that NASA would plan a mission that actually had prospectively the risk of radiation at the $LD_{50}$ or $LD_{90}$ level.[1]

WILLIAM THORNTON: That comment was presented simply as an extreme example of the mind-set of some individuals that have been associated with the space program. NASA, of course, would not think of approaching such a situation. No one else in their right mind would. However, these people are incredibly driven, believe me, and that was simply to illustrate the mind-set of the individual. It had nothing to do with NASA or what any other organization would consider.

JOHN GARRICK: I understand that. In fact, I thought the suggestion that NASA would charge in when it was $LD_{90}$ was really intended to be partly facetious. That individual astronauts would make such a choice, I think, is also really partly facetious.

WILLIAM THORNTON: I want to comment on the suggestion that we consider the use of focus groups. One place in which ethics would enter the picture is if you receive an answer that you don't like. That is obviously not an acceptable/ethical reason for not doing something. If the answer is that there is no support for the space program, and that the program ought to be closed, as a responsible public servant that's exactly the question that I must be willing to ask. The fact that you may be disappointed with the results is hardly a reason not to seek counsel from the people who are paying for the program.

[1]This discussion refers to information that was presented orally but not included in the formal papers prepared by the Symposium speakers.

JOHN GARRICK: I agree with that. But I didn't think that it reflected a lack of support for the space program *per se*. It's just that the majority of the U.S. population thinks that the most appropriate radiation exposure that one would plan for prospectively is zero. Or close to that.

ELLEN BAKER: I am the representative to the Institutional Review Board (IRB) at the Johnson Space Center. In a sense, I am the voice for the astronaut office. When the IRB says that an experiment is safe and it shows up on the manifest, every astronaut is able either to sign up or not. However, they are not voluntarily allowed to take more risk than the IRB says they can take. I would suggest that a similar process be used in assigning some kind of risk-benefit. Astronauts would be free either to accept that risk or not, but they would not be free to accept more risk than the institution is willing to allow them to accept.

CHRIS WHIPPLE: Let me get back just briefly to the discussion on congressional focus groups and such. Although I have been around radiation controversies for a long time, I'm surprised to think that there is any association whatsoever between NASA's dose limit and its budget—considering that financial support for the space program comes from appropriations provided by the Congress. If NASA is establishing radiation protection practices consistent with the wishes of the astronauts, and consistent with the recommendations of groups such as the NCRP, that is one thing. However, I would be very surprised to see this fact coming to the attention of the Congress. They're busy with other things.

HARRY HOLLOWAY: The reason I suggested using congressional focus groups was not because I thought it might have an effect on NASA's budget. The reason for my suggestion, surprising as it may seem, is that I honestly believe that congressional staffs and the members of Congress, itself, make ethical judgments about these issues and are concerned about the processes used in establishing the dose limits for the astronauts. This is not a lot different than what Walter Reed did many years ago. He actually had an institutional review board, that he invented, that reviewed his yellow fever experiments prior to their implementation. He subsequently shared this information with the congressional committee that, at that time, was responsible for the Army. He involved the Congress in a discussion of the associated risks.

It might be noted, in this case, that Dr. Jesse Lazear, an overly-motivated young man, permitted himself to be bitten by an infected mosquito, developed yellow fever, and died as a result. This relates back to Bill Thornton's comment—would somebody undertake a mission in which he had a 90 percent chance of dying. This young man undertook an experiment in which he had a 100 percent chance of dying!

What I am talking about is the fact that Walter Reed involved the Congress in a discussion of the risk. I believe NASA should do the same thing. The purpose of my suggestion is one of ethics, not of budget.

PAUL SLOVIC: I'd like to call this discussion to a close, and to thank the panel members for a very spirited and insightful discussion.

NCRP

# Summary and Conclusions

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## Introduction

The Program Committee has requested that I, as rapporteur, summarize the key issues that have been raised. The assigned task included highlighting areas of consensus, and drawing any conclusions that appear to be justified. Although this is a challenging assignment, it has been made easier by the excellence of the oral presentations and discussions that have taken place.

As outlined in the announcement, the purpose of the Symposium was to provide an opportunity for a wide ranging discussion among scientists, radiation biologists, public health professionals, and members of the public on the rationale for establishing an acceptable lifetime risk of fatal cancer due to exposures to ionizing radiation in space. Subject areas that were to be addressed included:

1. The nature of the radiation environment in space, and its biological effects;
2. The basis for dose limitations as recommended in years past by the National Academy of Sciences/National Research Council and in more recent times by the National Council on Radiation Protection and Measurements;
3. Alternative endpoints for evaluating dose limits for astronauts, including mortality, morbidity, and years of life lost;
4. Comparisons of the risks of radiation exposures to other risks associated with space travel, including whether the exposures are considered to be controllable; and
5. The philosophy of astronaut protection, including the perspectives within the National Aeronautics and Space Administration as well as those of the astronauts.

Using the sequence of talks and these objectives as a guide, my comments are as follows.

## The Space Radiation Environment

As pointed out by Dr. Robbins, the space radiation environment has three major components—(1) galactic cosmic rays (GCR), consisting of energetic protons and heavier ions that originate outside the solar system; (2) radiation resulting from solar particle events (SPE), consisting primarily of protons (with perhaps as much as 10 percent alpha particles), and (3) near the Earth there is trapped-belt radiation, including an inner belt composed primarily of protons and an outer belt composed primarily of electrons. The intensities of GCR in the vicinity of the Earth vary with the approximate 11 y solar cycle and are highest during a period of solar minimum. In contrast, the probabilities for the occurrence of SPE are highest during a period of solar maximum. For interplanetary missions, the trapped-belt radiation would be of concern only during the time of passage of the spacecraft through the belt as it leaves the Earth. Because this would contribute only a small amount to the total mission dose, exposures from this source need not be further considered.

Although uncertainties remain, it is estimated that the annual whole body dose from GCR during solar minimum would be in the range of 0.4 to 0.7 Sv, depending on the effects of the Earth's magnetic field and the amount of shielding, the higher value being for essentially no shielding, the lower value being for an aluminum equivalent of about 40 g $cm^{-2}$. As pointed out by Dr. Robbins, the GCR dose rate during a period of solar maximum, is estimated to be a factor of approximately three less than in solar minimum.

Depending on circumstances, SPE appear to pose the largest threat to interplanetary space missions. In fact, if no operational procedures were employed, a crew on an interplanetary mission, if provided no protection, could receive a lethal exposure from such an event. In the main, however, dose rates due to such events will probably be in the range of what is considered to be a low dose rate in terms of acute or deterministic effects (that is, below 10 to 20 mGy $min^{-1}$). Total estimated doses to the blood forming organs of an astronaut, that would have resulted due to exposure to the series of major solar flare events that occurred in October, 1989, assuming a shielding thickness equivalent to 1 g $cm^{-2}$, would have been about 1 Sv. With a shielding thickness of 10 g $cm^{-2}$, the dose would have been reduced to about 0.2 Sv. If the astronauts could take refuge in a protective shield (shelter) having a thickness equivalent to 20 g $cm^{-2}$, the dose would have been reduced to about 0.1 Sv.

Expected doses during an interplanetary mission will depend on its duration, the period within the solar cycle during which the mission takes place, and other particulars such as operational procedures and the amount of shielding provided. Assuming a spacecraft with average shielding, the total dose in 1 y from GCR radiation and SPE could equal 1 Sv. On this basis, a mission to Mars, which could require from 2 to 5 y, could yield total doses as high as 4 Sv. With good operational procedures and a warning system, however, it should be possible to manage the exposures from SPE, and to restrict total doses on interplanetary missions to acceptable levels.

## Biology Relevant to Space Radiation

The unique feature of the space radiation environment is the abundance of particulate radiations. Although protons, neutrons, and heavy ions have been studied in various biological systems, Dr. Fry indicated that the amount of information on their effects in humans is far from complete. As a result, the estimation of their effects must be largely based on data generated through laboratory experiments. Although molecular and cellular effects can help explain early or acute effects, studies involving whole organisms are generally required to adequately assess late or delayed effects. In the case of exposures to x or gamma radiation, early effects assume clinical significance only with whole-body doses in excess of one to two Sv received within a relatively short period of time (minutes to hours). Lower doses or doses received over a longer period of time, may only lead to late or delayed effects. Such potential effects include impairment of fertility, lens opacifications, cancer induction, and heritable effects.

The protection of astronauts taking part in extended space missions involves consideration both of acute and delayed, as well as possible hereditary, effects. Assessments to date indicate that the primary biological risks to such personnel in all but the most extreme or rare scenarios will be the latent (delayed) effects, the most significant of which is cancer induction. Data obtained experimentally indicate that damage to the central nervous system (CNS) may also pose a risk. Other effects, such as opacifications of the lenses of the eyes, might result from exposures in space, and synergistic effects arising from the microgravity environment cannot be excluded. There is little evidence, however, that these types of effects represent risks comparable to those of carcinogenesis. The consequences of radiation exposure of personnel in space to the total genetic pool is generally considered to be small, especially in light of the relatively small number of people who will be involved in such activities. In terms of the individual astronauts, however, the consequences are considered of importance during their reproductive years.

The threshold dose for most acute effects is on the order of 1 Sv or more. As a result, radiation doses from exposures to GCR radiation should not pose a risk of early effects to spacecraft personnel. As indicated above, the principal risk for such effects will be SPE and the accompanying high fluences of protons of varying energies.

## Associated Uncertainties

Although progress is being made in understanding the key factors associated with exposures to ionizing radiations during deep space missions, many uncertainties remain. The assumption is that cancer induction in humans due to exposures to energetic particles will be substantially higher than that for x and gamma rays and electrons. Some studies show that GCR radiation may have a quality factor of about three, that is to say, the accompanying health effects per unit of energy absorbed will be triple those for low-LET (x or gamma) radiation. The high energy particles associated with SPE may have a quality factor in the range of 1.5 to 2. More research on this subject, however, is needed, particularly in terms of the late effects of heavy, medium, and high-LET particles, as well as the effects of shielding on these types of nuclei and their energy spectra. Without such data, it will be difficult to optimize the amount and types of shielding required in the spacecraft. Also in need of better assessment are the possible interrelationships of the effects of radiation, microgravity, and the long-term confinement of the astronauts within a spacecraft.

## Radiation Standards for Human Space Activities

In reviewing the history of the development of radiation protection standards for space travel, Dr. Sinclair pointed out that initial recommendations were made in 1970 by the Radiobiological Advisory Panel of the Committee on Space Medicine, National Academy of Sciences. Using a risk-based approach and taking into consideration a range of factors (including the fact that the radiation risk is probably low in comparison to the other risks associated with space missions), the Panel proposed that "the primary reference risk should correspond to an added probability of radiation-induced neoplasia over a period of 20 y that is equal to the natural probability for the specific population under consideration." Following this approach, the Panel recommended an overall career limit of 4 Sv. Because it was assumed that only small numbers of people would be involved (as noted above), most of whom would be in excess of 30 y of age, the question of genetic effects did not appear to be of concern in relation to the population gene pool. The assumed risk coefficients used in formulating the 1970 recommendations were $3 \times 10^{-3}$ $Sv^{-1}$ for leukemia and $3 \times 10^{-3}$ $Sv^{-1}$ for solid tumors, yielding a total estimate of $6 \times 10^{-3}$ $Sv^{-1}$.

On the basis of subsequent epidemiological findings, the values of the risk coefficients were increased. As a result of this and other findings, the National Aeronautics and Space Administration (NASA) asked the National Council on Radiation Protection and Measurements (NCRP) to undertake a re-examination of both the risks and the philosophy for protecting astronauts involved in space travel. This resulted in the publication of NCRP Report No. 98 (NCRP, 1989). In undertaking this task, the NCRP decided to treat the radiation exposures of crew members and payload specialists as an occupational hazard. One consideration was to compare the risks of fatal cancers due to space travel to fatal accident rates in other occupations. Following this approach, it was noted that workers in safe industries, such as manufacturing and services, have annual risks in the range of $1 \times 10^{-4}$ and lifetime risks of about 0.5 percent. Workers in less safe industries, such as agriculture and construction, have annual risks in the range of 2 to $6 \times 10^{-4}$, and lifetime risks up to about three percent. Workers in more hazardous occupations, such as steeplejacks, deep sea fishermen, and test pilots, have even higher annual risks.

Given the exceptional nature of the occupation, and the difficulty of reducing exposures in space, the NCRP concluded in 1989 that it appeared unreasonable to restrict the radiation exposures and associated risks of space travel to those of the safest earthly occupations. On the other hand, given the exceptional character of space travel, comparison of the radiation risks to the astronauts with the risks of excess mortality in the most hazardous occupations on the ground also appeared unreasonable because crew members have other additional risks to face. As an outgrowth of these deliberations, the NCRP decided to compare the radiation risks of the astronauts with those of workers in the "less safe" occupations, that is, those who have lifetime mortality risks of about three percent.

Using a three percent lifetime excess mortality as a base, the NCRP recommended dose limits as a function of both age and sex. Following this approach, the NCRP recommended a career limit for 25 y olds of 1 Sv for females and 1.5 Sv for males. Since the risk decreases with age at which exposure begins, higher limits were recommended for older astronauts culminating with a career limit of 3.0 Sv for females and 4.0 Sv for males whose initial exposure occurred at age 55. In essence, the NCRP was saying that older crew members could take part in more missions than younger crew members, and that females could take part in fewer missions than males. These recommendations were based on an assumed nominal value of lifetime risk of fatal cancers for all ages of $2 \times 10^{-2}$ $Sv^{-1}$.

In making these recommendations, the NCRP took into consideration the following factors:

1. The proposed limits would apply only to near-Earth orbiting missions. It was also assumed that the number of people involved would be relatively small.
2. A formal radiation hazards appraisal would be conducted prior to each mission. This would include preflight exposure estimates, including doses that might be received during extravehicular activity. Factors taken into consideration would include the proposed mission plan and time line, the model of the radiation environment, a detailed mass distribution model of the spacecraft, components, and inhabitants, and a radiation transport program.
3. Detailed crew exposure records would be maintained. Every crew member would wear a passive dosimeter which had been calibrated on the basis of international comparisons.
4. The flight planning would ensure that crew exposures were "as low as reasonably achievable."
5. Formal protocols, including the use of calibrated active and passive radiation measurement systems, and flight rules covering any radiation exposure contingency would be developed and documented.

During the period from 1988 to 1993, substantial revisions were made in the estimates of the risks of fatal cancers due to ionizing radiation. As a result, the values for the risk coefficients were increased. The latest estimate for adult workers is $4 \times 10^{-2}$ $Sv^{-1}$ (NCRP, 1993). For this and other reasons, NASA has requested that the NCRP re-examine the situation. This re-examination is now underway. One of the outcomes of this exercise is the conclusion that, if the newer risk coefficients are applied and the lifetime absolute excess risk limit remains at three percent, the career dose limit for astronauts whose initial exposure occurs at age 25 would be 0.5 Sv for females and 0.8 Sv for males. The corresponding career limit for astronauts whose initial exposure occurs at age 55 would be 1.7 Sv for females and 3 Sv for males. If the acceptable life-time absolute excess of risk were reduced to 1.5 percent, the corresponding career limits at age 25 would be 0.25 Sv for females and 0.4 Sv for males; at age 55 the limits would be 0.8 Sv for females, and 1.5 Sv for males. The new NCRP report, which will contain revised recommendations based on this new understanding, is nearing completion. It will be published after additional review and evaluation.

Clearly demonstrated, especially by the people attending the Symposium, was that the latent cancer risk deemed acceptable for astronauts is dependent on a variety of factors. Whatever limits are established must be ethically defensible, and the ALARA criterion must be made an integral part of the associated radiation protection program. Every effort should also be taken to assure that recommendations are not discriminatory, in terms of men versus women.

## Technical, Social and Philosophical Perspectives on Acceptable Risk

In his presentation, Dr. Garrick addressed the analytic concepts for assessing risk. One such concept is to approach the subject by seeking answers to three basic questions:

1. What can go wrong?
2. How likely is it?, and
3. What are the consequences?

The result is a performance assessment consisting of scenarios, likelihoods, and the possible outcomes or consequences of the scenarios. The outcomes of performance measures of interest include time dependent dose rates and the numbers and types of anticipated health effects. Uncertainty is included in each of the performance measures to convey the confidence of the analyst in the results.

Risk-based performance assessments of space missions involve two broad assessments, the undisturbed and the disturbed case. Because of its potential contribution as a major source of exposure, the major factor to be considered in the disturbed case is the occurrence of an SPE. In this regard, uncertainties will arise due to questions about the adequacy of the database, the types and energies of the irradiating particles, the effectiveness of the spacecraft shielding in reducing the dose, and the complexities associated with evaluating the accompanying health effects.

The starting point of a risk assessment is the development of a set of initiating events or initiating event categories that become the building blocks for developing a series of scenarios that, if properly designed, will encompass the full range of possible events that can occur and will provide meaningful estimates of the associated risks. Structuring the scenario set requires a detailed understanding of the system involved and the physical processes associated with the events that make up the scenario. The resulting risk assessment consists of scenarios and consequences that can be presented in the form of probability curves which show the level of confidence the analyst has in the consequences, that is, in the outcomes of the different scenarios. The goal is to develop a complete set of scenarios and then to select those that lead to consequences of interest.

If there is large uncertainty in the performance measures, that is, if the probability curves are very broad, the analyst is conveying a poor state of knowledge about the performance measure. On the other hand, if the probability curves are narrow, the implication is that the analyst has a high state of knowledge of the various factors and processes that underlie that particular scenario. Both outcomes represent a quantification of the risk; the only difference is our states of knowledge. The significance of such calculations is what they tell us that we know, as well as what they tell us that we do not know. There is no need to fret over the quality of the data, etc., because that is a built-in feature of the uncertainties in the results. The analyst characterizes that uncertainty, including its origin, so that how to control it becomes visible. This is a critically important result of the quantitative risk assessment process. This is how risk is quantified in a mathematic or scientific sense.

As Dr. Whipple pointed out, however, the perceptions of the risks of radiation exposures, as viewed by NASA and the astronauts, will be strongly influenced by the risks associated with other aspects of the mission and its goals and objectives, as well as other risks in the daily lives of the astronauts. In terms of the establishment of radiation protection standards for space travel, Dr. Whipple suggested that past experience indicates that there are three basic decision processes that frequently appear. These are:

1. Cost-benefit analysis—this process or approach is based on the principle that a standard, to be acceptable, should be economically efficient, that is, the benefit should exceed the risk or cost, and marginal costs should equal marginal benefits.
2. Risk-level approaches—this approach is based on the objective of ensuring that individual risks are acceptably low. The advantages of this approach is that predictable levels of risk result, and innovation in risk control is encouraged.
3. Technology-based approaches—these have long been used in setting safety standards. One example is the requirement that good engineering practice, as exemplified by the best available control technology, must be applied. Another example is the requirement that the exposures must be maintained as low as reasonably achievable.

Dr. Whipple went on to point out that the analytic methods given above tend, by their quantitative nature, to emphasize the magnitude of the risks, costs and alternatives, and to downplay other facts, especially those that are not easily expressed in quantitative terms that affect acceptance or rejection of risk. He suggested some of the other factors that are not considered in the above analytic methods include such issues as risk perception and how and by whom risk decisions are made and of course, another consideration would be, were the procedures used acceptable ethically.

Continuing the discussion on the perceptions of risk, Dr. Slovic reviewed what he considered to be the key factors that influence how a person views a particular risk. Included among these factors, which he described by developing "personality profiles" of risks, were whether the risk is being accepted on a voluntary or involuntary basis; the degree to which the risk is believed to be controllable; whether it is considered to be short-term with no lingering implications, or continues as a "threat" to the person during subsequent years (as, for example, the possibility of the subsequent development of latent cancers due to earlier exposures to ionizing radiation); and the magnitude of the associated benefits that are to be gained as a result of being exposed to the given risk, as well as whether those who suffer the risks are also those who stand to reap the benefits. Another influencing factor is how family members view the risks. A spouse, for example, may well view the risks of radiation in a far different light than an astronaut.

According to Dr. Slovic, risk does not exist in the world independent of our minds and cultures, waiting to be measured. There is no such thing as real risk or objective risk. The nuclear engineer's probabilistic risk estimate for a nuclear power plant accident, or the toxicologist's quantitative estimate of a chemical's carcinogenic risk, are both based on theoretical models whose structure is subjective and laden with assumptions whose inputs are dependent on judgments. In fact, subjectivity permeates every aspect of risk assessment, beginning with the initial structuring of the situation to be assessed and including the decision of what end points or consequences will be included. The assessment of radiation risks in space is no exception. As indicated by Dr. Garrick, the structuring of the problem includes judgments related to the probability, magnitude, and effects of the various types of radiation likely to be encountered and assumptions related to the quantitative relationship between dose and a range of specific effects, all of which have associated uncertainties. Also of importance are the endpoints or consequences to be considered. In terms of the latter factor, the endpoint adopted for use by the NCRP is cancer mortality. One could readily ask whether it should include other effects, such as cancer morbidity and years of lost life expectancy.

The manner in which risk is viewed is also significantly influenced by the manner in which it is framed and presented. As a result, such framing has an influence on decision making, examples being whether the risk analyst attempts to consider the equivalence of lives saved versus lives lost, or mortality rates versus survival rates. Unfortunately, there is no right or wrong frame for portraying risk information. There are just different frames. In the end, a given risk is characterized by some combination of attributes, such as its probability, its intentionality, its equity and, as indicated above, whether it is voluntary or involuntary. In many respects, risk assessment is a game and the conflicts between the risk analysts and the people undergoing the risks may arise from the fact that each side believes that the rules of the game should be different. As will be indicated below, Dr. Thornton has pointed out that this is particularly true in the case of the astronauts.

Risk assessment is inherently subjective and it is incredibly complex, and it involves both science and politics. The risk analyst must recognize the importance of the social, cultural, and political aspects in controversies about risk. The establishment of acceptable dose limits for interplanetary space travel is no exception. Risk assessment breeds fear. This is not to say that risk assessments should not be conducted; it is just that its side effects must be recognized. In the end, a risk that is deemed acceptable does not depend on some magical number. It is the result of the weighing of risks and benefits and the selection of the option that appears to be best.

## Steps for Reducing the Dose

There are a variety of steps that can be taken to limit the radiation doses that astronauts taking part in deep space missions might incur. One is to schedule the mission so as to minimize the potential doses from the combination of GCR radiation and SPE. As in many aspects of risk assessment, this involves trade-offs as well as perhaps ethical considerations. For example, scheduling a mission during a period of solar minimum would minimize the probability of the occurrence of SPE, but it would maximize the dose from GCR radiation. In contrast, scheduling the mission during a period of solar maximum would minimize the dose from GCR radiation, but would maximize the probability of the occurrence of SPE. Regardless of when a mission takes place, there would be a need to institute a system to alert the astronauts of impending SPE so that they can take protective measures, such as moving into a special shelter within the spacecraft. A second step would be to limit the duration of the mission. Such a step would not only reduce the dose from GCR radiation but it would also reduce the probability of the occurrence of SPE. Reducing the duration of a mission, however, may not be readily possible. Other steps that might be taken, which are beyond the scope of this Symposium, would be to restrict higher dose missions to older members of the astronaut team, or to develop protective drugs or protective dietary supplements.

## Philosophy on Astronaut Protection

Dr. Holloway initiated this session by calling attention to the fact that NASA has a responsibility to assure that proper ethical standards are applied in establishing and applying limits for the control of radiation doses to the astronauts. Such a responsibility obviously includes assuring that the astronauts are properly informed of the hazards associated with individual missions and that they agree to accept the associated risks. The responsibility, however, does not end there. It includes a need to discuss how to initiate a discourse for developing the related ethical standards and how to determine who should be involved in their establishment. To assure that such a discourse can be developed, there is a need to determine how to foster proper communications on matters that encompass the realms of policy, science, and politics. It was generally agreed by the Symposium participants that the meshing of public perceptions of risk with those of the scientific and technical community will be a significant undertaking.

In the presentation that followed, Dr. Baker highlighted what she considered to be differences in the risks of the launch of a spacecraft, its journey, and its subsequent return to Earth, as contrasted to the risks of latent cancers that may develop as a result of the associated radiation exposures. Once the spacecraft has landed, following a successful mission, the risks of mission related accidental death are over. The risks of latent cancers, however, will remain with the astronauts for the rest of their lives. The same may be true for many of the effects of the space environment, including microgravity. Compounding the problem with respect to radiation are the large uncertainties accompanying the estimates of the associated latent cancer risks.

Another aspect brought into the discussion by Dr. Baker, and one that relates to the matter of ethics, was the significant contribution to the radiation doses to the astronauts that have occurred in the past as a result of medical examinations and experiments conducted to obtain data on the effects of the space environment on humans. Since the experiments were considered to be a part of the "job" of being an astronaut, the resulting doses were included in their occupational radiation exposure records. Following this approach, the accompanying doses were counted against the career limits being imposed on each astronaut. As a result, volunteering for such experiments could possibly cause an earlier termination of the career of an astronaut than would otherwise have occurred. Through cooperative efforts, these doses have been significantly reduced in recent years. In fact, one of the outcomes of these efforts has been the incorporation of the ALARA concept into the radiation protection program for the astronauts, as recommended in NCRP Report No. 98 (NCRP, 1989). As Dr. Baker also emphasized, the fact that a space mission has a range of risks, including some that are relatively large, **is no justification for not reducing** the accompanying radiation doses.

Dr. Thornton pointed out that the concepts of risk perception and acceptable risk, as viewed by NASA and the astronauts, are in many cases different than those of scientists, politicians, and the public. This was especially true during the early years when he was active in the space program. According to Dr. Thornton, the individual astronauts at that time were incredibly goal oriented, they had an overwhelming desire to demonstrate success, and they were driven to the extent of routinely taking risks that were not generally accepted by other professionals and most notably by the public. One of the stimulants for these attitudes was that failure to complete a mission successfully (or failure of some other boundary or limit—physical or mental) would result in their removal from the program. In closing, Dr. Thornton urged that everyone keep in mind that space exploration is an inherently risky business; if we demand total assurance of safety, little or nothing will be accomplished. What is needed is the most objective and accurate advice that can be provided.

## Commentary

One of the prime observations that emerged from the Symposium was the key role of ethics in many of the decisions being faced by NASA, and the accompanying need for the establishment of sound policies for incorporating adequate ethical considerations into the related decision-making process. Such decisions include not only the selection of radiation dose limits for the astronauts but also the criteria or bases for the limits. For example, are the limits to be based on those currently being applied to radiation workers on Earth; is the risk of latent cancer fatalities an acceptable endpoint or should other effects be considered; are individual career, as well as annual and mission limits to be specified; and should the limits be flexible depending on the assumed importance or anticipated benefits of a specific mission?

One of the major ethical considerations, raised by Dr. Baker, was the role that individual astronauts should play in medical experiments, using radiopharmaceuticals, that are designed to obtain data on the effects of the space environment on humans, and whether the resulting radiation doses should be included in assessing whether they have exceeded their cumulative career dose limit. Experience has shown that such experiments are essential if the data for protecting existing and future astronauts are to be available. Other considerations include whether career and mission *dose* limits for women and men should be the same, or whether their *risk* limits should be the same, and whether the limits should be different for workers involved in assembling a space station versus astronauts taking part in interplanetary exploration.

The Symposium served as a vehicle for illuminating the relevant questions, and it provided an excellent review and summary of much of the basic scientific data that must be taken into consideration in order to recommend acceptable limits of risk for space activities. It also clarified other aspects related to the acceptability of risk. Questions to be addressed include:

- Is the risk controllable?
- Do those bearing the risk receive reasonable benefit?
- Does the expected benefit outweigh the real and perceived risk
- Is the risk short- or long-term?
- Is the risk to be accepted on a voluntary or involuntary basis?
- Is the perception of the risk adequately considered?
- Are good engineering practices followed?
- Is the cost of reducing the risk reasonable, *i.e.*, is the risk ALARA?
- Are ethical considerations fully addressed, *e.g.*, are the procedures used in ultimately establishing a maximum level of risk acceptable to the individuals bearing the risk, to those who bear the cost of reducing the risk, to those responsible for imposing the risk on others and to society at large?

**When the above aspects and others are considered, it has to be kept in mind that there is no magic formula that will lead to a precise level of acceptable risk from exposure to radiation in space. Acceptable risk levels must evolve through a process of negotiation that integrates a large number of social, technical and economic factors. In the end, a risk that is deemed to be acceptable will be the outgrowth of the weighing of risks and benefits and the selection of the option that appears to be best.**

In addition, the Symposium revealed a consensus that the relatively large risks to which astronauts are exposed, for example, during lift-off, should not be used as an excuse for relaxing the dose limits for ionizing radiation. In fact, several of those present, led by Dr. Baker, emphasized the need for the incorporation of the ALARA criterion as a integral part of the space radiation protection program.

The Symposium also demonstrated a universal need to educate those involved in applying radiation dose limits to ensure that they understand that the limits are not there to "be used up;" rather their purpose is to serve as a constraint on operations and as a guide for the design of the associated radiation protection systems.

## Summary and Conclusions

On the basis of the information presented, it appears that there is a variety of steps that can be taken to protect astronauts involved in interplanetary missions. These steps include optimum scheduling of the missions, the provision of shielding designed to protect against high energy particles, and the establishment of a system to warn of SPE. Should the estimated doses still be relatively high, other steps that can be considered include restricting such missions to older members of the astronaut team and the provision of protective drugs or diet supplements to help ward off the effects of acute exposures.

At the same time, however, the information presented showed that there are many uncertainties in assessing the risks from radiation sources likely to be encountered in such missions. These include the types and energies of the particles constituting the exposures, the associated effects of shielding, and the biological effects that the associated exposures may entail. Obviously, more research is needed.

Also demonstrated by the information presented and the audience participation is that the specific latent cancer risk which an astronaut should be permitted to experience is dependent on a variety of factors. As indicated by the preceding section, whatever limits are established must be ethically defensible, they must be designed so as not to be discriminatory, and they must be sufficiently flexible to enable the later incorporation of possible changes in the radiation risk coefficients and in the perspectives of the public relative to what risks are considered acceptable. In every case, the determination of an acceptable limit must involve a careful weighing of the risks and the benefits.

## References

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# Closing Remarks

Paul Slovic
Symposium Chairman

Dade's summary reminds me of a bumper sticker that I saw on a car. It said, "If I had known how much fun grandchildren were I would have had them first." Well, if we had known how informative this summary was going to be, we would have had it first! It's very, very impressive.

I'd like now to draw this Symposium to a close. I believe that all would agree that it has been a terrific day. Let me at this time thank a few of the people who made it possible. First, Dade Moeller really was behind the scenes administering many of the details throughout the development and execution of this program. He was assisted at the NCRP by Bill Beckner and, of course, Charlie Meinhold and Wil Ney, along with Laura Atwell and Tabitha Buck. Let me also express my appreciation to the Program Committee, most especially, Michael Fry, Dade Moeller and Chris Whipple. John Garrick also was of immense help to us. Last, but not least, I would like to thank our speakers, all of whom did an excellent job today. So, thanks to all these people. We hope you will enjoy the written report of the Symposium as well. Thank you.

NCRP

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The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection.
2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations.
3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection.
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units and measurements and with radiation protection.

The Council is the successor to the unincorporated association of scientists known as the National Committee on Radiation Protection and Measurements and was formed to carry on the work begun by the Committee in 1929.

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- SC 1-6 Basis for the Linearity Assumption
- SC 1-7 Information Needed to Make Radiation Protection Recommendations for Travel Beyond Low-Earth Orbit
- SC 1-8 Risk to Thyroid from Ionizing Radiation

SC 9 Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV

SC 46 Operational Radiation Safety
- SC 46-8 Radiation Protection Design Guidelines for Particle Accelerator Facilities
- SC 46-10 Assessment of Occupational Doses from Internal Emitters
- SC 46-11 Radiation Protection During Special Medical Procedures
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SC 57 Dosimetry and Metabolism of Radionuclides
- SC 57-9 Lung Cancer Risk
- SC 57-10 Liver Cancer Risk
- SC 57-14 Placental Transfer
- SC 57-15 Uranium
- SC 57-16 Uncertainties in the Application of Metabolic Models
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SC 64 Radionuclides in the Environment
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SC 66 Biological Effects and Exposure Criteria for Ultrasound

SC 72 Radiation Protection in Mammography

SC 75 Guidance on Radiation Received in Space Activities

SC 85 Risk of Lung Cancer from Radon

SC 86 Hot Particles in the Eye, Ear or Lung

SC 87 Radioactive and Mixed Waste
- SC 87-1 Waste Avoidance and Volume Reduction
- SC 87-2 Waste Classification Based on Risk

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SC 89 Nonionizing Electromagnetic Fields

SC 89-1 Biological Effects of Magnetic Fields

SC 89-3 Extremely Low-Frequency Electric and Magnetic Fields

SC 89-4 Modulated Radiofrequency Fields

SC 89-5 Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields

SC 91 Radiation Protection in Medicine

SC 91-1 Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides

SC 91-2 Dentistry

SC 92 Policy Analysis and Decision Making

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In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. Collaborating Organizations provide a means by which the NCRP can gain input into its activities from a wider segment of society. At the same time, the relationships with the Collaborating Organizations facilitate wider dissemination of information about the Council's activities, interests and concerns. Collaborating Organizations have the opportunity to comment on draft reports (at the time that these are submitted to the members of the Council). This is intended to capitalize on the fact that Collaborating Organizations are in an excellent position to both contribute to the identification of what needs to be treated in NCRP reports and to identify problems that might result from proposed recommendations. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

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United States Department of Transportation

United States Environmental Protection Agency
United States Navy
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United States Public Health Services
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The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the Special Liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the Special Liaison Program:

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National Radiological Protection Board (United Kingdom)
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Russian Scientific Commission on Radiation Protection
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The NCRP values highly the participation of these organizations in the Special Liaison Program.

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| 11 | *Radiation Protection Today—The NCRP at Sixty Years*, Proceedings of the Twenty-fifth Annual Meeting held on April 5-6, 1989 (including Taylor Lecture No. 13) (1990) |
| 12 | *Health and Ecological Implications of Radioactively Contaminated Environments*, Proceedings of the Twenty-sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991) |
| 13 | *Genes, Cancer and Radiation Protection*, Proceedings of the Twenty-seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992) |
| 14 | *Radiation Protection in Medicine*, Proceedings of the Twenty-eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No. 16) (1993) |
| 15 | *Radiation Science and Societal Decision Making,* Proceedings of the Twenty-ninth Annual Meeting held on April 7-8, 1993 (including Taylor Lecture No. 17) (1994) |
| 17 | *Environmental Dose Reconstruction and Risk Implications,* Proceedings of the Thirty-First Annual Meeting held on April 12-13, 1995 (including Taylor Lecture No. 19) (1996) |

18 *Implications of New Data on Radiation Cancer Risk*, Proceedings of the Thirty-Second Annual Meeting held on April 3-4, 1996 (including Taylor Lecture No. 20) (1997)

## Lauriston S. Taylor Lectures

| No. | Title |
|---|---|
| 1 | *The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977) |
| 2 | *Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978) |
| 3 | *Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk*, see above] |
| 4 | *From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980) |
| 5 | *How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits*, see above] |
| 6 | *Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches*, see above] |
| 7 | *The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above] |
| 8 | *Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above] |
| 9 | *Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste*, see above] |
| 10 | *Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions* by Herman P. Schwan (1987) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound*, see above] |
| 11 | *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above] |
| 12 | *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon*, see above] |
| 13 | *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today*, see above] |
| 14 | *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [Available also in *Health and Ecological Implications of Radioactively Contaminated Environments*, see above] |
| 15 | *When is a Dose Not a Dose?* by Victor P. Bond (1992) [Available also in *Genes, Cancer and Radiation Protection*, see above] |

16 *Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992)[Available also in *Radiation Protection in Medicine*, see above]
17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993)[Available also in *Radiation Science and Societal Decision Making*, see above]
18 *Mice, Myths and Men* by R.J. Michael Fry (1995)

## Symposium Proceedings

| No. | Title |
|---|---|
| 1 | *The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack*, Proceedings of a Symposium held April 27-29, 1981 (1982) |
| 2 | *Radioactive and Mixed Waste—Risk as a Basis for Waste Classification,* Proceedings of a Symposium held November 9, 1994 (1995) |
| 3 | *Acceptability of Risk from Radiation—Application to Human Space Flight*, Proceedings of a Symposium held May 29, 1996 (1997) |

## NCRP Statements

| No. | Title |
|---|---|
| 1 | "Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63**, 428 (1954) |
| 2 | "Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. **84**, 152 (1960) and Radiology **75**, 122 (1960) |
| 3 | *X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968) |
| 4 | *Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements* (1973) |
| 5 | *NCRP Statement on Dose Limit for Neutrons* (1980) |
| 6 | *Control of Air Emissions of Radionuclides* (1984) |
| 7 | *The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992) |

## Other Documents

The following documents of the NCRP were published outside of the NCRP report, commentary and statement series:

*Somatic Radiation Dose for the General Population*, Report of the Ad Hoc Committee of the National Council on Radiation Protection and Measurements, 6 May 1959, Science, February 19, 1960, Vol. 131, No. 3399, pages 482-486

*Dose Effect Modifying Factors In Radiation Protection,* Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service Springfield, Virginia)

The following documents are now superseded and/or out of print:

## NCRP Reports

| No. | Title |
|---|---|
| 1 | *X-Ray Protection* (1931) [Superseded by NCRP Report No. 3] |
| 2 | *Radium Protection* (1934) [Superseded by NCRP Report No. 4] |
| 3 | *X-Ray Protection* (1936) [Superseded by NCRP Report No. 6] |
| 4 | *Radium Protection (1938)* [Superseded by NCRP Report No. 13] |
| 5 | *Safe Handling of Radioactive Luminous Compound* (1941) [Out of Print] |
| 6 | *Medical X-Ray Protection Up to Two Million Volts* (1949) [Superseded by NCRP Report No. 18] |
| 7 | *Safe Handling of Radioactive Isotopes* (1949) [Superseded by NCRP Report No. 30] |
| 9 | *Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951) [Out of print] |
| 10 | *Radiological Monitoring Methods and Instruments* (1952) [Superseded by NCRP Report No. 57] |
| 11 | *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953) [Superseded by NCRP Report No. 22] |
| 12 | *Recommendations for the Disposal of Carbon-14 Wastes* (1953) [Superseded by NCRP Report No. 81] |
| 13 | *Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954) [Superseded by NCRP Report No. 24] |
| 14 | *Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts* (1954) [Superseded by NCRP Report No. 51] |
| 15 | *Safe Handling of Cadavers Containing Radioactive Isotopes* (1953) [Superseded by NCRP Report No. 21] |
| 16 | *Radioactive-Waste Disposal in the Ocean* (1954) [Out of Print] |
| 17 | *Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposures to Man, Addendum to National Bureau of Standards Handbook 59* (1958) [Superseded by NCRP Report No. 39] |
| 18 | *X-Ray Protection* (1955) [Superseded by NCRP Report No. 26] |

19 *Regulation of Radiation Exposure by Legislative Means* (1955) [Out of print]

20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957) [Superseded by NCRP Report No. 38]

21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958) [Superseded by NCRP Report No. 37]

24 *Protection Against Radiations from Sealed Gamma Sources* (1960) [Superseded by NCRP Reports No. 33, 34 and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961) [Superseded by NCRP Reports No. 33, 34, 35 and 36]

28 *A Manual of Radioactivity Procedures* (1961) [Superseded by NCRP Report No. 58]

29 *Exposure to Radiation in an Emergency* (1962) [Superseded by NCRP Report No. 42]

31 *Shielding for High-Energy Electron Accelerator Installations* (1964) [Superseded by NCRP Report No. 51]

33 *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV—Equipment Design and Use* (1968) [Superseded by NCRP Report No. 102]

34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation Handbook* (1970) [Superseded by NCRP Report No. 49]

39 *Basic Radiation Protection Criteria* (1971) [Superseded by NCRP Report No. 91]

43 *Review of the Current State of Radiation Protection Philosophy* (1975) [Superseded by NCRP Report No. 91]

45 *Natural Background Radiation in the United States* (1975) [Superseded by NCRP Report No. 94]

48 *Radiation Protection for Medical and Allied Health Personnel* (1976) [Superseded by NCRP Report No. 105]

51 *Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities* (1977) [Out of print]

53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally-Exposed Women* (1977) [Out of print]

56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977) [Superseded by NCRP Report No. 95]

58 *A Handbook of Radioactivity Measurements Procedures*, 1st ed. (1978) [Superseded by NCRP Report No. 58, 2nd ed.]

66 *Mammography* (1980) [Out of print]

91 *Recommendations on Limits for Exposure to Ionizing Radiation* (1987) [Superseded by NCRP Report No. 116]

## NCRP Commentaries

| No. | Title |
|---|---|
| 2 | *Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982) [Out of print] |

## NCRP Proceedings

| No. | Title |
|---|---|
| 2 | *Quantitative Risk in Standards Setting*, Proceedings of the Sixteenth Annual Meeting held on April 2-3, 1980 [Out of print] |