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# SPACE RADIATION HEALTH PROGRAM PLAN

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## STATEMENT OF PURPOSE

The Space Radiation Health Program intends to establish the scientific basis for the radiation protection of humans engaged in the exploration of space, with particular emphasis on the establishment of a firm knowledge base to support cancer risk assessment for future planetary exploration. This document sets forth the technical and management components involved in the implementation of the Space Radiation Health Program, which is a major part of the Life Sciences Division (LSD) effort in the Office of Space Science and Applications (OSSA) at the National Aeronautics and Space Administration (NASA). For the purpose of implementing this program, the Life Sciences Division supports scientific research into the fundamental mechanisms of radiation effects on living systems and the interaction of radiation with cells, tissues, and organs, and the development of instruments and processes for measuring radiation and its effects. The Life Sciences Division supports researchers at universities, NASA field centers, non-profit research institutes and national laboratories; establishes interagency agreements for cooperative use and development of facilities; and conducts a space-based research program using available and future spaceflight vehicles.

# RADIATION HEALTH PROGRAM PLAN

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## LIST OF ACRONYMS

ACE	Advanced Composition Explorer
AFRRI	Armed Forces Radiobiology Research Institute
ALARA	As Low As Reasonably Achievable
AMAC	Aerospace Medicine Advisory Committee
AO	Announcement of Opportunity
CIRRPC	Committee on Interagency Radiation Research and Policy Coordination
CNES	Centre Nationale d'Etudes Spatiales
CNS	Central Nervous System
CSA	Canadian Space Agency
CSBM	Committee on Space Biology and Medicine
DARA	Deutsche Agentur Für Raumfahrt Angelegenheiten
DNA	Deoxyribonucleic Acid
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
DWG	Discipline Working Group
ESA	European Space Agency
EVA	Extravehicular Activity
GCR	Galactic Cosmic Radiation
GSF	Gesellschaft Für Schwerionenforschung
GSM	Global Solar Monitors
HZE	High atomic number, Z, and high energy, E, particles
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LBL	Lawrence Berkeley Laboratory
LEO	Low Earth Orbit
LET	Linear Energy Transfer
LSAS	Life Sciences Advisory Subcommittee
LSD	Life Sciences Division
MOU	Memorandum of Understanding
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NCRP	National Council on Radiation Protection and Measurements
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NSCORT	NASA Specialized Center of Research and Training
OAST	Office of Aeronautics, Exploration, and Technology
OSF	Office of Space Flight
OSL	Orbiting Solar Laboratory
OSSA	Office of Space Science and Applications
POP	Program Operating Plan
RBE	Relative Biological Effectiveness

## LIST OF ACRONYMS (continued)

RBI	Radiation Biology Initiative
RTOPs	Research and Technology Operating Plans
SAA	South Atlantic Anomaly
SEI	Space Exploration Initiative
SEP	Solar Energetic Particle
SSAAC	Space Science and Applications Advisory Committee
SSF	Space Station Freedom
STS	Space Transportation System (Shuttle)
SWG	Science Working Group
TBD	To Be Determined
TDRSS	Tracking and Data Relay Satellite System
USSR	Union of Soviet Socialist Republics

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SPACE RADIATION HEALTH PROGRAM PLAN**

1.0 INTRODUCTION

Protection from the hazards due to ionizing radiation in the space environment has been identified as a critical area, essential to the support of space exploration by humans, and of the utmost importance both for journeying to and living on other planetary bodies. A broad spectrum of radiation, ranging from the infrared to galactic cosmic rays (GCR), exists in the space environment, external to the life-supporting enclosures in which humans will live and work (habitats, spacecraft, and space suits). The Space Radiation Health Program is committed to understanding, predicting and preventing radiation insults and their biological effects during space travel and habitation. In this context, the concerns of the program are the ionizing components of the space radiation environment, the radiation events produced by interactions of this environment with the materials of spacecraft and habitats, and with the interactions of primary and secondary radiation with cells and tissues in vivo.

The biological effects of exposure to radiation and, in particular, the risk of cancer, depend on a multitude of factors. Among the most important are: the dose, the dose rate, the rate of energy deposition along a particle trajectory ("linear energy transfer" or LET), the age at exposure, the organ or organs irradiated, etc. Dose (or, more precisely, "absorbed dose") is the average energy deposition per unit mass, under suitably defined radiation equilibrium conditions. The unit of dose is the *Gray* (abbreviated "Gy") corresponding to an energy deposition of 1 J/kg. An older unit, the *rad*, is still used in many publications; one Gy is equal to 100 rad. For neutrons and charged particles, another important quantity is the particle *fluence*, i.e., the number of particles per unit area traversing a surface; the rate at which the particles are incident, or fluence per unit time, is the *flux*.

The same dose, delivered by different types of radiation, does not always result in the same biological effect. To account for this, and to convert different doses of different types of radiation into a common scale related to biological risk, dose is usually weighted by multiplication with a *Quality Factor*, Q (or QF). The product of Q and dose



is known as *dose equivalent*; it is given in *Sievert* (Sv). An older unit, the *rem*, is also used in many publications; one Sv is equal to 100 rem. The quality factor is a legislated quantity, which is generally related to LET. This corresponds to the fact that relative biological effectiveness (RBE) is correlated with, although not a unique function of, LET. Contrary to Q, RBE is an observed biological quantity, defined as the ratio of the dose of a reference radiation (generally 250 kV x-rays) to the dose of the radiation under study, resulting in the same biological effect. The greater the RBE, the greater the effectiveness for inducing biological damage.

Space flight unavoidably increases the exposure of crews to radiation. The ability to predict the doses delivered to crew members by the complex radiation fields described above, to measure precisely the actual doses received in a given mission by different organs, and to predict the probability that this exposure will have given biological consequences, is critical for establishing the radiation risks of current and future missions.

Management of the risks associated with exposure to ionizing radiation in space is best accomplished by a combination of shielding and reduction of the exposure period. On a Mars expedition, such a reduction could be achieved by minimizing the trip time, when the crew is exposed to GCR radiation in a spacecraft of limited shielding capabilities. Dose reduction can also be achieved by judicious scheduling of a mission or activity (e.g., to coincide with reduced radiation levels resulting from their modulation by solar activity); by selecting appropriate materials to interpose between the radiation environment and humans (e.g., spacecraft shielding); or by a combination of both strategies (e.g., use of a "storm shelter").

Since some exposure to radiation is unavoidable, it would be important to develop strategies to minimize the biological consequences. Such approaches are, at present, seriously limited by our inadequate understanding of the biological effects of exposure to radiation. The methods that have been considered include the use of radioprotective pharmaceuticals, activation of cellular repair mechanisms, selection of individuals with reduced radiation sensitivity, and other biomedical approaches.

Decisions involving mission planning and crew assignments depend on an accurate understanding of the biological consequences of the actual radiation profile for every mission. Conceptually, these decisions are equivalent to setting acceptable levels of

risk. For Space Shuttle and Space Station Freedom (SSF) missions, dose limits have been and continue to be reviewed by the National Council on Radiation Protection and Measurements (NCRP). Current recommendations have been accepted by the NASA Administrator, and approved by the Department of Labor. These limits are based on epidemiological analyses of the effects of sparsely ionizing radiation (i.e., having low LET). In low Earth orbit (LEO), where most of the radiation of interest in this context is due to the energetic trapped protons, these limits are considered to be adequate. However, for exploration class missions of the type proposed by the Space Exploration Initiative (SEI), radiation exposure limits cannot be established because the current level of knowledge about the interplanetary radiation environment, its interaction with matter, and its biological effects, including cancer, is insufficient to define radiation exposure limits. Thus, neither the biological effects nor the radiation profile of missions outside the Earth's magnetic field can be adequately predicted at this time. The development of methods to enable accurate predictions, to define the corresponding radiation limits and to ensure that they are not exceeded is at the heart of the Space Radiation Health Program. The NCRP recommendations are examined on an ongoing basis, so that new information can be used to keep them up-to-date.

The major radiation hazards for exploration class missions outside the Earth's magnetosphere are due to protons from solar energetic particle (SEP) events and to the protons and highly charged, energetic (HZE) particles of elements with higher atomic numbers, that constitute the GCR. The SEP radiation consists of high intensity bursts of protons increasing in a short time period of the order of hours to a maximum flux that can then decay in a matter of hours or days. The radiation hazard posed by SEP events requires substantial improvements in prediction and warning techniques; the development of such techniques should be aggressively pursued, among others, by investigators associated with the Space Physics Division of OSSA and with the National Oceanic and Atmospheric Administration (NOAA). Since the radiation levels associated with SEP events can be life-threatening, the reduction of radiation exposure to acceptable levels must be achieved by sufficient shielding. In a spacecraft, the episodic nature of SEP events means that a well-shielded enclosure of relatively small mass can satisfy the shielding requirement. Upon warning of an SEP event, the crew would seek refuge in such a "storm shelter" and could remain there for the relatively short duration of the event (hours or days.).

HZE particles are a major source of the background radiation that is continuously present on the surface of the Earth. In the case of HZE particles, exposure to low levels of radiation is chronic, occurring continuously and over the entire duration of a mission or term of duty. The fluence of particles outside the protection afforded by the Earth's magnetic field and atmosphere, is substantially greater; estimates indicate that a significant number of the cells in a crew member's body will have been traversed by an HZE particle in the course of a year.

Protons are usually considered to be low LET radiation. This assumption has not been proven and needs to be verified. The dose rate from SEP events is also not quite the same as the acute, high dose-rate exposures on which most epidemiological data are based, and it is necessary to ascertain whether extrapolations from high dose-rate data provide adequate estimates of radiation effects. Radiation shielding against protons is relatively well understood, although further studies are needed to realize mass reductions. Biological countermeasures may be of importance if a significant exposure occurs after warning of an SEP event is issued, while crew members are in transit (e.g., from extravehicular activity - EVA - or a planetary surface sortie) to a radiation shelter. Radioprotectants have been found to be of some effectiveness for this type of radiation and their development will be encouraged for this application.

The most important biological hazards associated with HZE particles are so-called "late effects," occurring during the remaining lifespan of the individual after exposure. Life threatening and life shortening effects, in particular, cancer, are of greatest concern. Mutagenesis and other tissue damage, including cataract formation, are also significant adverse health effects. Neurological and behavioral effects and their consequences for crew performance also need to be understood. The HZE particles are capable of producing biological effects not seen at comparable doses of x-rays (e.g., causing entire chromosomes to break up). At a given dose, the RBE for most HZE effects is greater than 1; in some experiments, RBE values of 30 or greater have been measured, indicating the greater effectiveness of HZE particles relative to low-LET radiation. The HZE particles, although contributing less than 1 percent of the GCR flux, make a much larger contribution to the dose due to their higher rate of energy deposition, and may be biologically the most significant component of GCR radiation.

The assessment of life-shortening effects, (e.g., carcinogenesis) and other effects (e.g., cataract formation, central nervous system damage), due to these types of radiation is

necessary in order to estimate the excess risk probabilities used for the definition of radiation risk, and to make informed decisions on whether these increased risks are acceptable; these predictions are similarly critical for the design of exogeomagnetic mission architectures. Risk estimates are affected by a series of uncertainties, listed in Table 1. These uncertainties are not listed in order of importance, but are in the same order in which a transport calculation would make use of descriptions of the interplanetary environment, of the modification of the incident radiation by spacecraft materials and crew members' tissues, of models of biological effect, and of interpretations of biological effects in terms of human risk.

The uncertainties associated with the prediction of radiation risk in interplanetary space are cumulative; their magnitude in most cases is not well known. The differential fluxes of GCR particles, especially at lower energies, are modulated by solar activity and can increase by an order of magnitude going from solar maximum (where the heliomagnetosphere contributes to exclude GCR particles) to solar minimum. Even at solar minimum, where the best measurements of HZE particle abundances and energy spectra exist, the imprecision of the measurements can be as high as  $\pm 25\%$  (Although models of GCR differential fluxes at solar minimum are currently consistent at the 10% level.) The calculation of radiation transport across spacecraft materials depends on a knowledge of nuclear interaction cross sections; the nuclear physics of HZE particles is still under development, and cross section data for nuclear reactions of HZE particles are very sparse. Phenomenological interpolations are expected to have errors of the order of 30 percent. For thick shields, in which most of the incident HZE particles have interacted, so that only the lightest particles remain, large increments in shielding correspond to small changes in attenuation of the radiation dose. For this reason, relatively small errors in the intensity of incident HZE particles and in the HZE cross sections lead to substantially larger estimates of shielding thickness (and, hence, mass), for a constant permissible risk level.

The uncertainty in the shielding mass required to reduce radiation fluxes in the interior of a spacecraft to a predetermined level has been estimated to be as large as a factor of 10. This includes the effect of errors in the estimation of the incident radiation environment and in the nuclear interaction cross sections, as well as estimates of the accuracy of the radiation transport codes. Large errors in the composition of the

## **Table 1**

### **Areas of Greatest Uncertainty**

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- SEP events (not currently predictable).
  - Models used to describe the external space radiation environment.
  - Models of the transport of HZE radiation through shielding, spacecraft materials and tissue.
  - Biological effects of HZE particles and protons.
  - Exposure to radiation under microgravity.
- 

interior radiation field, especially in the small flux of high-LET particles that are of greatest biological significance, can also lead to substantial uncertainty in the estimate of risk as given, e.g. by a calculated average Q. In addition, the extent to which the description of risk in terms of Q is applicable to the biological effects of HZE particles, is not known. A better way to predict risk might be based on a calculation of the direct probabilities per incident particle fluence but, although calculations estimate that approximately 30% of the cells in the body could be traversed by HZE particles with charge  $Z > 10$  in the course of a Mars mission, the probability of inducing cancer by passage of a few charged particles is not known. Taking these sources of uncertainty into account, the prediction of cancer occurring several years after such a mission has been estimated to be uncertain by as much as a factor of 30. Thus, it may not be possible at the present time to predict whether the radiation exposure incurred in an interplanetary mission will result in a small increase in the probability of occurrence of

cancer, relative to the natural probability of incidence, or whether it will result in a very large increase in probability. Prescriptions for the design of spacecraft and habitat shielding, that take the uncertainties described above into account, lead to unmanageable mass requirements. Therefore, the uncertainties in our knowledge of space radiation and its effects must be significantly reduced.

To enable human exploration class missions, it will be necessary to understand the basic scientific problems and to significantly reduce the uncertainties involved in the prediction of radiation risk. In order to meet the time table currently under consideration for the Space Exploration Initiative (SEI), the Space Radiation Health Program has adopted the objective of reducing these uncertainties to within a factor of two (50 - 200 percent range) by 1997, and to within  $\pm 25$  percent by 2010. These objectives are somewhat arbitrary and the actual prediction to which they apply (radiation dose inside a spacecraft or lunar habitat, carcinogenesis, etc.) cannot be narrowly defined at this time. They do represent a best guess of the extent to which our knowledge of the GCR environment, the interaction (nuclear and atomic) of HZE particles with matter, and models of biological effects can be made more accurate. Our knowledge of the GCR environment will improve substantially with missions presently under consideration by the Space Physics community; e.g., the Advanced Composition Explorer (ACE), that would increase the available data by two orders of magnitude. Studies of nuclear fragmentation and improvements in radiation transport codes, currently under way, are likely to result in calculations of internal radiation fields that are accurate at the 30 percent level or better; such precision has been attained in ground-based, laboratory studies using relatively light neon particles and spermatogonial cell survival as a biological end point. The objectives also represent the hope that, if predictions of several biological effects in cellular or animal models can be made with this precision, the uncertainties in the predictions of other effects will have been reduced correspondingly. The program designed to accomplish these improvements in radiation risk prediction is described in what follows.

## **2.0 BACKGROUND**

The Earth's magnetic field acts as a shield against radiation emitted from solar energetic particle events (SEPs) and from a large fraction of galactic cosmic rays (GCRs). In addition, near the surface of the Earth, the thickness of the atmosphere is equivalent to about 10 meters of water. Particles passing through the atmosphere will

undergo nuclear and atomic interactions in it, as a consequence of which they will lose energy and may be removed entirely from the flux reaching the surface. At altitudes greater than a few Earth radii, the radiation environment is different in type, magnitude, and biological effects from radiation encountered at the Earth surface or even in low altitude Earth orbits because the strength of the Earth magnetic field and the residual density of the Earth atmosphere have become negligible and no longer afford shielding against incoming cosmic radiation. For this reason, radiation risk estimates developed previously for low Earth orbit (LEO) are not applicable to future exploration missions.

The ability to predict radiation effects and protect against the risks arising from exposure is an enabling technology for human exploration of deep space. Space-based measurements are required to characterize the radiation environment traversed by the spacecraft, as a function of location in the interplanetary magnetic field. Ground-based experiments, using particles and energies to simulate selected portions of the interplanetary radiation environment, are required to study the interaction of the environment with the materials of which spacecraft, habitats and their contents consist. Such ground-based experiments also are required to develop a biological data base from which risk predictions for HZE particles can be derived. Models must be developed that permit interpolation between data points; theories are required that permit extrapolation beyond the region accessible to measurement. Models and theories must be validated in spaceflight experiments by comparison of predicted results with measured results in the complete space radiation environment. All stages of this process require development of instrumentation, both for improvement of experimentation and for implementation of the required spaceflight validation procedures.

The core element of the Space Radiation Health Program supports fundamental research in radiation biology, in the physics of the interaction of radiation with tissue and its constituents, and the development of experimental methods and instruments peculiar to the radiation fields encountered in space. Fundamental and applied scientific research in space physics and solar physics, and in applied technology and materials, carried out by other divisions of NASA, is integrated into the Space Radiation Health Program as appropriate.

Space physics research defines the space radiation environment described by the source term in equations used to calculate the radiation field in matter (e.g., shielding, spacecraft, tissue, etc.). Research in radiation biophysics is concerned with the way in which the external space particle radiation environment is transformed by interactions in the materials surrounding radiosensitive cells and organs in living organisms, with the interactions of the transformed radiation fields with the biological targets, and with the interpretation of these interactions in terms of quantities useful for the prediction of biological effects (i.e., fluence, LET - spectra, etc.). Radiobiology encompasses the research needed to understand the basic mechanisms involved in the response of living systems to radiation exposure, simulate the human response to radiation, and exploit epidemiological studies of populations exposed to radiation. To the extent that the available data base for HZE particles is very sparse, new data are required. More importantly, the development of the chains of reasoning required to assess risk in manned space flight, incorporating the data, is the basic problem addressed by this program.

Current methods of risk assessment are based on the use of dose equivalent, which is the product of dose and quality factor, and is generally interpreted as providing a measure of risk on a scale common for all types of radiation. The direct probability per incident particle is a different way of looking at biological effects. For example, approximately a thousand protons, but only a few high LET iron particles, result in the same probability to induce loss of contact inhibition in cultured cells and subsequent tumor growth in mice into which the transformed cells have been implanted. The extent to which such experiments may be used for the prediction of carcinogenesis in humans is unknown at present. An extension of current methods of risk assessment to define radiation limits for exogeomagnetic radiation exposures, or to develop direct risk predictions based on the fluence of identified particles and their energy or LET distribution ("fluence-based risk assessment") depends on the results of HZE radiation biology research. Given the nature of the radiation fields, development of such methods seems particularly desirable, but must be pursued carefully and prudently, maintaining adequate equivalence to current methods where the two overlap.

The fourth component of the Space Radiation Health Program focuses on instrument science and engineering activities. Instruments are required for experimental measurements (e.g., particle spectrometers, proportional counters, remote biochemical sensors, etc.). Instruments need to be validated by experimental testing.

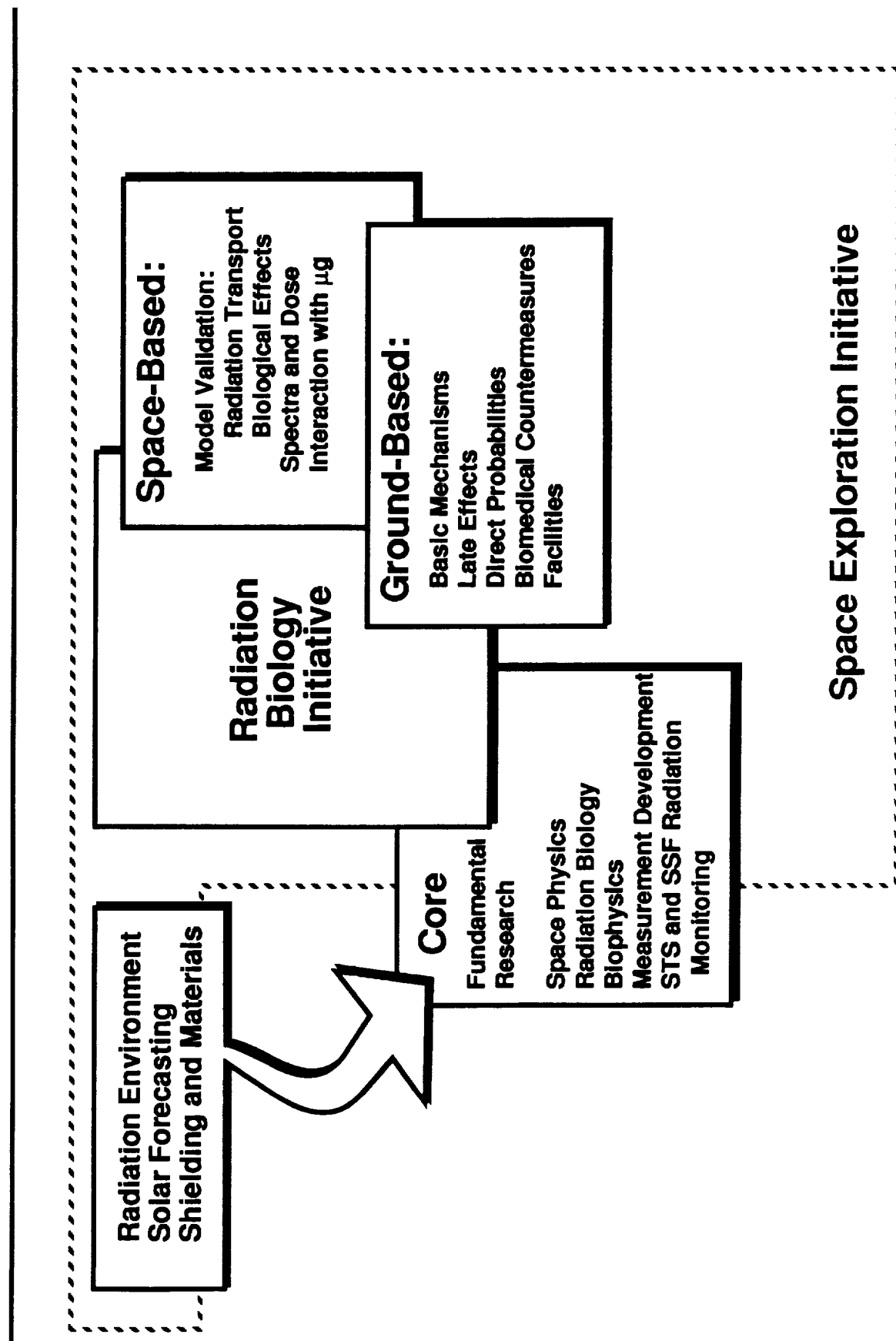


New instruments are also essential for verification of actual cumulative radiation exposures and for interpretation of the associated biological risks.

The Radiation Biology Initiative, a new component of the Space Radiation Health Program, addresses the particular needs of the Space Exploration Initiative (SEI) with an expanded research program into the biological effects of SEPs and GCR. The Radiation Biology Initiative, in turn, has two components. The ground-based component involves support of experimental and theoretical studies leading to the development of predictive models of the mechanisms of radiation action. The main goals of the space-based program are the validation of ground-based studies in the actual space radiation environment, the understanding of how radiobiological effects may be modified as a consequence of weightlessness, and the development of instrumentation characterizing the radiation field (by means of particle identification, fluence measurements, energy or LET spectrometry, etc.). The development of instrumentation is particularly important for the development of fluence-based risk assessment since one dose can result in significantly different biological effects for different charged-particle radiation fields.

Figure 1 schematically shows the components of the Space Radiation Health Program. The core program described above overlaps with the Radiation Biology Initiative, which is the response of the Life Sciences Division to the radiation concerns of SEI. The Radiation Biology Initiative comprises research applied to SEI needs, centered around a ground-based accelerator facility (currently the Lawrence Berkeley Laboratory BEVALAC) that simulates selected portions of the space radiation environment; critical predictions of the ground-based research must be tested in a spaceflight program that should also include the study of the effects of weightlessness. Research in cosmic rays, solar physics and shielding materials is conducted independently, but in close coordination with the program by investigators in other divisions and offices of NASA, as well as in other Federal agencies. Basic core program research is performed at universities and NASA centers; the establishment of a NASA Specialized Center of Research and Training (NSCORT), housing basic research, is not shown in the figure.

**FIGURE 1  
SPACE RADIATION HEALTH PROGRAM**



The program described in this plan is based on recommendations of previous advisory committees, the most recent being the Life Sciences Strategic Planning Study Committee (1988). The recommendations of this committee regarding radiation health protection included:

- NASA should vigorously pursue basic research in solar physics in order to model and predict catastrophic radiation events, and to investigate short-time warning systems that will provide time for the crew to seek protection.
- NASA should vigorously pursue basic research in the radiation biology of high LET radiation.
- NASA should direct efforts for additional work in shielding and transport code research. These efforts should include conducting measurements of the free-space radiation environments, and studying the interaction of radiation with shielding materials through the development of the transport computer codes and accelerator experiments. A balanced approach in studying the free-space radiation environment, the radiation environment inside the spacecraft, and accelerator-based experiments is desirable.
- NASA should support basic research in instrumentation and measurement of the space radiation environment.
- NASA should make a commitment to continued and enhanced support for basic research on the biological effects of radiation.

### **3.0 SPACE RADIATION HEALTH PROGRAM GOALS AND OBJECTIVES**

The Space Radiation Health Program has been developed within the context of the Life Sciences Division Strategic Implementation Plan and the recommendations of internal and external advisory committees.

The overall goal of the Space Radiation Health Program is as follows:

- Establish the scientific basis for the radiation protection of humans engaged in the exploration of space, with particular emphasis on cancer risk for lunar and Mars missions.

The objectives of the program are as follows:

- Develop methods to characterize space radiation fields in the manner needed for predicting the biological consequences.
- Determine the biological effects of space radiation, especially the biological effects of HZE particles and protons, and predict their probability of occurrence.
- Reduce the overall uncertainty in the prediction of deleterious health effects incurred during relevant periods of time (mission, tour of duty, year, or career) to be within a factor of 2 (50% to 200% range) by 1997 and within  $\pm 25\%$  by 2010.
- Using space-based experiments, validate the ground-based approaches for predicting biological effects in the full spectrum of the particulate space radiation environment.
- Apply the improvements in space radiation health science to operational radiological support.

#### 4.0 TECHNICAL APPROACH

##### 4.1 SPACE SHUTTLE ERA

Space Shuttle missions are not a primary concern since currently available information is sufficient for radiation health protection purposes for low inclination Shuttle missions. The exceptions for the Shuttle missions include the trapped protons in the South Atlantic Anomaly (SAA), and, for low Earth orbits above inclinations of 50 degrees, the impact of major solar flare activity. In addition, there is an uncertainty in the electron dose received during EVA operations, where the suits do not completely

arrest the penetration of electrons and resulting Bremsstrahlung (secondary photon radiation produced by the deceleration of charged particles — in this case, electrons — stopping in matter). This uncertainty is particularly important at inclinations above 45 degrees, where the Shuttle intercepts the horns of the van Allen belts, and for other missions on which crew members will encounter trapped electrons during EVA operations.

All Shuttle flights are equipped with routine passive dosimetry; routine active dosimetry should be planned for the future based on current mission procedures and experience. The Shuttle may also be used as a testbed for development of space-based experiments.

STS missions provide information for guidance on astronaut space radiation exposure limits and dosimetry for radiation biology experiments. Comparison of radiation measurements by on-board instruments with theoretical predictions, and comparison of space-based biological measurements with ground-based studies, provide important tests of the progress of the Space Radiation Health Program.

#### 4.2 SPACE STATION FREEDOM (SSF) ERA

Space Station Freedom (SSF) is intended to orbit the Earth at a nominal altitude range of 370 to 550 km, at a 28.5-degree inclination, beginning in the latter half of this decade. Current dose calculations indicate that, at altitudes below 500 km, low inclination, and with nominal shielding, orbital stays of 90 to 180 days result in radiation exposures within current guidelines. For Space Station Freedom, the predominant part of the radiation dose to the crew will come from energetic protons trapped in the South Atlantic Anomaly. At Space Station Freedom operational altitudes, the flux gradient is steep and alterations in the station's altitude (e.g., as contemplated in constant drag orbits) can be a countermeasure to the dose received by a crew member over a period of time. There is a small and fairly constant contribution by low intensity GCR to the total dose and virtually no contribution from SEPs.

Radiation research on Space Station Freedom must, therefore, be largely confined to the energetic proton environment, but should also involve studies of secondary neutron production. Important topics include:

- Development and testing of active dosimetry
- Development, testing and utilization of biological dosimetry
- Radiobiological studies of the induction of carcinogenesis and mutagenesis in experimental vertebrates and invertebrates, vital human body tissues, microorganisms, and cell cultures
- Transport and shielding studies to determine organ dose distributions and to allow optimization of shielding design for minimum mass and reduction of dose at minimum cost (in support of extended duration crew stay times)
- Cataractogenesis and neural damage studies (related to behavioral changes) in experimental animals.

#### 4.3 SPACE EXPLORATION ERA

A significant program of space radiation health research is essential to enable all phases of the human exploration missions. The radiation environment for exploration missions is not yet sufficiently understood but, on the basis of what is known about ionizing radiation, it is likely to have serious health implications. The acute effects of conventional radiation exposure include radiation sickness and even death, while the long-term chronic effects include cataract formation, and cancer. In order to protect crews, to the extent possible, from the various harmful effects of radiation, it is necessary to thoroughly characterize the radiation environment, understand the biological effects of HZE radiation and protons (leading to the establishment of appropriate risk levels and limits for radiation exposure), and accurately predict and provide warning of any increased levels of radiation.

NASA is legally bound to provide a system of radiation risk management for all astronauts that adheres to a principle known as ALARA (As Low As Reasonable Achievable). The ALARA principle recognizes that even though an acceptable upper limit of exposure is set, the residual should be minimized even further wherever it is reasonable to do so. As in the past, NASA will rely upon the guidance of the National Council on Radiation Protection and Measurements (NCRP) and other appropriate organizations establish radiation exposure limits. New radiation health standards will have to be developed that take into account the specific types and fluence spectra of

space radiation outside low Earth orbit, the biological response to spectral elements and the overall balance of risks inherent in exploration missions.

Lunar colonists and Mars crew members are subject to the highest dose-rates of ionizing space radiation during SEP events. On the surface of the Moon, the Lunar Outpost can be protected by adding regolith cover as shielding. For personnel engaged in lunar exploration, the maximum distance away from the Outpost is determined by the requirement that travel time back to the base or to a shielded location (i.e., safe haven) be less than a reference time between warning and arrival of an SEP event. However, a "storm shelter" incorporated into a lunar rover vehicle would greatly reduce the need for long-range SEP forecasting. In transit to and from Mars, this reference time will affect normal operations. For these reasons, a prediction and warning system is required to signal the occurrence and indicate the magnitude of an impending SEP event in sufficient time for all personnel at risk to take refuge. Precursor data are therefore required to accurately characterize the dynamic range of the radiation that will be encountered. Solar physics research is required to define and optimize the elements of a solar particle warning system.

Determination of appropriate shield thickness for safe havens for the lunar surface, the transit to and from Mars, and the martian surface requires accurate measurement of space radiation. If exploration vehicles, habitats, and operations were to be designed based on a worst-case assumption, the excess weight due to massive shielding, together with the severe limitations on scientific EVA activities, would be prohibitive. For example, due to uncertainties in the current computational models for predicting the transport of radiation through materials, shielding estimates can vary by a factor of 10 or more for a given flux. Therefore, the upper bounds of current uncertainties require increasing the weight of the shielding to between a factor of 2 to 10 times the weight of the habitation module. In addition, current plans envision extensive EVA hours for the construction of the Lunar Outpost and other space structures; exposures to radiation might severely restrict EVA time or result in very massive shielding requirements for lunar and Mars habitats and safe havens.

Because of the characteristics of the energy deposition of HZE particles, the concern is whether biological effects are different from those observed with low LET radiation (e.g., with x-rays). Biological effects of HZE particles such as chromosome fragmentation have been observed. Such effects, as well as the consequences of

highly correlated cellular damage along the trajectory of heavy charged particles need to be studied and understood. Late effects of HZE particles, especially carcinogenesis, need to be understood in much greater detail than is now the case. Given the high cost in mass incurred as a consequence of uncertainties in risk prediction, the radiation biology studies need not only be qualitatively correct, but accurate as well.

A comprehensive research program in radiation biology is needed to determine the implications of the radiation environments for human exploration missions. These research areas include:

- **Basic studies**: molecular radiobiology and radiation damage in genomic DNA, cellular and tissue radiobiology (genetics, tissue culture, etc.), especially with cells of human origin; risk extrapolation.
- **System-level studies**: longitudinal study (mice); retrospective study (primates); radioprotectants; genetics and radiation sensitivity; CNS and behavioral effects.
- **Theoretical studies**: modelling, interspecies extrapolation, development of fluence-based risk assessment methods.

It is important to establish a data base (physical or biological) that is of sufficient resolution to minimize interpolation errors, so that the step from one system to another (particle to particle, energy deposition to biological effect, biological effect in one organism or tissue to biological effect in another organism or tissue, etc.) is as small as possible.

#### 4.3.1 Radiation Biology Initiative

The Radiation Biology Initiative (RBI) is intended to build on the ongoing core research to meet the needs of SEI in a timely manner, and to integrate the results of ancillary research programs into reliable methods to predict radiation risk. The RBI depends for its execution on the availability of a ground-based facility to simulate critical components of the space radiation environment and on the availability of space-based platforms for the validation and space certification of the ground-based research.



The ground-based research will be focused on understanding the range of biological effects of HZE particle beams, using particles and energies that provide an adequate sample of GCR composition (particles ranging from protons to iron at energies up to ~2 GeV/nucleon). The extent to which the observed biological effects contribute to the prediction of radiation risk to human beings will be an important factor in selection of this research.

One possible, long-term consequence of the fundamental research into the biological effects in cells (especially human cell lines), tissues, and animal models is the development of possible countermeasures other than shielding (viz., crew selection, pharmaceutical radioprotectants, diet, methods to enhance cellular repair mechanisms, tissue banking, etc.). Progress in the development of such countermeasures could be of importance for accidental exposures due to unforeseen delays in reaching a safe shelter during an SEP event. Such countermeasures could also be an important adjunct in minimizing shielding material mass and in implementing ALARA. Research in this field, even for conventional, low-LET radiation, is not now at a stage where rapid progress can be expected, although it remains a tantalizing possibility. For this reason, such research is not emphasized in the current radiation program.

The radiation biology studies will be integrated with physical characterization (as a minimum, fluence and energy spectra of identified particles) of the radiation fields at the biological targets. This work is complemented by the detailed materials-science particle-physics studies of shielding materials currently under the sponsorship of the Materials and Structures Division of the Office of Aeronautics and Space Technology (OAST). The experimental work will be accompanied by a commensurate theoretical effort to improve the understanding of biological mechanisms and their regulation by intact organisms, and of the extent to which the physical characteristics of radiation fields must be known in order to uniquely predict biological effects. The latter is of importance in defining the instrumentation required for SEI radiation measurements. The product of the ground-based program will be the capability to predict the probability of biological effects in biological targets surrounded by inhomogeneous shielding materials in space. Experimental studies of the interactions and transport of radiation in structural materials and tissue, and of the buildup of secondary particles, continue at the Lawrence Berkeley Laboratory BEVALAC and are closely coordinated with theoretical studies at the NASA Langley Research Center.

Space radiation biology studies will be conducted using living biological specimens, including plants, cell and tissue cultures, and small organisms. For these studies, satellites are required to have access to orbits that the Space Shuttle may not fly due to avoidance of excess radiation exposures (e.g., passing through trapped radiation belts), extended flight (e.g., 30 to 60 days), and should include exposure to varying gravity levels (e.g., 0 to 1.5 g). Sophisticated radiation measurements and telemetry are needed in order to enable detailed analysis of the radiation fields. Such biosatellite experiments can compare the predictions derived from ground-based studies with physical and biological measurements made inside and outside the spacecraft. Agreement of such predictions with on-board measurements at some level of precision, will test the "null hypothesis" that space-based factors do not alter the validity of ground-based predictions in a statistically significant way. Disagreement will provide a measurement of the extent to which the uncontrolled space-based factors (e.g., weightlessness, exposure to the full spectrum of space radiation, etc.) alter the outcome of space-based experiments, i. e., the uncertainty in the predictions. Disagreement will also provide the means, through sensitivity analysis, to determine which factors account for the disagreement, and to refine the ground-based research and existing data base to meet the desired predictive capability.

Some of the required work can be performed on existing space platforms, such as the Shuttle and Space Station. Some work may be performed by capitalizing on other means to obtain flight opportunities, including international collaborations. Extensive work has been done to define the science requirements for a dedicated biosatellite and the feasibility of procuring such a spacecraft for the Space Radiation Health Program will continue to be explored. The Program, through the collaborations of the Principal Investigators, will also be able to capitalize on flight opportunities made available aboard unmanned, exomagnetospheric, robotic missions. Exploiting such flight opportunities is a high priority of the program.

## 5.0 MANAGEMENT APPROACH

The management of the Space Radiation Health Program is organized in a three-level management structure. Level I responsibilities include primarily program oversight and development; Level II responsibilities include grant administration, technical

monitoring and coordination; Level III responsibilities consist primarily of program implementation.

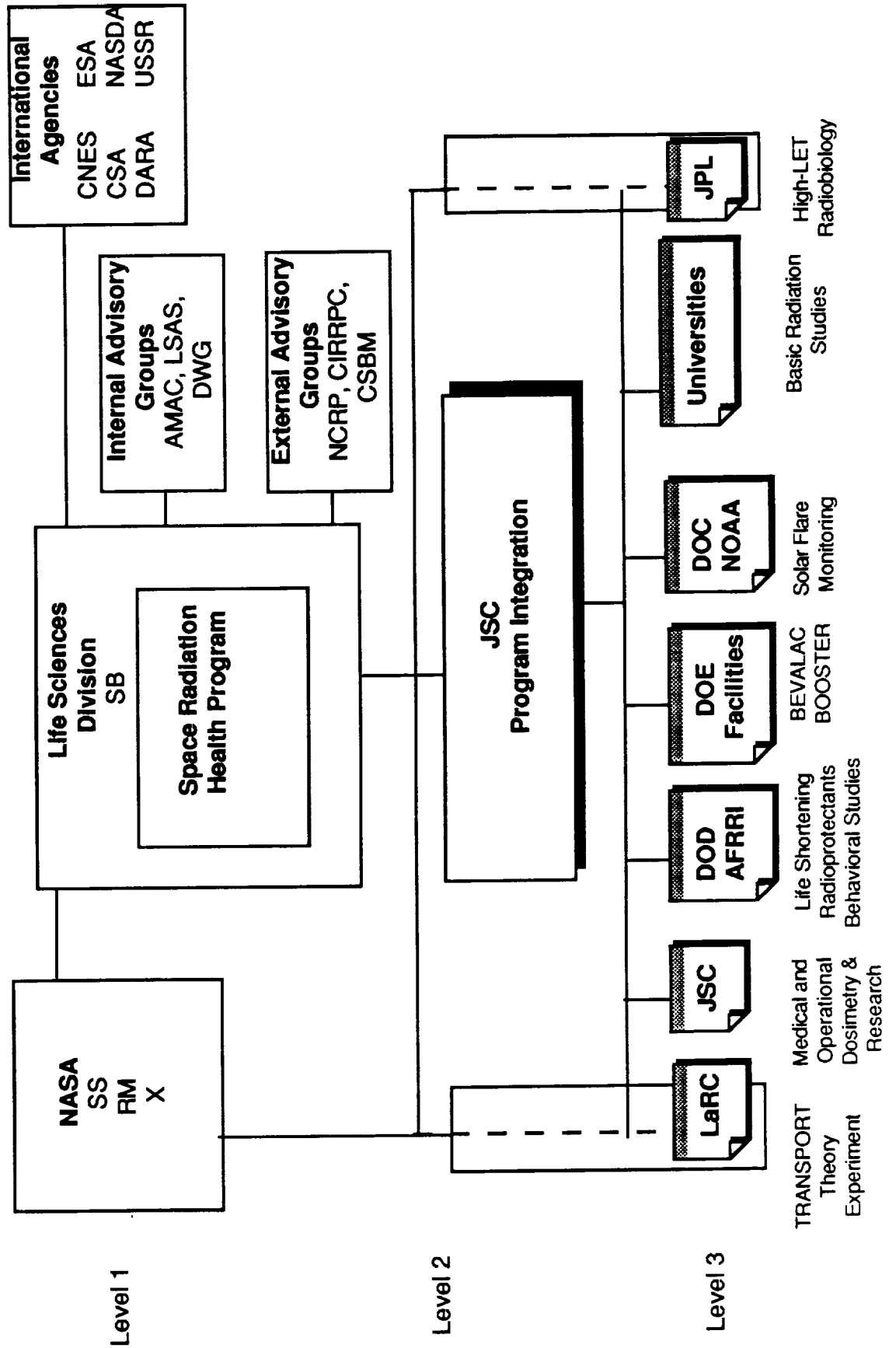
## 5.1 HEADQUARTERS PROGRAM OFFICE

The Space Radiation Health Program will be managed by the Life Support Branch (Code SBM), Life Sciences Division, Office of Space Science and Applications, NASA Headquarters. The Chief, Life Support Branch, Life Sciences Division, appoints the Space Radiation Health Program Manager. The Space Radiation Health Program is also closely linked with the Operational Medicine Program, providing the information on which radiation exposure control and recording procedures are based.

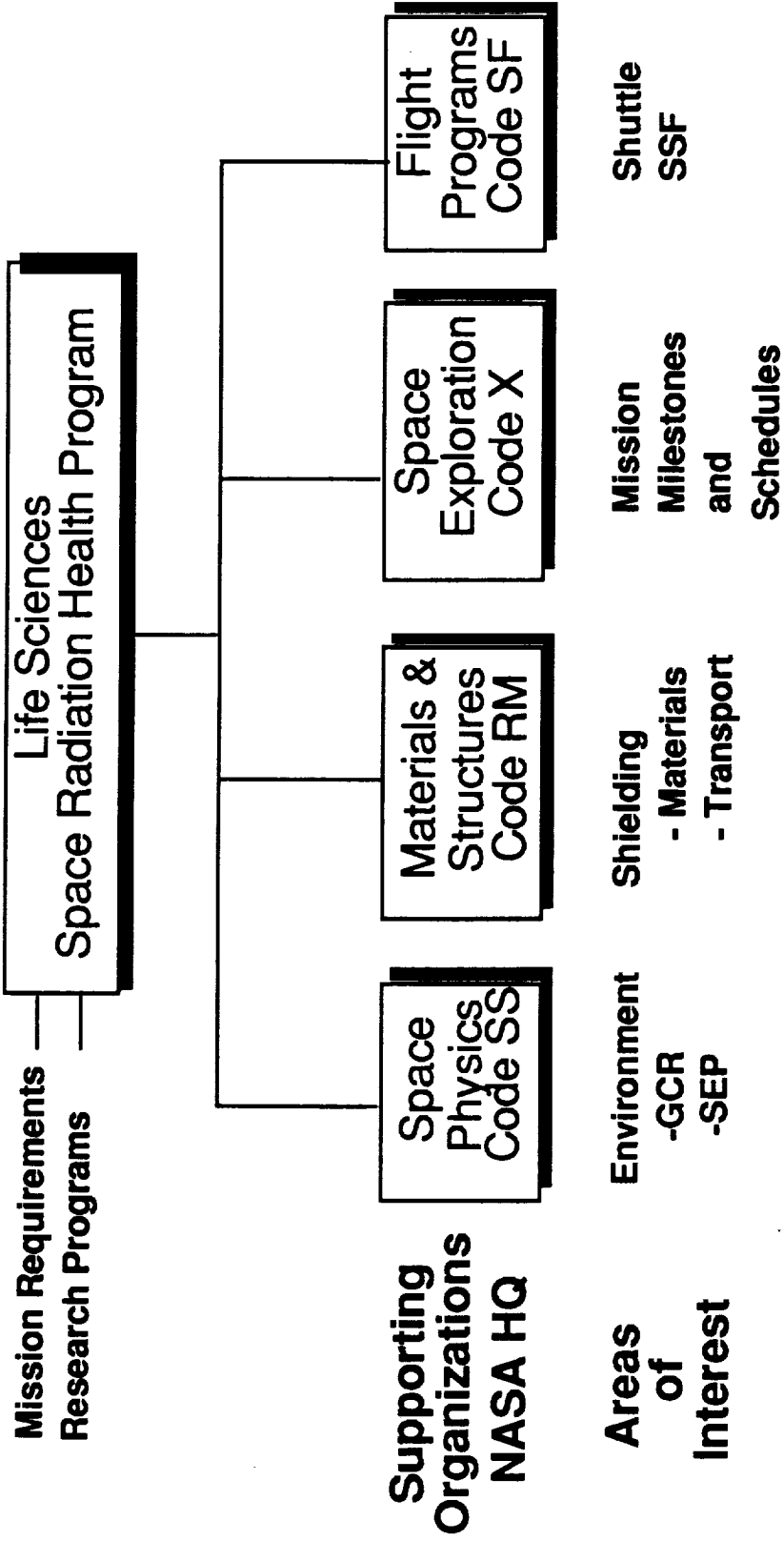
The Space Radiation Health Program Manager exercises normal NASA Level 1 responsibilities for planning, budgeting, and program oversight; review, approval, and update of Project Plans, Program Operating Plans (POPs), and Research and Technology Operating Plans (RTOPs); overall responsibility for the direction and execution of the program; integration and coordination of all elements and participants involved in radiation health activities; and issuance of general program announcements such as NASA Announcements of Opportunity (AO) and NASA Research Announcements (NRAs).

One of the most important responsibilities of the Space Radiation Health Program Manager is coordination of all of the radiation-health related activities. This coordination function extends across NASA Headquarters program offices, other Government agencies, internal and external advisory committees, NASA field centers, and the university and international communities. Figures 2 and 3 show the organization and management structure of the Space Radiation Health Program, and Figure 4 shows the participating NASA organizations involved in the Agency's radiation activities.

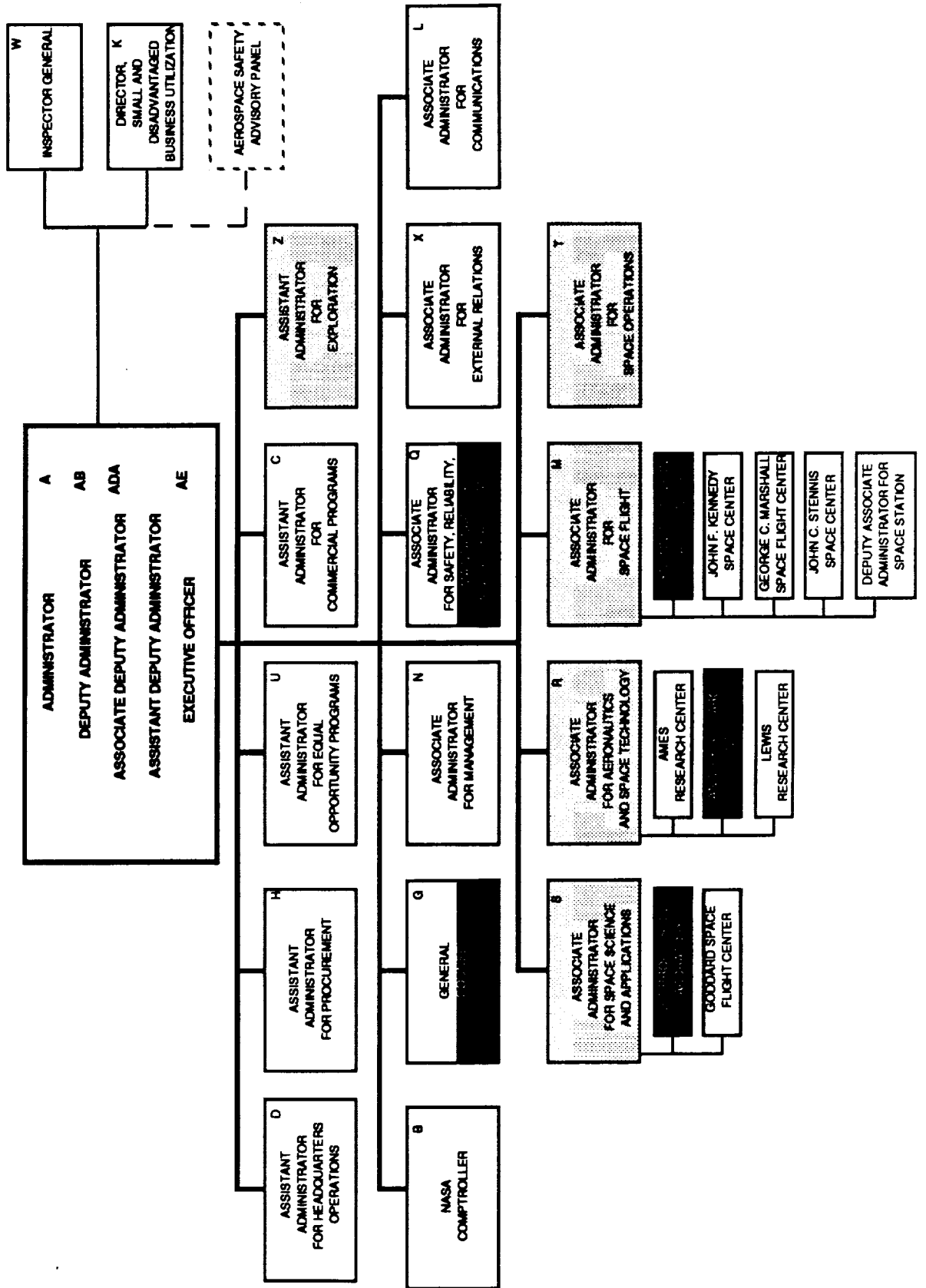
**FIGURE 2  
ORGANIZATION OF SPACE RADIATION HEALTH PROGRAM**



**FIGURE 3  
SPACE RADIATION HEALTH MANAGEMENT STRUCTURE**



**Figure 4**  
**Headquarters Codes and Centers Involved in Radiation**



The Space Radiation Health Program Manager is responsible for briefing all concerned NASA authorities (i.e., Associate Administrator for OSSA, Office of Space Flight [OSF], and Office of the General Counsel) on the status and implications of the proposed guidance.

The Space Physics Division (SS) of OSSA investigates solar phenomena, including solar flares, and for providing measurements of the energy spectra of galactic and solar cosmic rays. In this role, SS coordinates with the Space Radiation Health Program Manager to help develop the requirements for a solar flare monitoring system to accurately, reliably, and efficiently detect SEPs. The Space Physics Division also provides information to the Space Radiation Health Program on the deep space radiation environment. The Space Physics Division has access to existing data from solar system exploration missions (e.g., Voyager and Pioneer) and current plans envision using the Advanced Composition Explorer (ACE) satellite to monitor GCR, an Orbiting Solar Laboratory (OSL) for studying solar flare activity, and development of a system of Global Solar Monitors (GSMs) which will consist of up to four identical spacecraft orbiting at 90 or 120 degree intervals around the Sun. The GSM system is planned for the early part of the next decade.

The Office of Aeronautics and Space Technology is responsible for the materials and shielding, and develops the enabling technologies for future exploration missions. This Office has a major concurrent program in the experimental and theoretical study of the interaction and transport of radiation in structural materials, based on the use of the Lawrence Berkeley Laboratory BEVALAC.

The Exploration Office (Code X) is responsible for developing options and recommendations for a focused program enabling human exploration missions. For the Space Radiation Health Program, the Exploration Office supports trade studies and scientific workshops, and also provides information on exploration scenarios, milestones, and schedules.

## 5.2 NASA FIELD CENTERS

The major field centers participating in the program are Johnson Space Center (JSC), Langley Research Center (LaRC), and the Jet Propulsion Laboratory (JPL).

### 5.2.1 Johnson Space Center (JSC)

Level II management of the Space Radiation Health Program is the responsibility of the Radiation Health Research Project Manager/Scientist at JSC. The primary functions include preparation of annual operating plans, technical oversight and coordination of activities across the respective activities of the centers, administration of radiation health grants and contracts, and publication of the results of radiation health experiments. The Project Manager/Scientist also participates in working-level committees (Discipline Working Group), organizes workshops and meetings and publishes their proceedings. JSC personnel also provide real-time support to mission control during ongoing missions, measure the radiation exposure of crew members for all types of radiations and provide long-term monitoring of crews. JSC also incorporates advances in space radiation health science into operational radiological support programs.

### 5.2.2 Langley Research Center (LaRC)

LaRC is responsible for developing and validating improved SEP/GCR transport codes and their nuclear/atomic interaction inputs. In addition, LaRC is responsible for incorporating the evolving risk criteria into the transport codes, and using them in conjunction with experimental laboratory measurements, to provide data on the transport of HZE particles and their interaction with tissue. LaRC is also responsible for the development, design, testing, and evaluation of optimized shielding materials to be used for crew protection — including spacecraft, habitat, and personal shielding applications.

### 5.2.3 Jet Propulsion Laboratory (JPL)

JPL's efforts include measurement and evaluation of lesions induced by accelerated particles and neutrons, comparison of these effects with those of gamma radiation, and



characterization of biological repair processes for radiation-induced damage. JPL is also performs investigations examining the interaction between microgravity and radiation. Modeling and space radiobiology for the development of space experiment concepts are also ongoing activities.

### 5.3 OTHER GOVERNMENT AGENCIES

NASA-supported researchers currently utilize the Department of Energy (DOE) facilities for studying the effects of heavy ions on biological systems, instrument calibration, and measuring input fragmentation for updating transport codes.

The Department of Defense (DOD) has several programs of interest to the NASA Life Sciences Division. The Armstrong Laboratory of the Human Systems Division conducts ongoing radiation research on the biological effects in mammals (i.e., rhesus monkeys) exposed to protons. This continuing research program was initiated in the 1960's and currently includes a longitudinal study of a rhesus monkey colony.

The Armed Forces Radiobiology Research Institute (AFRRI) of the Defense Nuclear Agency supports a comprehensive biomedical research program on ionizing radiation. The purpose of the program is to develop medical treatments (i.e., radioprotectants) and performance measures required to support operations in a radiation environment. Radiation biochemistry is an important part of AFRRI's program; the primary focus is on fission neutrons. To this effect, NASA and AFRRI have signed a memorandum of understanding (MOU) in FY 1990, that supports research of mutual interest at AFRRI.

### 5.4 ADVISORY GROUPS — EXTERNAL

The National Council on Radiation Protection and Measurements (NCRP) established Scientific Committee 75, in response to a Life Sciences Division request, to provide guidance on radiation received in space activities. The new guidelines, which apply to the Space Station Freedom, were formally submitted to NASA's Medicine Policy Board by the Director of the Life Sciences Division, and a medical recommendation was made to the NASA Administrator and approved by the Department of Labor. These guidelines do not apply to exploration class missions.

The National Academy of Sciences provides advice concerning radiation biology and microgravity through the Committee on Space Biology and Medicine (CSBM). The Space Radiation Health Program Manager interacts and coordinates with the CSBM during meetings held over the course of the year. The CSBM helps provide direction regarding radiation health research priorities.

The Federally chartered Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) provides legal and technical information across all agencies involved in radiation protection responsibilities. The Space Radiation Health Program Manager or his representative is responsible for interacting with the CIRRPC and exchanging information.

## **5.5 ADVISORY GROUPS — INTERNAL**

There are three primary internal advisory groups that interact with the Space Radiation Health Program: the Aerospace Medicine Advisory Committee (AMAC) , the Life Sciences Advisory Subcommittee (LSAS) and the Radiation Discipline Working Group (DWG).

AMAC is concerned with all Agency activities related to the science and practice of aerospace medicine, including radiation health. AMAC is a Federally chartered advisory committee that reports directly to the NASA Advisory Council. Committee membership includes experts in many biomedical areas. This committee provides advice to the Space Radiation Health Program and reviews program planning documents.

The Life Sciences Advisory Subcommittee is a subcommittee of the Space Science and Applications Advisory Committee (SSAAC), a standing committee of the NASA Advisory Council (NAC). The Life Sciences Advisory Subcommittee is chartered to provide advice to the Life Sciences Division of NASA's Office of Space Science and Applications concerning all of the Division's programs in the space life sciences, including all associated ground-based and space-flight projects and missions.

The Radiation Discipline Working Group is responsible for providing technical expertise to help define scientific objectives of the program and for developing recommendations concerning radiation-health related program strategy and content.

The membership of the DWG consists of senior members of the scientific or user community. The DWG will assist the Radiation Program Manager/Scientist in the preparation and periodic revision of an appropriate science strategy plan. The Space Radiation Health Program Manager coordinates closely with the DWG and provides the group with policy-level guidance in the scope and content of the program.

## 5.6 UNIVERSITY COMMUNITY

The university community is involved in the Level 3 execution of the Space Radiation Health Program. Research is carried out by individual investigators, and monitored by Level 2 management. Most university-based research is oriented toward problems that are more basic than applied. Proposals for a university-based NASA Specialized Center for Research and Training (NSCORT) in the field of radiation health have been solicited and are currently receiving peer review. It is expected that this center will become the major site for university-based basic research. Universities are also the major source for trained scientists and technicians on which the future of the program hinges. This is also a major reason for the establishment of the NSCORT.

## 5.7 INTERNATIONAL COMMUNITY

The international community that participates in the Space Radiation Health Program has representatives from all the spacefaring nations. Recognition of radiation protection research as an enabling technology has resulted in an expanded program, and international participation will be increased commensurately.

Five international space agencies have actively participated in biosatellite planning, science working groups, and studies since 1987. These are: the Canadian Space Agency (CSA), the Centre National d'Études Spatiales (CNES), the Deutsche Agentur für Raumfahrt Angelegenheiten (DARA), the European Space Agency (ESA), and the National Space Development Agency of Japan (NASDA). These agencies are expected to participate by providing investigations, experiment hardware, facilities and instruments, the ESA Microgravity Module, and management and operational support. In addition, access to ground-based irradiation facilities at the accelerators of the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt and other facilities will be facilitated through international cooperation.

## **6.0 RESOURCES AND FACILITIES**

### **6.1 DEPARTMENT OF DEFENSE FACILITIES**

In addition to four research departments, AFRRRI maintains support departments whose services are available to every investigator at AFRRRI. The support departments include the Radiation Sources Department, with large-scale Cobalt-60 sources, an electron linear accelerator and a TRIGA Mark-F pulsing nuclear reactor; the Veterinary Sciences Department, a 32,000 square-foot animal facility accredited by the American Association of Laboratory Animal Care, which houses 15,000 animals; and a large variety of shop and instrument facilities for radiobiological work.

The Armstrong Laboratory at Brooks Air Force Base has excellent facilities for physiological and behavioral studies of primates and extended data bases on 28 years of radiation carcinogenesis and related studies on radiation effects. Ongoing studies deal with life shortening, cataractogenesis, late immunological changes and endometriosis.

### **6.2 DEPARTMENT OF ENERGY FACILITIES**

Lawrence Berkeley Laboratory (LBL) is a multiprogram national laboratory managed by the University of California for the U.S. Department of Energy. Research conducted at the laboratory, that is of direct relevance to space, ranges from studies in pure astrophysics and cosmology to biological experiments on Spacelab. A substantial part of the research supported by NASA is centered around the BEVALAC accelerator, which is capable of producing beams of HZE particles throughout the range of cosmic-ray energies. The beams used for research in life sciences are shared with those used in nuclear sciences. It is to be expected that DOE funding for nuclear science will be discontinued after September 1993. The situation for funding of life sciences research is not clear after that date, but plans are being formulated to continue biomedical research either at the BEVALAC or at a suitable facility whose parameters are currently being defined.

Life sciences research in the physics and biology of HZE particles is mainly concentrated at the BEVALAC Biomedical Facility. This is a facility specially designed for tumor, tissue, cellular, and molecular biology, neurobiology, developmental and space radiobiology, radiography, and radiological physics. The beams normally available are protons, helium, carbon, neon, silicon, argon, iron, niobium, lanthanum, gold, and uranium. Of these, the beam of greatest interest for space-related studies is iron, which is available at energies (limited by existing beam transport magnets) up to 850A MeV and intensities up to  $10^8$  particles per ~1 sec pulse.

A possible facility to succeed the BEVALAC may be constituted by the Booster Synchrotron under construction at Brookhaven National Laboratory in Upton, New York. This particle accelerator will provide beams of particles up to gold nuclei at energies that, for iron, will be approximately 1.5A GeV. A NASA-funded study of the technical requirements for a dedicated facility, providing high-energy heavy ion beams for use by the entire NASA research community, has been completed. A panel to examine NASA requirements, and to advise NASA on the capability of such a facility to meet them in a timely and cost-effective manner, has been constituted and has submitted a final report to NASA management. The recommendations of this panel will be used to decide the policy to be followed.

### 6.3 PERSONNEL AND TRAINING

There is an acute need for additional well-trained and well-qualified researchers in space radiation physics and biology. There is a dearth of multidisciplinary programs that bridge the gap between conventional areas of science.

A continuous supply of trained researchers needs to be developed and adequate numbers of trained research personnel need to be available to enable program expansion.

The recent establishment of a NASA Specialized Center of Research and Training (NSCORT) in Space Radiation Health at the Lawrence Berkeley Laboratory will help satisfy the needs of the core program.