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Space Radiation Health Program
Life and Biomedical Sciences and Applications Division
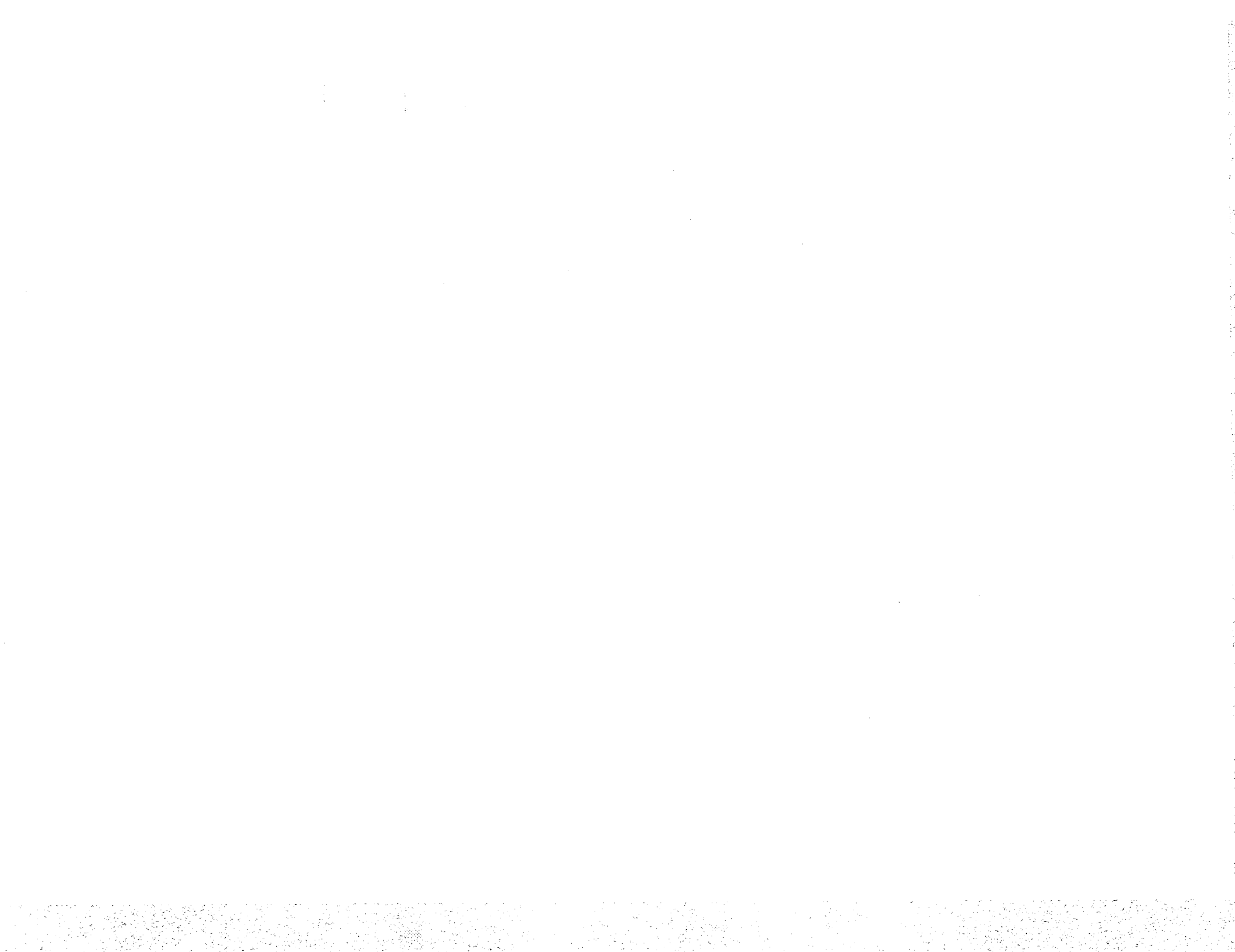**NASA Office of Life and Microgravity Sciences and Applications**
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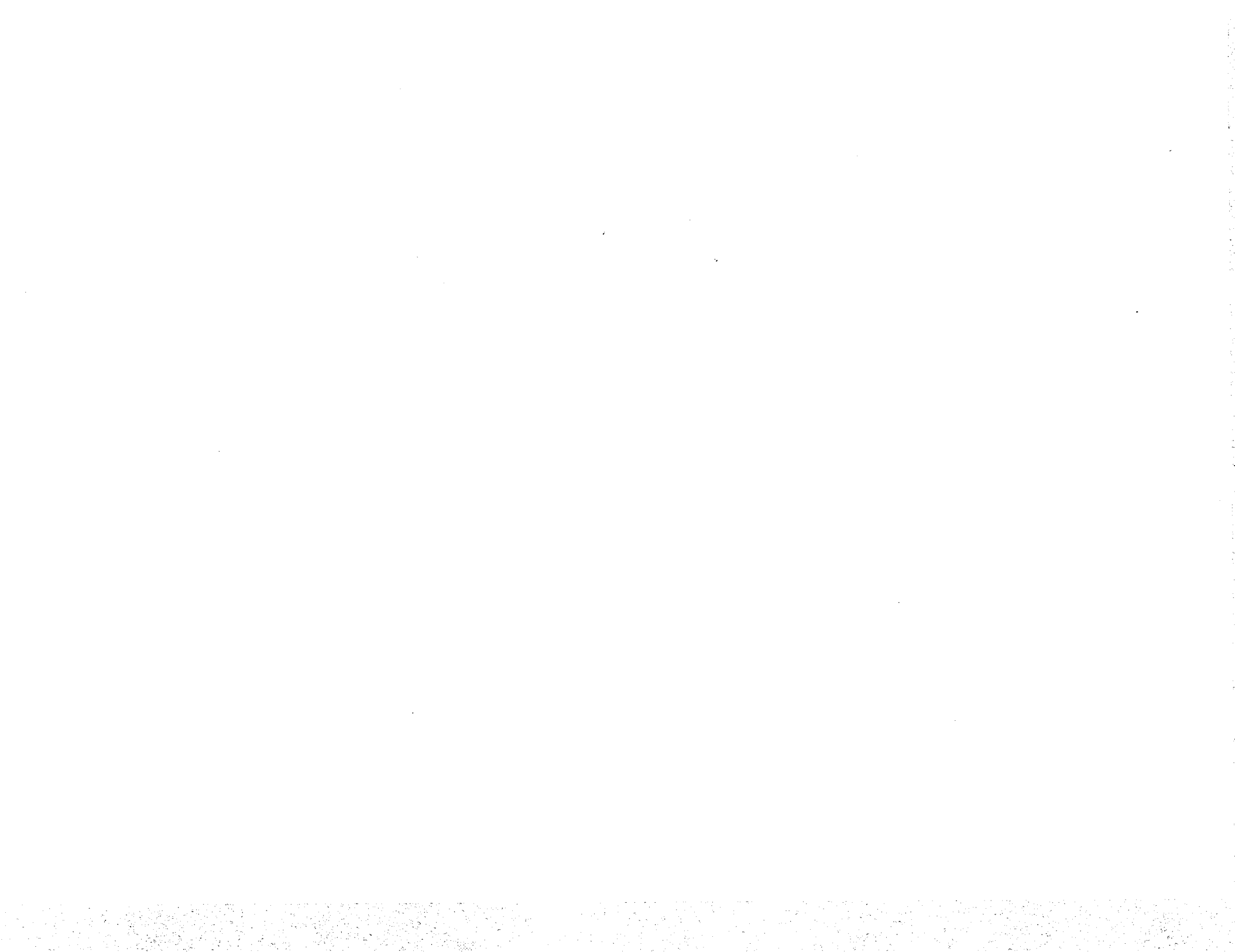
Scientific and Technical Information Program

INTRODUCTION

The present volume is a collection of abstracts of radiation research sponsored by the NASA Space Radiation Health Program, for the period 1991-1992. Section I contains refereed journals; Section II contains reports/meetings. A collection of abstracts spanning the period 1986-1990 was issued previously as NASA Technical Memorandum 4270; it is hoped that similar collections will be published biennially. In this edition, we have included papers that were not part of the 1986-1990 edition. The purpose of this series is to make available a concise summary of current research, for use by active investigators, prospective investigators, interested administrators, and the community at large.

Humans engaged in space activities are exposed to extraterrestrial radiation, consisting of protons and heavier charged particles. Doses and dose rates typical of those caused by solar disturbances may impair crew performance whereas doses and dose rates typical of the galactic cosmic ray environment are likely to result in longer term effects, most notably an increase in the probability of cancer induction. The goal of the NASA Space Radiation Health Program is to establish the scientific basis for the radiation protection of humans in space. It supports scientific research into the fundamental mechanisms of radiation effects on living systems and the interaction of radiation with cells, tissues and organs, as well as the development of instruments and processes dealing with the measurement of radiation and its effects. In pursuit of the Space Radiation Health Program, the Life and Biomedical Sciences and Applications Division supports researchers at universities, NASA centers and national laboratories, establishes interagency agreements for cooperative use and development of facilities, and promotes international collaboration with similar organizations in other spacefaring nations.

The present publication was made possible by the efforts of many people. The principal investigators took time from their busy schedules to provide the abstracts. The report was ably compiled by M.H. Jablin, C. Brooks, and G. Ferraro of the Lockheed Engineering and Sciences Company, and K.J. Dickson, J.V. Powers, J. Wallace-Robinson, and B. Zafren of The George Washington University, Washington, DC.

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TABLE OF CONTENTS
REFEREED JOURNALS

1. PHYSICS

ATOMIC PHYSICS

Wilson, J.W., Cucinotta, F.A., and Hajnal, F. (1991) Analytical relationships of nuclear field and microdosimetric quantities for target fragmentation in tissue systems. Health Physics 60(4): 559-565.

Nuclear fragments, Fragmentation experiment, Dosimetry, Tissue response

A simple analytic formula for the nuclear fields formed by target fragmentation in tissue systems is derived using the continuous slowing down approximation (CSDA). The energy fluctuations in sensitive localized sites within the tissue system caused by these nuclear events are defined by microdosimetry. In that CSDA is used, the energy fluctuations exclude the role of secondary electrons. The relations also relate to the response of microdosimetric devices to nuclear fragmentation fields.

THEORY

Townsend, L.W., Wilson, J.W., Khan, F., and Khandelwal, G.S. (1991) Momentum transfer in relativistic heavy ion charge-exchange reactions. Physical Review C 44(1): 540-542.

Momentum transfer, Radiation fragment, Optical model, Heavy ion collision

Relativistic heavy ion charge-exchange reactions yield fragments ($\Delta Z = +1$) whose longitudinal momentum distributions are downshifted by larger values than those associated with the remaining fragments ($\Delta Z = -1, -2, \ldots$). Kinematics alone cannot account for the observed downshifts; therefore, an additional contribution from collision dynamics must be included. In this work, an optical model description of collision momentum transfer is used to estimate the additional dynamical momentum downshift. Good agreement between theoretical estimates and experimental data is obtained.

EXPERIMENTAL

Dudkin, V.E., Kovalev, E.E., Nefedov, N.A., Antonchik, V.A., Bogdanov, S.D., Ostroumov, V., Benton, E.V., and Crawford, H.J. (1991) Target fragments in collisions of 1.8 GeV/nucleon ^{56}Fe nuclei with photoemulsion nuclei, and the cascade-evaporation model. Nuclear Physics A530: 759-769.

Nuclear reaction, Target-nucleus, Photoemulsion method, Cascade-evaporation model, Fragmentation, Relativistic nuclear collision

Nuclear photographic emulsion is used to study the dependence of the characteristics of target-nucleus fragments on the masses and impact parameters of interacting nuclei. The data obtained are compared in all details with the calculation results made in terms of the Dubna version of the cascade-evaporation model (DCM).

Hirzebruch, S.E., Heinrich, W., Tolstov, K.D., Kovalenko, A.D., and Benton, E.V. (1992) Fragmentation cross sections of ^{16}O between 0.9 and 200 GeV/nucleon. *Physical Review* C 46(4): 1487-1494.

Nuclear interaction, Electromagnetic cross section, Nuclear fragments, Fragmentation

Inclusive cross sections for high energy interactions at 0.9, 2.3, 3.6 and 13.5 GeV/nucleon of ^{16}O with C, CR-39 ($C_{12}H_{18}O_7$), CH_2, Al, Cu, Ag, and Pb targets were measured. The total charge-changing cross sections and partial charge-changing cross sections for the production of fragments with charge Z=6 and Z=7 are compared to previous experiments at 60 and 200 GeV/nucleon. The contributions of Coulomb dissociation to the total cross sections are calculated. Using factorization rules the partial electromagnetic cross sections are separated from the nuclear components. Energy dependence of both components are investigated and discussed.

ENVIRONMENTS AND ENVIRONMENTAL MODELS

Adams, J.H., Jr. (1992) **Cosmic radiation: Constraints on space exploration.** *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(3): 397-401.

Mars, Lunar mission, Cosmic ray, Radiation risk, Radiation environment

The hazard from cosmic radiation is examined using present cosmic ray models and the current definition of the quality factor. Current crew exposure limits are also assumed. Cosmic radiation is found to place strong constraints on manned missions to Mars. A workshop to discuss new measurements and models of galactic cosmic ray fluxes was held in August 1991. The motivation for the workshop will be explained by describing how galactic cosmic radiation constrains plans for manned space exploration and why an accurate knowledge of the absolute cosmic ray fluxes is needed to plan a manned mission to Mars.

Badhwar, G.D. and O'Neill, P.M. (1992) **An improved model of galactic cosmic radiation for space exploration missions.** *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(3): 403-410.

Model development, Radiation shielding, CREME model, Solar modulation, GCR, Model verification, Transport code

The need for an accurate model that describes the galactic cosmic radiation (GCR) environment is becoming increasingly important in light of planned space exploration missions. There is a concern about the effects of heavy ions on crew health and electronic components. Recent studies have indicated that H, He, C, O, Ne, Mg, Si, and Fe nuclei contribute about 80% of the radiation dose-equivalent under realistic shielding conditions. Small uncertainties in the

absolute differential flux of these particles lead to large uncertainties in the amount of shielding mass needed for crew radiation protection. The absolute flux and the associated errors have received less attention than charge composition measurement. We have fitted the hydrogen, helium, and iron spectra from 1965 to 1990, and have shown that a consistent set of local interstellar spectra and solar modulation parameters can be developed that applies to all species. A thorough analysis of uncertainties shows that the model spectra can be defined to an absolute accuracy of ±10%. A reference spectrum at solar minimum, which will be the limiting GCR spectrum for exploratory class missions, has been defined.

Curtis, S.B. and Letaw, J.R. (1989) Galactic cosmic rays and cell-hit frequencies outside the magnetosphere. *Advances in Space Research* 9(10): 293-298.

GCR, Cell-hit frequency, Shielding thickness, High-LET, Radiation risk assessment

An evaluation of the exposure of space travelers to galactic cosmic radiation outside the earth's magnetosphere is made by calculating fluences of high-energy primary and secondary particles with various charges traversing a sphere of area 100 μm^2. Calculations relating to two shielding configurations are presented: the center of a spherical aluminum shell of thickness 1 g/cm^2, and the center of a 4 g/cm^2 thick aluminum spherical shell within which there is a 30 g/cm^2 diameter spherical water phantom with the point of interest 5 g/cm^2 from the surface. The area of 100 μm^2 was chosen to simulate the nucleus of a cell in the body. The frequencies as a function of charge component in both shielding configurations reflect the the odd-even disparity of the incident particle abundances. For a three-year mission, 33% of the cells in the more heavily shielded configuration would be hit by at least one particle with Z greater than 10. Six percent would be hit by at least two such particles. This emphasizes the importance of studying single high-Z particle effects both on cells which might be "at risk" for cancer induction and on critical neural cells or networks which might be vulnerable to inactivation by heavy charged particle tracks. Synergistic effects with the more numerous high-energy protons and helium ions cannot be ruled out. In terms of more conventional radiation risk assessment, the dose equivalent decreased by a factor of 2.85 from free space to that in the more heavily shielded configuration. Roughly half of this was due to the decrease in energy deposition (absorbed dose) and half to the decrease in biological effectiveness (quality factor).

Dudkin, V.E., Kovalev, E.E., Kolomensky, A.V., Sakovich, V.A., Semenov, V.F., Demin, V.P., and Benton, E.V. (1992) Radiation shielding estimates for manned Mars space flight. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 29-32.

Radiation shielding, Mars, Solar activity, Long-duration space mission, GCR, Solar cosmic ray

In the analysis of the required radiation shielding protection of spacecraft during a Mars flight, specific effects of solar activity (SA) on the intensity of galactic and solar cosmic rays were taken into consideration. Three spaceflight periods were considered: (1) maximum SA; (2) minimum SA; and (3) intermediate SA, when intensities of both galactic and solar cosmic rays are moderately high. Scenarios of spaceflights utilizing liquid-propellant rocket engines, low- and intermediate-thrust nuclear electrojet engines, and nuclear rocket engines, all of which have been designed in the Soviet Union, are reviewed. Calculations were performed on the basis of a set of standards for radiation protection approved by the U.S.S.R. State Committee for Standards. It was found that the lowest estimated mass of a Mars spacecraft, including the radiation shielding mass, obtained using a combination of a liquid propellant engine with low and intermediate thrust nuclear electrojet engines, would be 500-550 metric tons.

SOLAR ACTIVITY AND PREDICTION

Cucinotta, F.A., Wilson, J.W., Townsend, L.W., Shinn, J.L., and Katz, R. (1992) Track structure model for damage to mammalian cell cultures during solar proton events. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 177-184.

Solar particle event, Track structure, Nuclear reaction, Secondary electron production, Delta ray

Solar particle events (SPEs) occur infrequently and unpredictably, thus representing a potential hazard to interplanetary space missions. Biological damage from SPEs will be produced principally through secondary electron production in tissue, including important contributions due to delta rays from nuclear reaction products. We review methods for estimating the biological effectiveness of SPEs using a high energy proton model and the parametric cellular track model. Results of the model are presented for several of the historically largest flares using typical levels and body shielding.

Townsend, L.W., Cucinotta, F.A., Shinn, J.L., and Wilson, J.W. (1992) Risk analyses for the solar particle events of August through December 1989. *Radiation Research* 130: 1-6.

Transport code, BRYNTRN, Radiation risk, Radiation shielding, Dose, Dose-equivalent

The solar particle events of August through December 1989, among the largest ever recorded, are analyzed to assess the potential hazards to humans on interplanetary missions from events of these types. Using the coupled neutron-proton space radiation transport computer code, BRYNTRN, risk estimates for the effects of exposures to the skin, ocular lens, and bone marrow are made for nominal thicknesses of the spacecraft aluminum shielding. Risk assessment in terms of absorbed dose is made for each event. Also presented are estimates of organ absorbed dose and dose equivalent for pairs of events which occurred within 30-day periods, and for the cumulative August through December 1989 period.

Townsend, L.W., Shinn, J.L., and Wilson, J.W. (1991) Interplanetary crew exposure estimates for the August 1972 and October 1989 solar particle events. *Radiation Research* 126: 108-110.

BRYNTRN, Radiation shielding, Risk assessment, Skin, Lens

Using the coupled neutron-proton space radiation transport computer code (BRYNTRN), estimates of human exposure in interplanetary space, behind various thicknesses of aluminum shielding, are made for the large solar proton events of August 1972 and October 1989. A comparison of risk assessment in terms of total absorbed dose for each event is made for the skin, ocular lens, and bone marrow. Overall, the doses associated with the August 1972 event were higher than those with the October 1989 event and appear to be more limiting when compared with current guidelines for dose limits for missions in low Earth orbit and more hazardous with regard to potential acute effects on these organs. Both events could be life-threatening if adequate shielding is not provided.

EXPERIMENTS

Benton, E.V., Heinrich, W., Parnell, T.A., Armstrong, T.W., Derrickson, J.H., Fishman, G.J., Frank, A.L., Watts, J.W., Jr., and Wiegel, B. (1992) Ionizing radiation exposure of LDEF (pre-recovery estimates). *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 75-100.

Long Duration Exposure Facility, STS-32, Ionizing radiation, Space Station Freedom, GCR, Radiation environment

The Long Duration Exposure Facility (LDEF), launched into a 258 nautical mile orbit with an inclination of 28.5°, remained in space for nearly 6 yr. The 21,500 lb NASA satellite was one of the largest payloads ever deployed by the Space

Shuttle. LDEF completed 32,422 orbits and carried 57 major experiments representing more than 200 investigators from 33 private companies, 21 universities and nine countries. The experiments covered a wide range of disciplines including basic science, electronics, optics, materials, structures and power and propulsion. A number of the experiments were specifically designed to measure the radiation environment. These experiments are of specific interest, since the LDEF orbit is essentially the same as that of the Space Station Freedom. Consequently, the radiation measurements on LDEF will play a significant role in the design of radiation shielding of the space station. The contributions of the various authors presented here attempt to predict the major aspects of the radiation exposure received by the various LDEF experiments and therefore should be helpful to investigators who are in the process of analyzing experiments which may have been affected by exposure to ionizing radiation. The paper discusses the various types and sources of ionizing radiation including cosmic rays, trapped particles (both protons and electrons) and secondary particles (including neutrons, spallation productions and high-LET recoils), as well as doses and LET spectra as a function of shielding. Projections of the induced radioactivity of LDEF are also discussed.

Dudkin, V.E., Karpov, O.N., Potapov, Yu.V., Akopova, A.B., Magradze, N.V., Moiseenko, A.A., Benton, E.V., Frank, A.L., and Watts, J.W., Jr. (1992) Experimental and calculated LET distributions in the Cosmos-2044 biosatellite orbit. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* **20(1): 143-147.**

Cosmos-2044, PNTD, Radiation detector, GCR, Track detector

During the flight of the Cosmos-2044 biosatellite, joint U.S.S.R.-U.S.A. investigations of different characteristics of cosmic radiation (CR) in the near-Earth environment were carried out. The U.S. dielectric track detectors CR-39 and Soviet BYa- and BR-type nuclear photo-emulsions were used as detectors. The present work shows some results of experimental measurements of linear energy transfer (LET) spectra of CR particles obtained with the use of these detectors, which were placed both inside and outside the satellite. The LET spectra measurement with plastic detectors is composed of two parts: the measurement of galactic cosmic rays (GCR) particles, and of short-range particles. The contributions of these components to the total LET distribution at various thicknesses of the shielding were analyzed and the results of these studies are presented. Calculated LET spectra in the Cosmos-2044 orbit were compared with experimental data. On the basis of experimental and calculated values of the LET spectra, absorbed and equivalent CR doses were calculated. In the shielding range of 1-1.5 g cm^{-2}, outside the spacecraft, the photo-emulsions yielded 10.3 mrad d^{-1} and 27.5 mrem d^{-1} (LET > 2 MeV cm^{-1}) while the CR-39 yielded averages of 1.43 mrad d^{-1} and 13.4 mrem d^{-1} (LET > 40 MeV cm^{-1}). Inside the spacecraft (> 10 g cm^{-2}) the photo-emulsions yielded 8.9 mrad d^{-1} and 14.5 mrem d^{-1}.

Dudkin, V.E., Kovalev, E.E., Potapov, Yu.V., Benton, E.V., Frank, A.L., Benton, E.R., Watts, J.W., Jr., Parnell, T.A., Schopper, E., Balcan, B., Reitz, G., Bücker, H., Facius, R., Beaujean, R., and Heilmann, C. (1992) Cosmic ray LET spectra and doses on board Cosmos-2044 biosatellite. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 149-155.

Cosmos-2044, Radiation detector, CR-39, Quality factor, Cosmic ray, PNTD

Results of the experiments on board Cosmos-2044 (Biosatellite 9) are presented. Various nuclear track detectors (NTD) (dielectric, AgCl-based, nuclear emulsions) were used to obtain the LET spectra inside and outside the satellite. The spectra from the different NTDs have proved to be in general agreement. The results of the LET spectra calculations using two different models are also presented. The resultant LET distributions are used to calculate the absorbed and equivalent doses and the orbit-averaged quality factors (QF) of the cosmic rays (CR). Absorbed dose rates inside (~20 g cm^{-2} shielding) and outside (1 g cm^{-2}) the spacecraft, omitting electrons, were found to be 4.8 and 8.6 mrad d^{-1}, respectively, while the corresponding equivalent doses were 8.8 and 19.7 mrem d^{-1}. The effects of the flight parameters on the total fluence of, and on the dose from, the CR particles are analyzed. Integral dose distributions of the detected particles are also determined. The LET values which separate absorbed and equivalent doses into 50% intervals are estimated. The CR-39 dielectric NTD is shown to detect 20-30% of the absorbed dose and 60-70% of the equivalent dose in the Cosmos-2044 orbit. The influence of solar activity phase on the magnitude of CR flux is discussed.

Dudkin, V.E., Potapov, Yu.V., Akopova, A.B., Melkumyan, L.V., Rshtuni, Sh.B., Benton, E.V., and Frank, A.L. (1992) Neutron fluences and energy spectra in the Cosmos-2044 biosatellite orbit. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 139-141.

Cosmos-2044, Neutron flux density, Differential energy spectrum, Energy interval, Radiation detector, Space radiation, PNTD

Joint Soviet-American measurements of the neutron component of space radiation (SR) were carried out during the flight of the Soviet biosatellite Cosmos-2044. Neutron flux densities and differential energy spectra were measured inside and on the external surface of the spacecraft. Three energy intervals were employed: thermal (E_n < 0.2 MeV), resonance (0.2 MeV < E_n < 1.0 MeV) and fast (E_n > 1.0 MeV) neutrons. The first two groups were measured with U.S. ^{6}LiF detectors, while fast neutrons were recorded both by U.S. fission foils and Soviet nuclear emulsions. Estimations were made of the contributions to absorbed and equivalent doses from each neutron energy interval and a correlation was presented between fast neutron fluxes, measured outside the satellite, and the phase of solar activity (SA). Average dose equivalent rates of 0.018 and 0.14 mrem d^{-1} were measured for thermal and resonance neutrons, respectively, outside the spacecraft. The corresponding values for fast neutrons

were 3.3 (U.S.) and 1.8 (U.S.S.R.) mrem d^{-1}. Inside the spacecraft, a value of 3.5 mrem d^{-1} was found.

Marenny, A.M., Nymmik, R.A., Suslov, A.A., Benton, E.V., Frank, A.L., and Benton, E.R. (1992) Cosmic ray particles with different LET values under various thicknesses of shielding in low altitude orbits: Calculations and Cosmos-2044 measurements. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 157-160.

Cosmos-2044, LET, Radiation shielding, Model simulation, PNTD, CR-39, GCR, Proton

Fluxes of cosmic ray particles with different LET values were measured on board the Cosmos-2044 biosatellite under various thicknesses of shielding by stacks of CR-39 and nitrocellulose plastic nuclear track detectors (mounted outside the satellite). The component composition of the particles detected under shieldings of 0.1-2.5 g cm^{-2} is verified by comparing experimental data with the results of model simulations of the fluxes of galactic cosmic ray particles and of radiation belt protons.

Wiegel, B., Heinrich, W., Benton, E.V., and Frank, A.L. (1992) Measurements of LET spectra and comparison to models. *Advances In Space Research* 12(2-3): 349-353.

LET, Ionizing radiation, Stopping proton, Target recoil, Target fragment, Radiation belt proton, Galactic proton, Model evaluation, GCR, Transport model

We present measurements of LET spectra for near earth orbits with various inclinations and altitudes. A comparison with calculated LET spectra shows that the contribution from direct ionizing galactic cosmic rays is well described by the models. An additional contribution to the spectra originates from stopping protons and from nuclear interactions of particles with material. In the case of an interaction a large amount of energy is deposited in a small volume by target recoils or target fragments. These events will be called short range (SR) events. For a low inclination orbit, radiation belt protons are the main source of these events, while galactic protons become more important when increasing the inclination to near polar orbits. We show that the contribution of SR events for orbits with low altitude (324 km) and 57° inclination is comparable to that for an orbit with 28° inclination at high altitude (510 km).

THEORY AND MODEL DEVELOPMENT

Cucinotta, F.A., Katz, R., Wilson, J.W., Townsend, L.W., Shinn, J.L., and Hajnal, F. (1991) Biological effectiveness of high-energy protons: Target fragmentation. *Radiation Research* **127: 130-137.**

LET, Nuclear fragments, RBE, Track structure, Proton

High-energy protons traversing tissue produce local sources of high-linear-energy-transfer (LET) ions through nuclear fragmentation. We examine the contribution of these target fragments to the biological effectiveness of high-energy protons using the cellular track model. The effects of secondary ions are treated in terms of the production collision density using energy-dependent parameters from a high-energy fragmentation model. Calculations for mammalian cell cultures show that at high dose, at which intertrack effects become important, protons deliver damage similar to that produced by γ rays, and with fragmentation the relative biological effectiveness (RBE) of protons increases moderately from unity. At low dose, where sublethal damage is unimportant, the contribution from target fragments dominates, causing the proton effectiveness to be very different from that of γ rays with a strongly fluence-dependent RBE. At high energies, the nuclear fragmentation cross sections become independent of energy. This leads to a plateau in the proton single-particle-action cross section, below 1 keV/μm, since the target fragments dominate.

Shavers, M.R., Curtis, S.B., Miller, J., and Schimmerling, W. (1990) The fragmentation of 670A MeV neon-20 as a function of depth in water. II. One-generation transport theory. *Radiation Research* **124: 117-130.**

Heavy ion transport, Transport theory, Heavy ion fragmentation, Fluence spectra

The results of an experiment to study the interaction of a beam of 670A MeV neon ions incident on a water column set to different thicknesses were compared with a "first principles" transport calculation in the straight-ahead approximation. This calculation assumes that the nuclear interactions of the incident particles lead to a secondary particle with the velocity of the incident projectile at the interaction point moving in the direction of the incident projectile. Subsequent nuclear interactions of the fragments were taken into account partially, by calculating the nuclear attenuation of the fragments in the residual material, but were not taken into account as a source of further nuclear interaction products. Fluence spectra were calculated per unit incident neon fluence for 14 absorber thicknesses. The acceptance for each fragment was calculated based on a knowledge of the material in the beam and of the beam extraction energy. The theoretical spectra were multiplied by the calculated acceptance and convoluted with the measured LET resolution for comparison with the data. The stopping power used in the transport calculation was found to predict a range approximately 1.6% shorter than that given by experiment; this small difference resulted in significant discrepancies between theory and experiment in the

stopping region. For particles not stopping in the absorber, the transport calculation was accurate to within 30% for depths less than about 15 cm; the effects of tertiary particles become significant at greater depth.

Simonsen, L., Nealy, J.E., Townsend, L.W., and Wilson, J.W. (1991) Martian regolith as space radiation shielding. *Journal of Spacecraft and Rockets* **28(1): 7-8.**

Mars, Radiation shielding, Martian regolith, Radiation environment

In current Mars scenario descriptions, an entire mission is estimated to 500-1000 days round trip with a 100-600 day stay time on the surface. To maintain radiation dose levels below permissible limits, dose estimates must be determined for the entire mission length. With extended crew durations anticipated on Mars, the characterization of the radiation environment on the surface becomes a critical aspect of mission planning.

The most harmful free-space radiation is due to high energy galactic cosmic rays (GCR) and solar flare protons. The carbon dioxide atmosphere of Mars has been estimated to provide a sufficient amount of shielding from these radiative fluxes to help maintain incurred doses below permissible limits. However, Mars exploration crews are likely to incur a substantial dose while in transit to Mars that will reduce the allowable dose that can be received while on the surface. Therefore, additional shielding may be necessary to maintain short-term dose levels below limits or to help maintain career dose levels as low as possible. By utilizing local resources, such as Martian regolith, shielding materials can be provided without excessive launch weight requirements from Earth. The scope of this synopsis and of Ref. 3 focuses on presenting our estimates of surface radiation doses received due to the transport and attenuation of galactic cosmic rays and February 1956 solar flare protons through the Martian atmosphere and through additional shielding provided by Martian regolith.

Townsend, L.W., Cucinotta, F.A., and Wilson, J.W. (1992) Interplanetary crew exposure estimates for galactic cosmic rays. *Radiation Research* **129: 48-52.**

Radiation exposures, Transport code, Computerized Anatomical Man Model, Radiation shielding, GCR, Dose-equivalent

Using the Langley Research Center galactic cosmic-ray transport computer code and the Computerized Anatomical Man model, initial estimates of interplanetary exposure of astronauts to galactic cosmic rays, during periods of solar minimum activity, are made for a realistic human geometry shielded by various thicknesses of spacecraft aluminum shielding. Conventional dose assessment in terms of total absorbed dose and dose equivalent is made for the skin, ocular lens, and bone marrow. Included in the analyses are separate evaluations of the contributions from the incident primary ions, from subsequent-generation fragmentation products, and from target fragments. In all cases considered, the

equivalent sphere approximation yielded conservative overestimates for the actual organ exposures.

Townsend, L.W., Wilson, J.W., Shinn, J.L., and Curtis, S.B. (1992) Human exposure to large solar particle events in space. *Advances in Space Research* 12(2-3): 339-348.

Solar particle event, BRYNTRN, Transport code, Solar storm shelter, Shielding

Whenever energetic solar protons produced by solar particle events traverse bulk matter, they undergo various nuclear and atomic collision processes which significantly alter the physical characteristics and biologically important properties of their transported radiation fields. These physical interactions and their effect on the resulting radiation field within matter are described within the context of a recently developed deterministic, coupled neutron-proton space radiation transport computer code (BRYNTRN). Using this computer code, estimates of human exposure in interplanetary space, behind nominal (2 g/cm^2) and storm shelter (20 g/cm^2) thicknesses of aluminum shielding, are made for the large solar proton event of August 1972. Included in these calculations are estimates of cumulative exposures to the skin, ocular lens, and bone marrow as a function of time during the event. Risk assessment in terms of absorbed dose and dose equivalent is discussed for these organs. Also presented are estimates of organ exposures for hypothetical, worst-case flare scenarios. The rate of dose equivalent accumulation places this situation in an interesting region of dose rate between the very low values of usual concern in terrestrial radiation environments and the high dose rate values prevalent in radiation therapy.

EXPERIMENTAL STUDIES

Schimmerling, W. (1992) Ground-based measurements of galactic cosmic ray fragmentation in shielding. *Advances in Space Research* 12(2-3): 445-459.

GCR, HZE, Shielding, Fragmentation

The mean free path for nuclear interactions of galactic cosmic rays is comparable to shielding and tissue thicknesses present in human interplanetary exploration, resulting in a significant fraction of nuclear reaction products at depth. In order to characterize the radiation field, the energy spectrum, the angular distribution, and the multiplicity of each type of secondary particles must also be known as a function of depth. Reactions can take place anywhere in a thick absorber; therefore, it is necessary to know these quantities as a function of particle energy for all particles produced. HZE transport methods are used to predict the radiation field; they are dependent on models of the interaction of man-made systems with the space environment to an even greater extent than methods used for other types of radiation. Hence, there is a major need to validate these transport codes by comparison with experimental data. The most cost-effective method of validation is a comparison with ground-based experimental measurements. A research program to provide such validation measurements

using neon, iron and other accelerated heavy ion beams will be discussed and illustrated using results from ongoing experiments and their comparison with current transport codes. The extent to which physical measurements yield radiobiological predictions will be discussed.

INSTRUMENTATION

Oda, K., Csige, I., Henke, R.P., and Benton, E.V. (1992) A new method for internal calibration of nuclear track detectors. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* **20(3): 505-510.**

PNTD, Radiation detector, Multi-step etching, CR-39, Neutron

A new technique is proposed for an internal calibration of a two-layer detector assembly. Spatially coincident pairs of conical tracks on one surface and overetched tracks on the adjacent surface are selected for measurement. Both the etch rate ratio and the particle range can be obtained from the minor and major diameters of the elliptical track and the radii of the circular tracks for two etching steps. This technique was applied to CR-39 detectors exposed to fast neutrons and those flown on a high altitude balloon in order to evaluate the proton response. An improvement by using multi-step etching was also carried out. It was found that not only a single set of the etch rate ratio and the range but also the response curve could be estimated in an extended region by analyzing combined growth curves.

2. BIOLOGY

MOLECULAR BIOLOGY

Lett, J.T. and Peters, E.L. (1992) Deoxyribonucleoprotein structure and radiation injury: Cellular radiosensitivity is determined by LET$_\infty$-dependent DNA damage in hydrated deoxyribonucleoproteins and the extent of its repair. *Advances in Space Research* **12(2-3): 51-58.**

Cellular radiosensitivity, DNA repair, Risk assessment

For decades, theories of cellular radiosensitivity relied upon the initial patterns of energy deposition to explain radiation lethality. Such theories are unsound: cellular (DNA) repair also underlies cellular radiosensitivity. For the charged particles encountered in deep space, both the types of DNA damage caused in cellular deoxyribonucleoproteins and the efficacies of their repair are dependent on linear energy transfer (LET$_\infty$), and repair efficiency is also influenced by cell and tissue type, i.e., the actual recovery processes involved. Therefore, quality factors derived from radiation quality alone are inadequate parameters for assessing the radiation risks of space flight.

Until recently, OH radicals formed in bulk nuclear water were believed to be the major causes of DNA damage that results in cell death, especially for sparsely ionizing radiations. That hypothesis has now been challenged, if not refuted. Lethal genomic DNA damage is determined mainly by energy deposition in deoxyribonucleoproteins, and their hydration shells, and charge (energy) transfer processes within those structures.

TRANSFORMATION, MUTATION

Coohill, T., Marshall, T., Schubert, W.W., and Nelson, G.A. (1988) Ultraviolet mutagenesis of radiation-sensitive (rad) mutants of the nematode *Caenorhabditis elegans*. *Mutation Research* **209: 99-106.**

Nematode, Mutation, Ultraviolet radiation, Reproduction

A mutational tester strain (JP10) of the nematode *C. elegans* was used to capture recessive lethal mutations in a balanced 300 essential gene autosomal region. The probability of converting a radiation interaction into a lethal mutation was measured in young gravid adults after exposure to fluences of 254-nm ultraviolet radiation (UV) ranging from 0 to 300 Jm^{-2}. Mutation frequencies as high as 5% were observed. In addition, three different radiation-hypersensitive mutations, *rad-1*, *rad-3* and *rad-7* were incorporated into the JP10 background genotype, which allowed us to measure mutation frequencies in radiation-sensitive animals. The strain homozygous for *rad-3* was hypermutable to UV while strains in homozygous for *rad-1* and *rad-7* were hypomutable. Data showing the effects of UV on larval development and fertility for the rad mutants is also shown and compared for wild-type and JP10 backgrounds.

Yang, T-H., Craise, L.M., Prioleau, J., Stampfer, M.R., and Rhim, J.S. (1992) Chromosomal changes in cultured human epithelial cells transformed by low- and high-LET radiation. *Advances in Space Research* 12(2-3): 127-136.

Risk assessment, Epithelial cell, High-LET, Neoplastic transformation

For a better assessment of radiation risk in space, an understanding of the responses of human cells especially the epithelial cells, to low- and high-LET radiation is essential. In our laboratory, we have successfully developed techniques to study the neoplastic transformation of two human epithelial cell systems by ionizing radiation. These cell systems are human mammary epithelial cells (H184B5) and human epidermal keratinocytes (HEK). Both cell lines are immortal, anchorage dependent for growth, and nontumorigenic in athymic nude mice. Neoplastic transformation was achieved by irradiating cells successively. Our results showed that radiogenic cell transformation is a multistep process and that a single exposure of ionizing radiation can cause only one step of transformation. It requires, therefore, multihits to make human epithelial cells fully tumorigenic. Using a simple karyotyping method, we did chromosome analysis with cells cloned at various stages of transformation. We found no consistent large terminal deletion of chromosomes in radiation-induced transformants. Some changes of total number of chromosomes, however, were observed in the transformed cells. These transformants provide an unique opportunity for further genetic studies at a molecular level.

LETHALITY, SURVIVAL

Katz, R. and Cucinotta, F.A. (1991) RBE vs. dose for low doses of high-LET radiations. *Health Physics* 60(5): 717-718.

RBE, High-LET, Dose, Cellular track model, Cell damage, Neutron

According to track theory, the relative biological effectiveness (RBE) of high linear energy transfer (LET) radiations varies with cellular radiosensitivity parameters and the radiation environment. Of special interest is that the RBE varies as the dose of high-LET radiation to the power $(1/m-1)$ where m is the "target number" parameter, which varies from 2-4 in different cell lines. This applies to neutrons as well as to heavy ions at sufficiently low doses such that cells are not activated in the γ-kill mode; that is, the tracks of single heavy ions are sufficiently far apart so that there are few cases of inter-track inactivation.

DNA DAMAGE AND REPAIR

Quality factor, RBE, Double strand break, Chromatin

For several years, it has been evident that cellular radiation biology is in a necessary period of consolidation and transition (Lett 1987, 1990; Lett et al.; 1986, 1987). Both changes are moving apace, and have been stimulated by studies with heavy charged particles.

From the standpoint of radiation chemistry, there is now a consensus of opinion that the DNA hydration shell must be distinguished from bulk water in the cell nucleus and treated as an integral part of DNA (chromatin) (Lett 1987). Concomitantly, sentiment is strengthening for the abandonment of the classical notions of "direct" and "indirect" action (Fielden and O'Neill 1991, O'Neill, 1991; O'Neill et al. 1991; Schulte-Frohlinde and Bothe 1991 and reference therein). A layer of water molecules outside, or in the outer edge of, the DNA (chromatin) hydration shell influences cellular radiosensitivity in ways not fully understood. Charge and energy transfer processes facilitated by, or involving, DNA hydration must be considered in rigorous theories of radiation action on cells. The induction and processing of double strand breaks (DSBs) in DNA (chromatin) seem to be the predominant determinants of the radiotoxicity of normally radioresistant mammalian cells, the survival curves of which reflect the patterns of damage induced and the damage present after processing ceases, and can be modelled in formal terms by the use of reaction (enzyme) kinetics. Incongruities such as sublethal damage are neither scientifically sound nor relevant to cellular radiation biology (Calkins 1991; Lett 1990, Lett et al. 1987a).

Increases in linear energy transfer (LET_∞) up to 100-200 keV μm^{-1} cause increases in the extents of neighboring chemical and physical damage in DNA denoted by the general term DSB. Those changes are accompanied by decreasing abilities of cells normally radioresistant to sparsely ionizing radiation to process DSBs in DNA and chromatin and to recover from radiation exposure, so they make significant contributions to the relative biological effectiveness (RBE) of a given radiation. As the LET_∞ is raised a few hundred keV μm^{-1} the damage associated with DSBs continues to increase, but the efficiency of DSB induction declines to low values (~0.1), as do RBE and the effective processing of DSBs and chromatin breaks, and the decline in RBE seems to mimic the overall decline in suitable processing of DSBs. Hence, the quality factor (Q) for a given radiation cannot be based solely upon the pattern of energy deposition, a fact attested to also by the quite different RBE responses exhibited by repair-deficient mutant (or variant) cells.

Understanding of the biological effects of heavy ions is important not only for the welfare of astronauts who will undertake extended interplanetary missions in

space but also for the facilitation of a rigorous scientific basis for conventional radiation therapy.

TISSUE, ORGANS, AND ORGANISMS

Johnson, T.E. and Nelson, G.A. (1991) *Caenorhabditis elegans:* **A model system for space biology studies.** *Experimental Gerontology* 26: 299-309.

Nematode, Free-radical, DNA repair, Radiobiology, Model development, Oxidative stress, Aging, Metabolism, Genetics

The utility of the nematode *Caenorhabditis elegans* in studies spanning aspects of development, aging, and radiobiology is reviewed. These topics are interrelated via cellular and DNA repair processes especially in the context of oxidative stress and free-radical metabolism. The relevance of these research topics to problems in space biology is discussed and properties of the space environment are outlined. Exposure to the space-flight environment can induce rapid changes in living systems that are similar to changes occurring during aging; manipulation of these environmental parameters may represent and experimental strategy for studies of development and senescence. The current and future opportunities for such space-flight experimentation are presented.

IN VIVO/IN VITRO SYSTEMS

Brenner, D.J. and Hall, E.J. (1992) Radiation-induced oncogenic transformation: The interplay between dose, dose protraction, and radiation quality. *Advances in Radiation Biology* 16: 167-179.

Model development, Inverse dose rate, Radiation quality

There is now a substantial body of evidence for end points such as oncogenic transformation *in vitro*, and carcinogenesis and life shortening *in vivo*, suggesting that dose protraction leads to an increase in effectiveness relative to a single, acute exposure—at least for radiations of medium linear energy transfer (LET) such as neutrons.

This phenomenon has come to be known as the "inverse dose rate effect," because it is in marked contrast to the situation at low LET, where protraction in delivery of a dose of radiation, either by fractionation or low dose rate, results in a decreased biological effect; additionally, at medium and high LET, for radiobiological end points such as clonogenic survival, the biological effectiveness is independent of protraction.

The quantity and quality of the published reports on the "inverse dose rate effect" leaves little doubt that the effect is real, but the available evidence indicates that the magnitude of the effect is due to a complex interplay between dose, dose rate, and radiation quality.

Here, we first summarize the available data on the inverse dose rate effect and suggest that it follows a consistent pattern in regard to dose, dose rate, and radiation quality; second, we describe a model that predicts these features; and, finally, we describe the significance of the effect for radiation protection.

Rodriguez, A., Alpen, E.L., and Powers-Risius, P. (1992) The RBE-LET relationship for rodent intestinal crypt cell survival, testes weight loss and multicellular spheroid cell survival after heavy ion irradiation. *Radiation Research* 132: 184-192.

Cell survival, Mouse, LET, RBE, Inactivation cross section

This report presents data for survival of mouse intestinal crypt cells, mouse testes weight loss as an indicator of survival of spermatogonial stem cells, and survival of rat 9L spheroid cells after irradiation in the plateau region of unmodified particle beams ranging in mass from ^{4}He to ^{139}La. The LET values range from 1.6 to 953 keV/μm. These studies examine the RBE-LET relationship for two normal tissues and for an *in vitro* tissue model, multicellular spheroids. When the RBE values are plotted as a function of LET, the resulting curve is characterized by a region in which RBE increases with LET, a peak RBE at an LET value of 100 keV/μm, and a region of decreasing RBE at LETs greater than 100 keV/μm. Inactivation cross sections (σ) for these three biological systems have been calculated from the exponential terminal slope of the dose-response relationship for each ion. For this determination the dose is expressed as particle fluence and the parameter σ indicates effect per particle. A plot of σ versus LET shows that the curve for testes weight loss is shifted to the left indicating greater radiosensitivity at lower LETs than for crypt cell and spheroid cell survival. The curves for LET-cross section versus LET for all three model systems show similar characteristics with a relatively linear portion below 100 keV/μm and a region of lessened slope in the LET range above 100 keV/μm for testes and spheroids. The data indicate that the effectiveness per particle increases as a function of LET, and to a limited extent, Z, at LET values greater than 100 keV/μm. Previously published results for spread Bragg peaks are also summarized and they suggest that RBE is dependent both on the LET and the Z of the particle.

CARCINOGENESIS AND LIFE SHORTENING

Curtis, S.B., Townsend, L.W., Wilson, J.W., Powers-Risius, P., Alpen, E.L., and Fry, R.J.M. (1992) Fluence-related risk coefficients using the Harderian gland data as an example. *Advances in Space Research* 12(3): 407-416.

Fluence-related risk coefficient, Risk cross section, Galactic cosmic rays, Risk assessment, High-LET

The risk of radiation-induced cancer to space travelers outside the Earth's magnetosphere will be of concern on missions to the Moon and beyond to Mars.

High energy galactic cosmic rays with high charge (HZE particles) will penetrate the spacecraft and the bodies of the astronauts, sometimes fragmenting into nuclear secondary species of lower charge but always ionizing densely, thus causing cellular damage which may lead to malignant transformation. To quantitate this risk, the concept of dose equivalent (in which a quality factor Q as a function of LET is assumed) may not be adequate, since different particles of the same LET may have different efficiencies for tumor induction. Also, RBE values on which quality factors are based depend on response to low-LET radiation at low doses, a very difficult region for which to obtain reliable experimental data. Thus, we introduce a new concept, a fluence-related risk coefficient (F), which is the risk of a cancer per unit particle fluence and which we call the *risk cross section*. The total risk is the sum of the risk from each particle

type: $P = \sum_i \int F_i (L_i) \, \varphi_i(L_i) \, dL_i$, where L_i is the LET and $\varphi_i(L_i)$ is the fluence-LET

spectrum of the ith particle type. As an example, tumor prevalence data in mice are used to estimate the probability of mouse Harderian gland tumor induction per year on an extra-magnetospheric mission inside an idealized shielding configuration of a spherical aluminum shell 1 g/cm^2 thick. The combined shielding code BRYNTRN/GCR is used to generate the LET spectra at the center of the sphere. Results indicate a yearly prevalence at solar minimum conditions of 0.06, with 60% of this arising from charge components with Z between 10 and 28, and two-thirds of the contribution arising from LET components between 10 and 200 keV/μm.

Wood, D.H. (1991) Long-term mortality and cancer risk in irradiated rhesus monkeys. *Radiation Research* 126: 132-140.

Rhesus monkey, Life shortening, Proton irradiation, Nonleukemia cancer, Male vs female, Endometriosis, Animal model, NCRP

Continuous, 24-year observations on a group of 358 rhesus monkeys reveal that life shortening from exposure to protons in the energy range encountered in the Van Allen belts and solar proton events is influenced primarily by the dose rather than by the energy of radiation. Life shortening in groups exposed to similar surface doses of 138- 2300-MeV and 32- to 55-MeV protons are not significantly different, but the low-energy protons are associated with more deaths in the early years, while the high-energy protons contribute more to mortality in later years. In males, the most significant cause of life shortening is nonleukemia cancers. In females, radiation increased the risk of endometriosis (an abnormal proliferation of the lining of the uterus) which resulted in significant mortality in the years before early detection and treatment methods were employed. Animals exposed to 55-MeV protons had a high incidence of malignant brain tumors with latent periods ranging from 13 months to 20 years. The first fatal cancer among nonirradiated controls occurred 18 years after the study began. Analysis of the dose-response data supports the 1989 guidelines of the NCRP for maximum permissible radiation exposures in astronauts.

CATARACTOGENESIS

Brenner, D.J., Medvedovsky, C., Huang, Y., Merriam, G.R., Jr., and Worgul, B.V. (1991) Accelerated heavy particles and the lens, VI. RBE studies at low doses. *Radiation Research* 128: 73-81.

RBE, Rats, X-ray, Cataractogenesis, Quality factor, Heavy charged particle

We report on the prevalence, hazard, and relative biological effectiveness (RBE) for various stages of lens opacification in rats induced by very low doses of fast argon ions of LET 88 keV/μm, compared to those for X-rays. Doses of argon ions from 0.01 to 0.25 Gy were used and RBEs of these ions relative to X-rays estimated using a nonparametric technique. At the end of the follow-up period, which encompasses a significant fraction of the animals' lifetime, 90% confidence intervals for the RBE of the argon ions relative to X-rays were 4-8 at 0.25 Gy, 10-40 at 0.05 Gy, and 50-100 at 0.01 Gy. Our results are consistent with the point-estimate neutron RBEs in Japanese A-bomb survivors, though broad confidence bounds are present in the Japanese results. If a reasonable extrapolation to higher doses is used, our results are also consistent with data reported earlier at higher doses for argon-ion cataractogenesis in rats, mice and rabbits. We conclude from these results that at very low doses the RBE for cataractogenesis from HZE particles in space is considerably more than 20, and use of a quality factor of at least 50 would be prudent.

Cox, A.B., Lee, A., Williams, G.R., and Lett, J.T. (1992) Late cataractogenesis in primates and lagomorphs after exposure to particulate radiations. *Advances in Space Research* 12(2-3): 379-384.

Rhesus monkey, Cataractogenesis, Aging, Rabbit, Lens opacification

Rhesus monkeys that were exposed in 1969, at the age of ~2 years, to low doses of "mixed-energy" protons (10- and 110-MeV) /1/ are exhibiting progressive (degenerative) lenticular changes. We have conducted regular examinations of this group of monkeys for cataractogenic development since 1987, i.e., 18 years after irradiation, and the animals began to show enhanced degrees of lenticular opacification two years later. The lenses of age-matched controls (median lifespan in captivity ~24 years) continue to exhibit much lower levels of opacification (senile cataracts). Trends in the new data exposed at similar ages in 1964 and 1965 to protons of different energies /2-5/, and which we began to monitor only 20-21 years later. Therefore, the new information from the mixed-energy group of monkeys provides insight into the development of late cataractogenic sequelae in the other groups of animals during the 2-3 years before we began to measure them.

Comparisons are also made here among recent results from the different groups of primates and from New Zealand white (NZW) rabbits that were exposed when young to ^{56}Fe ions and *monitored continuously thereafter.* This is done because analogous expression of radiation-induced degenerative cataractogenesis also occurs late in the lifespan of the lagomorphs (control median lifespan in captivity

~5-7 years), but in this case the cataractogenic profile has been documented through most of the post-irradiation lifespan.

Lett, J.T., Lee, A., and Cox, A.B. (1991) Late cataractogenesis in rhesus monkeys irradiated with protons and radiogenic cataract in other species. *Radiation Research* **126: 147-156.**

Rhesus monkey, Proton, Cataractogenesis, Rabbit, Rats, Aging, Animal model, Heavy ion, Gamma rays

Rhesus monkeys (*Macaca mulatta*) which were irradiated at ca. 2 years of age with acute doses ($\leq$5 Gy) of protons (32-2300 MeV) are exhibiting the late progressive phase of radiation cataractogenesis 20-24 years after exposure, the period during which we have been monitoring the sequelae of irradiation of the lens. The median life span of the primate is ~24 years. Analogous late ocular changes also occur in a similar period of the lifetimes of New Zealand White (NZW) rabbits (*Oryctolagus cuniculus*) exposed at 8-10 weeks of age to 460-MeV ^{56}Fe ions. In this experiment, which has been in progress for ca. 6 years, we are following the development of radiation-induced lenticular opacification (cataractogenic profiles) throughout the life span. The median life span of the lagomorph is 5-7 years. Cataractogenic profiles for NZW rabbits irradiated with ^{20}Ne, and ^{40}Ar ions and ^{60}Co γ photons were obtained previously. Reference is also made to measurements of the cataractogenic profiles of a short-lived rodent, the Fischer 344 rat (*Rattus norvegicus*) during the first year after exposure at 8-10 weeks of age to spread-Bragg-peak protons of 55 MeV nominal energy. The median life span of the rodent is reported to be 2-3 years.

Medvedovsky, C. and Worgul, B.V. (1991) Neutron effects on the lens. *Radiation Research* **128: S103-S110.**

Cataractogenesis, Mutation, Inverse dose rate

Few *in vivo* systems have received the investigative attention or have provided the grist for our understanding of basic radiobiological principles as have the lens and the cataract. From Roentgen's time the lens has been recognized as a "biological dosimeter" for gauging radiation response. Its advantages range from its *in vivo* status to its qualification as an integrated tissue. From the time of the Hiroshima/Nagasaki experience, there has been some urgency in attempting to understand the breadth of neutron-radiation effects on humans. The major obstacle has been our understanding of the doses which were received by the individuals who express the damage. The majority of the work has been derived from experimental animals and findings related to photons: X and γ rays. Cataractogenesis provides insights in terms of not only ocular radiopathy but also the basic mechanisms of the action of radiation. Often referred to as the "classic" nonstochastic radiation effect, it is becoming increasingly clear that the suggestion of a threshold reflects the limitations imposed on expression by the life span. Thus the primary damage which appears to be somatic mutation is fully stochastic. This being the case, it is not surprising that, as is the case for simpler systems, the RBEs for cataracts following neutron exposure are

significantly higher than for X-rays, and that there is evidence for an inverse dose-rate effect in their production. This presentation focuses on these data and on the merits of the lens for the assessment of neutron effects on humans, the existing data for known dose levels in the human population, and the confounding issues associated with extrapolation from experimental work. Data from Western sources as well as those from the USSR are presented.

Riley, E.F., Lindgren, A.L., Andersen, A.L., Miller, R., and Ainsworth, E.J. (1991) Relative cataractogenic effects of X-rays, fission-spectrum neutrons, and ^{56}Fe particles: A comparison with mitotic effects. *Radiation Research* **125: 298-305.**

Eye, Rats, Lens opacification, X-ray, Neutron, Heavy charged particle, Cataracts, Mitotic abnormality

The eyes of Sprague-Dawley rats were irradiated with doses of 2.5-10 Gy 250-kVp X-rays, 1.25-2.25 Gy fission-spectrum neutrons (~0.85 MeV), of 0.1-2.0 Gy 600-MeV/A ^{56}Fe particles. Lens opacifications were evaluated for 51-61 weeks following X and neutron irradiations and for 87 weeks following X and ^{56}Fe-particle irradiations. Average stage of opacification was determined relative to time after irradiation, and the time required for 50% of the irradiated lenses to achieve various stages (*T50*) was determined as a function of radiation dose. Data from two experiments were combined in dose-effect curves as *T50* experimental values taken as percentages of the respective *T50* control values (*T50*-% control). Simple exponential curves best describe dose responsiveness for both high-LET radiations. For X-rays, a shallow dose-effect relationship (shoulder) up to 4.5 Gy was followed at higher doses by a steeper exponential dose-effect relationship. As a consequence, RBE values for the high-LET radiations are dose dependent. Dose-effect curves for cataracts were compared to those for mitotic abnormalities observed when quiescent lens epithelial cells were stimulated mechanically to proliferate at various intervals after irradiation. Neutrons were about 1.6-1.8 times more effective than ^{56}Fe particles for inducing both cataracts and mitotic abnormalities. For stage 1 and 2 cataracts, the X-ray *Dq* was 10-fold greater and the *Dq* was similar to those for mitotic abnormalities initially expressed after irradiation.

GENETICS/DEVELOPMENTAL

Nelson, G.A., Schubert, W.W., and Marshall, T.M. (1992) Radiobiological studies with the nematode *Caenorhabditis elegans*. Genetic and developmental effects of high LET radiation. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 227-232.

Nematode, Mutation, Chromosome aberration, Cell inactivation, Organogenesis, Damage repair, High-LET, Genetics

The biological effects of heavy charged particle (HZE) radiation are of particular interest to travellers and planners for long-duration space flights where exposure levels represent a potential health hazard. The unique feature of HZE radiation is the structured pattern of its energy deposition on targets. There are many consequences of this feature to biological endpoints when compared with effects of ionizing photons. Dose vs response and dose-rate kinetics may be modified, DNA and cellular repair systems may be altered in their abilities to cope with damage, and the qualitative features of damage may be unique for different ions. The nematode *Caenorhabditis elegans* is being used to address these and related questions associated with exposure to radiation. HZE-induced mutation, chromosome aberration, cell inactivation and altered organogenesis are discussed along with plans for radiobiological experiments in space.

OTHER EFFECTS

Fanton, J.W. and Golden, J.G. (1991) Radiation-induced endometriosis in *Macaca mulatta*. *Radiation Research* 126: 141-146.

Rhesus monkey, Dose, X-ray, Electron, Endometriosis, Proton

Female rhesus monkeys received whole-body doses of ionizing radiation in the form of single-energy protons, mixed energy protons, X-rays, and electrons. Endometriosis developed in 53% of the monkeys during a 17-year period after exposure. Incidence rates for endometriosis related to radiation type were: single-energy protons, 54%; mixed-energy protons, 73%; X-rays, 71%; and electrons, 57%. The incidence of endometriosis in nonirradiated control monkeys was 26%. Monkeys exposed to single-energy protons, mixed-energy protons, and X-rays developed endometriosis at a significantly higher rate than control monkeys ($\chi2$, $P < 0.05$). Severity of endometriosis was staged as massive, moderate, and minimal. The incidences of these stages were 65, 16, and 19%, respectively. Observations of clinical disease included weight loss in 43% of the monkeys, anorexia in 35%, space-occupying masses detected by abdominal palpation in 55%, abnormal ovarian/uterine anatomy on rectal examination in 89%, and radiographic evidence of abdominal masses in 38%. Pathological lesions were endometrial cyst formation in 69% of the monkeys, adhesions of the colon in 66%, urinary bladder in 50%, ovaries in 86%, and ureters in 44%, focal nodules of endometrial tissue throughout the omentum in 59%, and metastasis in 9%. Clinical management of endometriosis consisted of debulking surgery and

bilateral salpingo-oophorectomy combined in some cases with total abdominal hysterectomy. Postoperative survival rates at 1 and 5 years for monkeys recovering from surgery were 48 and 36%, respectively.

Konairek, J.P. and Worgul, B.V. (1992) Do heavy ions cause microlesions in cell membranes? *Advances in Space Research* **12(2-3): 417-420.**

Cell damage, Cornea, Rats, Microlesion theory, Electrophysiology, Iron ion

Heavy ions are a hazard in manned deep space missions. It has been theoretically postulated that when they interact with cells, localized damage in the forms of "microlesions" may occur. Purported morphological evidence of these lesions, however, has not been confirmed in the most extensively studied tissue so far, the cornea. Recent morphological evidence from rat corneas demonstrated that holes in membranes do not form as consequence of heavy ion irradiation. This does not mean, however, that some other form of damage is excluded. For example such damage may be physiological in nature, impairing the ability of cells or tissues to function properly.

In order to uncover any physiological effects, we investigated the microlesion question by monitoring the electrical potential difference across the endothelium of rat corneas *in vitro* before, during, and after irradiation. When the corneas were exposed to 1 Gy of ^{56}Fe ions (450 and 600 MeV/amu), we detected no effect on this parameter. These results suggest that direct physical damage to cell membranes, as predicted by the microlesion theory, does not take place.

Riley, E.F., Lindgren, A.L., Miller, R., Austin, B.T., and Ainsworth, E.J. (1989) Comparison of recovery from potential mitotic abnormality in mitotically quiescent lens cells after X, neutron, and 56Fe irradiations. *Radiation Research* **119: 232-245.**

Rat lens, Cell damage, X-ray, Iron ion, Mitotic abnormality, Dose-effect, RBE, High-LET

After exposure to various doses of 250 kVp X radiation, 0.85 MeV fission spectrum neutrons, of 600 MeV/A iron (Fe) particles, mitotically quiescent rat lens cells showed no visible evidence of radiation injury. However, following the mitogenic stimulus of wounding, mitotic abnormalities became evident when responding cells entered mitosis. Latent damage and recovery therefrom were monitored at 3, 7, 14, and 28 days after irradiation. Following doses of 1 to 10 Gy of X radiation, the recovery rate, indicated by a decrease in abnormalities with time, was proportional to dose, and the dose-effect slope decreased exponentially with time. Virtually no recovery occurred during the 28 days after 1.25 to 2.25 Gy of fission neutron radiation. After doses of 0.5 to 3.0 Gy of Fe particles, an increased expression of mitotic damage rather than recovery occurred. As a consequence of the differing patterns in time for expression of damage or recovery following X rays and the high-LET radiations, the relative biological effectiveness (RBE) increased from 3.6 to 16 for neutrons and from 2 to 10 for Fe particles over the 28-day observation period.

Worgul, B.V., David, J., Odrich, S., Merriam, G.R., Jr., Medvedovsky, C., Merriam, J., Trokel, S.L., and Geard, C.R. (1991) Evidence of genotoxic damage in human cataractous lenses. *Mutagenesis* 6(6): 495-499.

Cataracts, Lens epithelial fragment, Micronuclei

Lens epithelial fragments (tags) recovered from individuals during routine cataract extraction have been assessed for cellular changes reflective of genotoxic damage. A high percentage of tags exhibited a population of micronucleated and polyploid cells. The presence and number of micronuclei (MN) in the epithelia of cataract patients appears to be independent of age and sex. However, a large number of MN in the epithelial cells of some individuals strongly suggests a history of compromised genomic integrity. While the study was not designed to define the role of DNA damage in the development of cataracts or to monitor human populations at risk of exposure to exogenous mutagens/cataractogens, the potential of the methodology to address each is demonstrated.

3. RISK ASSESSMENT

RISK ASSESSMENT

Schimmerling, W. (1992) Radiobiological problems in space: An overview. *Radiation and Environmental Biophysics* **31: 197-203.**

Space radiation hazard, Radiation environment, Radiation exposures

An overview is presented on radiation problems in space, with emphasis on aspects of major interest for manned space exploration. A classification of the radiation hazards is presented and strategies for their evaluation are discussed. Space radiation problems are compared with characteristic aspects of radiation research in other disciplines, in order to provide further insight into those aspects that are unique to space.

RADIATION HEALTH AND EPIDEMIOLOGY

Worgul, B.V., Brenner, D.J., Medvedovsky, C., Merriam, G.R., Jr., and Huang, Y. (1991) Cataractogenesis following low doses of high LET radiation. *International Congress of Radiation Research* **9: 433.**

Eye, Argon, Neutron, Cataractogenesis, Lens opacification, Rats, X-ray, Quality factor

We studied the prevalence, hazard and relative biological effectiveness (RBE) for various stages of lens opacification in rats induced by very low doses of fast (570 MeV/amu) argon ions (LET $\approx$ 88 keV/μm), compared to those for 250 kVp X-rays. Doses of argon ions from 0.01 to 0.25 Gy were used and the RBE's were estimated using a non-parametric technique. At the end of the 67 week follow-up period, 90% confidence intervals for the RBE of the argon ions relative to X-rays were 4-8 at 0.25 Gy, 10-40 at 0.05 Gy and 50-100 at 0.01 Gy. The results are in reasonable accord with an RBE varying as: RBE = $(25/D_A)^{1/2}$ where D_A is the dose of argon ions in Gy. Our results are consistent with those RBE's for cataracts generated from the DS86 analysis of the Japanese A-bomb survivors. Furthermore when extrapolated to higher doses our findings are also consistent with previous high dose data for argon-ion cataractogenesis in rats, mice and rabbits. We conclude from these results that at very low doses the quality factor (Q) of 20 currently being suggested for neutron radiation protection standards may be inadequate and a Q of at least 50 should be considered.

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SPACE FLIGHT RADIATION HEALTH PHYSICS

Badhwar, G.D., Braby, L.A., Cucinotta, F.A., and Atwell, W. (1992) Dose rate, dose-equivalent rate, and quality factor in SLS-1. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(3): 447-451.

TEPC, STS-40, Spacelab, X-ray, Dose, Quality factor, Dose-equivalent, AP8MAX model, CREME model, SLS-1

A tissue-equivalent proportional counter (TEPC) sensitive to the lineal energy range of 0.26-300 keV μm-1 was flown on STS-40 (39° x 278 km x 296 km) inside the Spacelab. This instrument was previously flown on STS-31 but was modified to provide a finer resolution at lower lineal energies to better map the South Atlantic Anomaly (SAA) protons. The instrument was turned on 6 June 1991, and operated for 7470 min (124.5 h). The flight duration was characterized by a very large number of X-ray solar flares and enhanced magnetic field fluctuations; however, no significant dose from the solar particles was measured at the location of this instrument. The flight data can be separated into trapped and galactic cosmic radiation parts. The dose rate, dose-equivalent rate and quality factor for trapped radiation were 4.21 + 0.03 mrad day^{-1}, 7.72 + 0.05 mrem day^{-1}, and 1.83 + 0.1, respectively. The dose rate, dose-equivalent rate, and quality factor for galactic cosmic radiation were 5.34 + 0.03 mrad day^{-1}, 14.63 + 0.06 mrem day^{-1}, and 2.74 + 0.1, respectively. The overall quality factor for the flight was 2.38. The dose from the GCR is higher than from SAA protons because of the high inclination and low altitude of this flight. The AP8MAX model of the trapped radiation gives a dose rate of 2.43 mrad day^{-1} and a quality factor of 1.77. The CREME solar maximum model of galactic cosmic radiation gives a dose rate of 2.54 mrad day^{-1} and a quality factor of 2.91. Thus the AP8MAX model underestimates the dose by a factor of 1.8 whereas the CREME model leads to an underestimation of the dose by a factor of 2. A comparison of the LET spectra using the AP8MAX model and galactic cosmic radiation transport codes shows only a qualitative agreement.

Badhwar, G.D., Konradi, A., Hardy, A., and Braby, L.A. (1992) Active dosimetric measurements on Shuttle flights. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 13-20.

Dose distribution, LET, STS-31, AP8MAX model, Dosimetry, Active radiation detection

A tissue-equivalent proportional counter spectrometer capable of measuring the absorbed dose and dose distribution as a function of linear energy transfer (LET) and time, for all penetrating radiation in space, is described. This instrument weighs about 0.7 kg and was flown on the STS-31 (28.5° x 620 km) flight of the Space Shuttle, 24-29 April 1990. The measured total dose is in excellent agreement with the calculations based on the AP8MAX model of the trapped radiation belt protons. The observed LET frequency distribution is also in

excellent agreement with calculations based on this model. Active instruments can provide more detailed dosimetry for crew risk assessment than the thermoluminescent detectors or a plastic track detector system.

Golightly, M.J., Hardy, A., Atwell, W., and Hardy, K.A. (1992) Description, analysis and impact of major solar activity during recent U.S. Shuttle missions. *Advances in Space Research* 12(2-3): 335-338.

Radiation detector, Dosimetry, Solar particle event, RME-III, STS-26, STS-28, STS-29, STS-34

Since STS-26, three large solar events have occurred during Shuttle missions; a geomagnetic storm during STS-29 and solar particle events (SPEs) during STS-28 and -34. The maximum dose to a crew attributed to an SPE was estimated to be 30 μGy (70 μSv). Time-resolved dosimetry measurements of the SPE dose during STS-28 were made using the Air Force Radiation Monitoring Equipment (RME)-III. Comparison of calculated and measured dose demonstrated a discrepancy, possibly a result of deficiencies in the geomagnetic cutoff model used. This experience demonstrates that dose from an SPE is strongly dependent on numerous factors such as orbit inclination, SPE start time, spectral parameters and geomagnetic field conditions; the exact combination of these factors is fortuitous. New sources of data and procedures are being investigated, including real-time tracking of auroral oval positions or determination of particle cutoff latitudes, for incorporation into operational Shuttle radiation support practices.

Keith, J.E., Badhwar, G.D., and Lindstrom, D.J. (1992) Neutron spectrum and dose-equivalent in Shuttle flights during solar maximum. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* 20(1): 41-47.

Radiation detector, STS-28, STS-36, STS-31, HETC code, Dose-equivalent, ICRP-51, Neutron

This paper presents unambiguous measurements of the spectrum of neutrons found in spacecraft during spaceflight. The neutron spectrum was measured from thermal energies to about 10 MeV using a completely passive system of metal foils as neutron detectors. These foils were exposed to the neutron flux bare, covered by thermal neutron absorbers (Gd) and inside moderators (Bonner spheres). This set of detectors was flown on three U.S. Space Shuttle flights, STS-28, STS-36 and STS-31, during the solar maximum. We show that the measurements of the radioactivity of these foils lead to a differential neutron energy spectrum in all three flights that can be represented by a power law $J(E) \approx E^{-0.765}$ neutrons cm-2 day^{-1} MeV^{-1}. We also show that the measurements are even better represented by a linear combination of the terrestrial neutron albedo and a spectrum of neutrons locally produced in aluminum by protons, computed from the HETC code. We use both approximations to the neutron spectrum to produce a worst case and most probable case for the neutron spectra and the resulting dose-equivalents, computed using ICRP-51 neutron

fluence—dose conversion tables. We compare these to the skin dose-equivalents due to charged particles during the same flights.

Konradi, A., Atwell, W., Badhwar, G.D., Cash, B.L., and Hardy, K.A. (1992) Low Earth orbit radiation dose distribution in a phantom head. *Nuclear Tracks and Radiation Measurements: International Journal of Radiation Applications and Instrumentation, Part D.* **20(1): 49-54.**

Radiation detector, STS-28, STS-36, STS-31, Dose, Phantom head, Radiation shielding, GCR

In order to compare analytical methods with data obtained during exposure to space radiation, a phantom head instrumented with a large number of radiation detectors was flown on the Space Shuttle on three occasions: 8 August 1989 (STS-28), 28 February 1990 (STS-36), and 24 April 1990 (STS-31). The objective of this experiment was to obtain a measurement of the inhomogeneity in the dose distribution within a phantom head volume.

The orbits of these missions were complementary—STS-28 and STS-36 had high inclination and low altitude, while STS-31 had a low inclination and high altitude. In the cases of STS-28 and STS-36, the main contribution to the radiation dose comes form galactic cosmic rays (GCR) with a minor to negligible part supplied by the inner belt through the South Atlantic Anomaly (SAA), and for STS-28 an even smaller one from a proton enhancement during a solar flare-associated proton event. For STS-31, the inner belt protons dominate and the GCR contribution is almost negligible. The internal dose distribution is consistent with the mass distribution of the orbiter and the self-shielding and physical location of the phantom head.

Leavitt, D.D. (1991) Analysis of primate head irradiation with 55-MeV protons. *Radiation Research* **126: 127-131.**

Dose distribution, Dose, Isodose distribution, Dose threshold

The distribution of the dose to the head of a primate phantom due to 55-MeV proton irradiation was calculated using a clinical radiotherapy treatment planning system, with anatomical definition through computerized tomography scans. Dose profiles, isodose distributions, and differential and integral dose-volume histograms are used to describe the probable proton dose to the brain of rhesus monkeys, irradiated over two decades ago, in which brain tumors have now developed. The dose analysis shows that 59% of the brain received a dose in excess of the reference surface dose, and that portions of the brain received doses greater than 300% of the reference surface dose. The regions of high dose are illustrated in isodose distributions. This information may be useful in evaluating potential tumor induction following radiation exposure.

INTER- AND INTRASPECIES EXTRAPOLATION

Dalrymple, G.V., Lindsay, I.R., Mitchell, J., and Hardy, K.A. (1991) A review of the USAF/NASA Proton Bioeffects Project: Rationale and acute effects. *Radiation Research* **126: 117-119.**

RBE, Rhesus monkey, Mouse, Irradiation, Proton, Dosimetry, Depth-dose distribution

Ionizing radiation represented one of the important hazards facing the first manned lunar mission. A combined USAF/NASA project was conducted from 1963 through 1969 to estimate the relative biological effectiveness (RBE) of the radiations of space. Approximately 2000 primates (*Macaca mulatta*) and 5000 mice were irradiated with protons and electromagnetic radiations. The proton energies studied were selected to be representative of the proton spectrum in space. Much of the project was concerned with the use of cyclotrons for proton irradiations and with dosimetry. Biological measurements included clinical findings, physiological changes, hematological changes, histopathology, and mortality. When allowance was made for variation of response as a consequence of depth-dose distribution, the RBE for protons was approximately 1. This was anticipated from earlier theoretical studies and radiation therapy in humans with high-energy charged-particle beams.

RADIATION LIMITS AND STANDARDS

Shinn, J.L. and Wilson, J.W. (1991) Nuclear reaction effects in use of newly recommended quality factor. *Health Physics* **61(3): 415-419.**

Radiation risk, Quality factor, Fragmentation

The biological risk for energetic ion exposure cannot be reliably estimated exclusive of the target nuclear reaction products produced within the local tissue. A theoretical basis is derived for evaluating target fragment contributions that are evaluated for the newly proposed quality factor.

KEYWORD INDEX

KEYWORD INDEX

Active radiation detection 1-30
Aging 1-19, 1-22, 1-23
Animal model 1-21, 1-23
AP8MAX model 1-30
Argon 1-29

BRYNTRN 1-7, 1-13

Cascade-evaporation model 1-3
Cataractogenesis 1-22, 1-23, 1-29
Cataracts 1-24, 1-27
Cell damage 1-17, 1-26
Cell inactivation 1-25
Cell survival 1-20
Cell-hit frequency 1-5
Cellular radiosensitivity 1-16
Cellular track model 1-17
Chromatin 1-18
Chromosome aberration 1-25
Computerized Anatomical Man Model
    1-12
Cornea 1-26
Cosmic ray 1-4, 1-9
Cosmos-2044 1-8, 1-9, 1-10
CR-39 1-9, 1-10, 1-14
CREME model 1-4, 1-30

Damage repair 1-25
Delta ray 1-6
Depth-dose distribution 1-33
Differential energy spectrum 1-9
DNA repair 1-16, 1-19
Dose 1-7, 1-17, 1-25, 1-30, 1-32
Dose distribution 1-30, 1-32
Dose threshold 1-32
Dose-effect 1-26
Dose-equivalent 1-7, 1-12, 1-30, 1-31
Dosimetry 1-3, 1-30, 1-31, 1-33
Double strand break 1-18

Electromagnetic cross section 1-4
Electron 1-25
Electrophysiology 1-26

Endometriosis 1-21, 1-25
Energy interval 1-9
Epithelial cell 1-17
Eye 1-24, 1-29

Fluence spectra 1-11
Fluence-related risk coefficient 1-20
Fragmentation 1-3, 1-4, 1-13, 1-33
Fragmentation experiment 1-3
Free-radical 1-19

Galactic cosmic rays 1-20
Galactic proton 1-10
Gamma rays 1-23
GCR 1-4, 1-5, 1-6, 1-7, 1-8, 1-10, 1-12,
    1-13, 1-32
Genetics 1-19, 1-25

Heavy charged particle 1-22, 1-24
Heavy ion 1-23
Heavy ion collision 1-3
Heavy ion fragmentation 1-11
Heavy ion transport 1-11
HETC code 1-31
High-LET 1-5, 1-17, 1-20, 1-25, 1-26
HZE 1-13

ICRP-51 1-31
Inactivation cross section 1-20
Inverse dose rate 1-19, 1-23
Ionizing radiation 1-7, 1-10
Iron ion 1-26
Irradiation 1-33
Isodose distribution 1-32

Lens 1-7
Lens epithelial fragment 1-27
Lens opacification 1-22, 1-24, 1-29
LET 1-10, 1-11, 1-20, 1-30
Life shortening 1-21
Long Duration Exposure Facility 1-7
Long-duration space mission 1-6
Lunar mission 1-4

KEYWORD INDEX

KEYWORD INDEX

AUTHOR INDEX

AUTHOR INDEX

AUTHOR INDEX

TABLE OF CONTENTS
REPORTS/MEETINGS

1. PHYSICS

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THEORY

Cucinotta, F.A., Townsend, L.W., Wilson, J.W., and Norbury, J.W. (1991) *Corrections to the Participant-Spectator Model of High-Energy Alpha-Particle Fragmentation.* **NASA Technical Memorandum 4262.**

Nuclear fragmentation, Participant-spectator model, Triangle graph model, Model development

The participant-spectator model of nuclear fragmentation is described in terms of pole graphs from direct reaction theory. Corrections to the model for more than one projectile fragment scattering on the target are considered using a triangle graph model. Results for alpha-particle fragmentation at 1 GeV/A indicate that corrections to the participant-spectator model are significant, as indicated by the large interference effects found between the pole and triangle graph terms in the double- and single-differential cross sections.

Cucinotta, F.A., Townsend, L.W., and Wilson, J.W. (1991) *Target Correlation Effects on Neutron-Nucleus Total, Absorption, and Abrasion Cross Sections.* **NASA Technical Memorandum 4314.**

Heavy ions, Nuclear fragmentation, Cross section correlation

Second-order optical model solutions to the elastic scattering amplitude were used to evaluate total, absorption, and abrasion cross sections for neutron-nucleus scattering. Improved agreement with experimental data for total and absorption cross sections is found when compared with first-order (coherent approximation) solutions, especially below several hundred MeV. At higher energies, the first- and second-order solutions are similar. There are also large differences in abrasion cross-section calculations; these differences indicate a crucial role for cluster knockout in the abrasion step.

John, S., Tripathi, R.K., and Townsend, L.W. (1992) Geometric model for nuclear absorption from microscopic theory. *Bulletin of the American Physical Society* 37(2): 901.

Glauber theory, Transparency, Nucleon cross section

The nuclear absorption cross-section from Glauber theory is recast in an energy dependent form of the Bradt-Peters type. This form is based on an asymptotic evaluation of the integral for the transparency function $\exp[-2 \, \mathrm{Im} \, \chi(b)]$ which peaks for peripheral collisions. It is also shown that Gaussian-shaped variations of the surface density make the energy dependent term a function only of the skin thickness and independent of the sizes of the colliding nuclei.

Khan, F., Tripathi, R.K., and Townsend, L.W. (1992) Argon fragmentation at 1.65 A GeV. III. Momentum distributions. *Bulletin of the American Physical Society* 37(2): 1003.

Argon ions, Optical model

An optical model description of momentum transfer in intermediate and high energy, heavy ion collisions is used within the Goldhaber formalism to analyze transverse and longitudinal momentum distributions of projectile fragments produced by 1.65 A GeV argon ions fragmenting in carbon and KCl targets. Comparisons with recent measurements will be made. The observed longitudinal-transverse asymmetry of the momentum widths and shifts can be understood from the behavior of the underlying NN transition matrix.

Townsend, L.W., Kahn, F., and Tripathi, R.K. (1992) Argon fragmentation at 1.65 A GeV. I. Optical model cross sections. *Bulletin of the American Physical Society* 37(2): 1002.

Optical model, Argon ions

An optical potential abrasion-ablation-FSI collision model is used to calculate elemental and isotopic production cross sections for 1.65 A GeV argon ions fragmenting in carbon and KCl targets. Comparisons with recent measurements using the HISS detector will be made.

Townsend, L.W., Wilson, J.W., Tripathi, R.K., Norbury, J.W., and Khan, F. (1992) NUCFRAG: A semiempirical HZE particle fragmentation model. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Nuclear fragmentation, HZE particles, Transport model

A semiempirical, abrasion-ablation nuclear fragmentation model for use in HZE (high energy heavy ion) particle transport, shielding, and interaction studies is presented. Electromagnetic dissociation contributions to the single-nucleon removal cross sections are included in the model. Comparisons with recently published elemental, isobaric, and isotopic fragmentation cross-section measurements will be made. Additional improvements to the model will be discussed.

Tripathi, R.K., Townsend, L.W., and Kahn, F. (1992) Argon fragmentation at 1.65 A GeV. II. Semiempirical model cross sections. *Bulletin of the American Physical Society* 37(2): 1002-1003.

Transport calculation, Argon ions

The semiempirical, abrasion-ablation nuclear fragmentation model NUCFRG is used to calculate isotope production cross sections for 1.65 A GeV argon beams

fragmenting in carbon and KCl targets. Comparisons with recent measurements obtained using the HISS detector will be made.

COSMIC RAY AND ASTROPHYSICS

Adams, J.H., Jr. (1992) A Report on the Workshop on Galactic Cosmic Radiation at the 22nd International Cosmic Ray Conference. In: *Space Biology and Aerospace Medicine*, **p. 181-187.**

Mars, Lunar mission, GCR, Radiation hazard

A workshop entitled "Cosmic Radiation: Constraints on Space Exploration" was held at the 22nd International Cosmic Ray Conference on Friday, 16 August 1991. The motivation for the workshop was to access the potential hazard posed by galactic cosmic rays to interplanetary travel. Its purpose was to provide an opportunity for cosmic ray physicists to report measurements of the absolute galactic cosmic ray flux and to describe models of the galactic ray spectra that have been developed.

Adams, J.H., Jr., Badhwar, G.D., Mewaldt, R.A., Mitra, B., O'Neill, P.M., Ormes, J.F., Stemwedel, P.W., and Streitmatter, R.E. (1991) The absolute spectra of galactic cosmic rays at solar minimum and their implications for manned space flight. Presented at the 22nd International Cosmic Ray Conference, Dublin, Ireland, August 11-23, 1991.

GCR, Long-duration space mission, Radiation environment

The radiation dose from galactic cosmic rays during a proposed mission to Mars is near the annual dose limit for the crew. Since the absolute spectra of galactic cosmic rays critically influences mission planning and spacecraft design, these spectra must be determined as accurately as possible. We have fit published measurements with solutions of the spherically symmetric diffusion equation to made accurate representations of the spectra. We report preliminary determinations on the absolute differential energy spectra at 1 AU and discuss the implications for the proposed missions to Mars.

Csige, I., Benton, E.V., Soundararajan, S., and Benton, E.R. (1992) Light-heavy ion measurements in CR-39 located on the Earth side of LDEF. Presented at the Second LDEF Post-Retrieval Symposium, San Diego, CA, June 1-5, 1992.

Long Duration Exposure Facility, Azimuthal angle, Radiation detector, CR-39, PNTD

The azimuthal angle distribution and the charge and energy spectra of selected light-heavy ($5 \leq Z \leq 8$) stopping particles were measured in a single layer of CR-39 plastic nuclear track detector (PNTD) from the stack of the A0015 experiment located on the Earth-end of the LDEF satellite. The directional incidence of the trapped protons is studied by comparing the azimuthal angle distribution of

selected recoils, obtained in the LDEF detectors, to that obtained through calibrations of PNTDs with exposures performed with 200 MeV proton beams from different directions.

ENVIRONMENTS AND ENVIRONMENTAL MODELS

Adams, J.H., Jr., Badhwar, G.D., Letaw, J.R., Silberberg, R., and Tsao, C.H. (1992) Dose equivalent from cosmic rays in deep space. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 568.

Dose equivalent, GCR, Radiation shielding, Cosmic rays

We have calculated the dose equivalent (DE) in deep space due to galactic cosmic rays. The DE has been calculated at a depth of 5 cm in tissue within spherical aluminum shields of various thicknesses. In addition to the most probable values, upper limits on the DE are given at a 90% confidence level. Both uncertainties in the cosmic ray flux and uncertainties in the nuclear cross sections were considered in determining this upper limit. Results are given at various phases of the solar activity cycle.

Adams, J.H., Jr. and Lee, J. (1992) Radiation exposures on manned missions to Mars. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Radiation exposure, GCR, Model development

We will describe efforts during the last year to improve the accuracy of radiation exposure estimates in manned missions to Mars. We are participating in a collaboration to develop an accurate model of galactic cosmic ray environment. A status report on this work will be given. We have begun to investigate the uncertainties in exposure estimates. The uncertainties due to knowledge of the galactic cosmic ray flux will be discussed. We have also begun an investigation of the uncertainties due to knowledge of the nuclear cross sections used in the transport of the radiation through the walls of the spacecraft. Initial results on these uncertainties will also be described.

Badhwar, G.D., Braby, L.A., Konradi, A., Atwell, W., and Cucinotta, F.A. (1992) Measurements of trapped protons and cosmic rays from recent Shuttle flights. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 572.

Dosimetry, Shuttle flight, Tissue equivalent proportional counter (TEPC), Proton, AP8MAX

We have flown two new charged particle detector systems in a number of recent Shuttle flights. The tissue equivalent proportional counter measures the lineal energy spectrum of space radiation in the 0.26-300 keV/μm range. The charged particle spectrometer is a double dE/dx x E and dE/dx x Cerenkov detector

system, that provides a measurement of the differential energy spectrum of protons from 13 to 350 MeV and the dose rate in silicon. We report on the dose rate, dose equivalent rate, and quality factor for trapped protons and cosmic radiation. A comparison of the integral LET spectra, with recent transport code calculations, shows significant disagreement. Using the dose rate from the omnidirectional AP8MAX model (IGRF reference magnetic field epoch 1970), and the observed dose rate as a function of geographic latitude and longitude, the predicted westward drift of the South Atlantic anomaly has been measured.

Benton, E.V. (1991) Space radiation dosimetry. Presented at the 9th IAA Man In Space Symposium, Cologne, Germany, June 17-21, 1991.

Dosimetry, Russian spacecraft

Exposure to ionizing radiation of space crews engaged in extended space missions such as space stations, moon bases and travel to Mars, poses a set of complex scientific and technological problems which need to be resolved before adequate radiation protection can be achieved. Radiobiologists need to address a number of problems including those of investigating the induction of lesions such as mutations, cancers and cataracts. Physicists need to provide adequate radiation measurements and to understand the complex radiation environment and the effects of shielding on the different components of the incoming radiations. Both physicists and radiobiologists need to address the suggestion that the dose and dose rate are not appropriate quantities in which to express the radiation exposure in space. Rather, for some organs, the fluence and fluence rate of particles could be the more appropriate quantities. Past and current radiation measurements obtained on board US and Soviet spacecraft will be presented. This data and subsequent analysis will have an important bearing on the design of future spacecraft and the conduct of future space missions.

Nealy, J.E., Simonsen, L.C., and Striepe, S.A. (1992) Natural radiation environment fluence and dose predictions for missions to the moon and Mars. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding,* **Pasco, WA, April 26-May 1, 1992, p. 181-187.**

Natural radiation environment, Mars, Lunar mission

A computational procedure and associated data base are described that can be used to estimate particle fluence and resultant exposure for lunar and interplanetary missions. The data base contains modeled environments for galactic cosmic rays, large solar proton events, and ordinary solar proton flares. Available options and required inputs for the algorithm are described, and results from applications to both Mars and lunar missions are presented. Comparisons of modeled dose estimates for the Apollo lunar missions with reported flight data are shown to be generally favorable.

Shea, M.A., Nealy, J., Wilson, J., and Smart, D.F. (1992) Proton flare and magnetic storm effects in the vicinity of the Earth. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 562.

Model development, Transmission function, Radiation exposure

We have developed a model and associated computational procedure for estimating energetic proton exposures during a major solar proton event in combination with a large magnetic storm. Transmission functions for solar protons are computed using geomagnetic vertical cutoff data for both quiescent and disturbed conditions. Predicted exposures in low altitude polar orbit are found to be orders of magnitude greater for severe magnetic storm conditions than are corresponding exposures in the absence of major disturbances. We examine the response scenario for the events of November 1960 as an example. The transitory nature of such enhanced exposures is also examined and found to be strongly dependent on geographic location with respect to both latitude and longitude. The model developed should be useful in analyses of dose enhancements for both orbiting spacecraft and high-altitude aircraft.

Watts, J.W., Parnell, T.A., Derrickson, J.H., Armstrong, T.W., and Benton, E.V. (1992) Prediction of LDEF ionizing radiation environment. In: *LDEF— 69 Months In Space*, Ed. A.S. Levine. NASA Conference Publication 3134, Part 1, p. 213-224.

Long Duration Exposure Facility, Radiation shielding, Radiation detector

The LDEF spacecraft flew in a 28.5° inclination circular orbit with an altitude in the range from 172 to 258.5 nautical miles. For this orbital altitude and inclination two components contribute most of the penetrating charge particle radiation encountered—the galactic cosmic rays and the geomagnetically trapped Van Allen protons. Where shielding is less than 1.0 g/cm^2 geomagnetically trapped electrons make a significant contribution. The "Vette" models together with the associated magnetic field models were used to obtain the trapped electron and proton fluences. The mission proton doses were obtained from the fluence using the Burrell proton dose program. For the electron and bremsstrahlung dose we used the MSFC electron dose program. The predicted doses were in general agreement with those measured with on-board thermoluminescent detector (TLD) dosimeters. The NRL package of programs, CREME, was used to calculate the linear energy transfer (LET) spectrum due to galactic cosmic rays (GCR) and trapped protons for comparison with LDEF measurements.

Wilson, J.W. and Nealy, J.E. (1992) Model and data base for background radiation exposure of high-altitude aircraft. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding*, Pasco, WA, April 26-May 1, 1992, p. 425-441.

Radiation risk, Model development, Model verification

An extensive data base on atmospheric radiations was generated by a measurements program extending from solar cycle XIX through cycle XX. A time dependent atmospheric radiation model is derived for use in aircraft radiation monitoring. According to newly proposed protection standards, crew counciling on associated risk seems advisable.

SOLAR ACTIVITY AND PREDICTION

Cucinotta, F.A., Townsend, L.W., Wilson, J.W., Golightly, M.J., and Weyland, M. (1992) Analysis of radiation risk from alpha particle component of solar particle events. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 561-562.

Solar particle event, Alpha particle, Radiation shielding, Fragmentation, LET, GOES-7

The large solar particle events (SPE) will contain a primary alpha particle component, representing a possible increase in the potential risk to astronauts during an SPE over the often studied proton component. We discuss the physical interactions of alpha particles important in describing the transport of these particles through spacecraft and body shielding. Models of light ion reactions, such as fragmentation and stripping, are presented and their effects on energy and linear energy transfer (LET) spectra in shielding discussed. Using measured spectra from the Geostationary Operational Satellite (GOES-7), we present predictions of particle spectra, dose and dose equivalent in organs of interest for several of the largest SPE occurring in recent solar cycles.

Simonsen, L.C., Atwell, W., Nealy, J.E., and Cucinotta, F. (1992) *Radiation Dose to Critical Body Organs for October 1989 Proton Event.* NASA Technical Paper 3237.

Computerized anatomical model, October 1989 solar proton event, Radiation shielding, GOES-7, Solar particle event, Proton flux, Risk assessment

The Geostationary Operation Environmental Satellite (GOES-7) provides high-quality environmental data about the temporal development and energy characteristics of the protons emitted during a solar particle event. The GOES-7 time history of the hourly averaged integral proton flux for various particle kinetic energies are analyzed for the solar proton event occurring October 19-29, 1989. This event is similar to the August 1972 event that has been widely studied to estimate free-space and planetary radiation-protection requirements. By

analyzing the time-history data, the dose rates, which can vary over many orders of magnitude in the early phases of the flare, can be estimated as well as the cumulative dose as a function of time. When basic transport results are coupled with detailed body organ thickness distributions calculated with the Computerized Anatomical Man and Computerized Anatomical Female models, the dose rates and cumulative doses to specific organs can be predicted. With these results, the risks of cancer incidence and mortality are estimated for astronauts in free space protected by various water shield thicknesses.

Simonsen, L.C., Cucinotta, F.A., Atwell, W., and Nealy, J.E. (1992) Time analysis of the October 1989 proton flare using computerized anatomical models. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding*, Pasco, WA, April 26-May 1, 1992, p. 212-219.

GOES-7, Computerized anatomical model, Transport code, Water, Radiation risk, Radiation shielding

The GOES-7 time history data of hourly-averaged integral proton fluxes at various particle kinetic energies are analyzed for the solar proton event occurring between October 19-29, 1989. By analyzing the time-history data, the dose rates which may vary over many orders of magnitude in the early phases of the flare can be predicted as well as the cumulative dose as a function of time. Basic transport calculations are coupled with detailed body organ thickness distributions from computerized anatomical models to predict dose rates and cumulative doses to 20 critical body organs. For a 5-cm thick water shield, cumulative skin, eye, and blood-forming organ dose equivalents of 127 cSv, 123 cSv, and 41 cSv, respectively, are estimated. These results are approximately 40-50 percent less than the widely used 0- and 5-cm slab dose estimates. The risk of cancer incidence and mortality are also estimated for astronauts protected by various water shield thicknesses.

Simonsen, L.C., Nealy, J.E., Sauer, H.H., and Townsend, L.W. (1991) Solar flare protection for manned lunar missions: Analysis of the October 1989 proton flare event. Presented at the 21st International Conference on Environmental Systems, San Francisco, CA, July 15-18, 1991, 11 p. SAE Paper 911351.

GOES-7, Manned space station, Radiation shielding, Lunar mission

Several large solar proton events occurred in the latter half of 1989. For a moderately shielded spacecraft in free space, the potential exposure would have been greatest for the flare which occurred between October 19 to 27, 1989. This flare was comparable to the large flare event of August 1972. The temporal variations of the proton energy spectra at approximately 1 AU were monitored by the GOES-7 satellite. These data, recorded and processed at the NOAA-Boulder Space Environment Laboratory, provide the opportunity to analyze dose rates and cumulative doses which might be incurred by astronauts in transit to, or on, the moon. Of particular importance in such an event is the time development of

exposure in the early phases of the flare, for which dose rates may range over many orders of magnitude in the first few hours. Consequently, special attention is given to the early time variation of the dose rate. The cumulative dose as a function of time for the entire event is also predicted. In addition to basic shield calculations, dose rate contours are constructed for flare shelters in free-space and on the lunar surface. For longer duration lunar missions, the impact of such a flare exposure is assessed in relation to the predicted steady dose rate of the galactic cosmic rays.

Townsend, L.W., Cucinotta, F.A., and Wilson, J.W. (1992) Estimates of HZE particle contributions to SPE radiation exposures on interplanetary missions. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 562.

HZE particles, Solar particle event, Transport code, Radiation shielding, HZETRN

Estimates of radiation doses resulting from a possible HZE (high energy heavy ion) component of solar particle events (SPEs) are presented for crews of manned interplanetary missions. The calculations use an assumed model spectrum obtained by folding solar flare HZE particle abundances, measured at low energies, with the measured energy spectra of SPE alpha particles. These hypothetical HZE SPE spectra are then transported through aluminum spacecraft shielding using the Langley Research Center space radiation transport code (HZETRN). The results are presented as estimates of absorbed dose and dose equivalent, as a function of aluminum shield thickness, for the skin, ocular lens, and bone marrow. The sensitivities of the predicted doses to the assumed spectral hardness parameters will also be discussed.

Weyland, M.D., Atwell, W., Cucinotta, F.A., Wilson, J.W., and Hardy, A.C. (1991) *Analyses of Risks Associated with Radiation Exposure from Past Major Solar Particle Events*. NASA Technical Paper 3137.

Radiation risk, Baryon transport code, Radiation shielding, Solar particle event

This study investigated radiation exposures and cancer induction/mortality risks for several major solar particle events (SPEs). The SPEs included in this study are February 1956, November 1960, August 1972, October 1989, and September, August, and October 1989 (combined). The three 1989 events were treated as one since all three could affect a single lunar or Mars mission. A baryon transport code was used to propagate particles through aluminum and tissue shield materials. This study used a free space environment for all calculations. Results show the 30-day blood forming organs (BFO) limit of 25 rem was surpassed by all five events using 10 g/cm^2 of shielding. The BFO limit is based on a depth dose of 5 cm of tissue, while this study used a more detailed shield distribution of the BFO. A comparison between the 5 cm depth dose and the dose found using the BFO shield distribution shows the 5 cm depth value slightly higher than the BFO dose. The annual limit of 50 rem was exceeded by the August 1972, October 1989, and three combined 1989 events with 5 g/cm^2 of shielding. Cancer mortality risks ranged from 1.5 to 17% at 1 g/cm^2 and 0.5 to

1.1% behind 10 g/cm^2 of shielding for the five events. These ranges correspond to those for a 45-year old male. It is shown that secondary particles comprise about 1/3 of the total risk at 10 g/cm^2 of shielding. Using a computerized Space Shuttle shielding model to represent a typical spacecraft configuration in free space at the August 1972 SPE, average crew doses exceeded the BFO limit.

EXPERIMENTS

Armstrong, T.W., Colborn, B.L., Harmon, B.A., Parnell, T.A., Watts, J.W., Jr., and Benton, E.V. (1992) Comparison of model predictions with LDEF satellite radiation measurements. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 569.

Long Duration Exposure Facility, Model development, Doses, Radiation measurement

Data from radiation dosimeters aboard the LDEF satellite, as well as measurements of the radioactivity induced in numerous spacecraft components, are being utilized to evaluate the accuracy of models currently in use for predicting ionizing radiation environments and effects for low Earth orbit missions. The extensive LDEF radiation results allow validation of several types of models to be made, including those for predicting the trapped proton flux environment, anisotropy of the trapped proton exposure, GCR environment, absorbed dose and LET spectra at various shielding thicknesses, and secondary particle fluxes. Assessments of model accuracies based on comparisons with these LDEF radiation measurements will be reported.

Benton, E.V., Csige, I., Frank, A.L., Benton, E.R., Parnell, T.A., Derrickson, J., Harmon, A., Fishman, G., Watts, J., and Armstrong, T.W. (1992) Radiation and activation measurements performed on LDEF. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 569.

Long Duration Exposure Facility, Radiation detector, Model development, Activation measurement, LET, Space Station Freedom

The ionizing radiation measurements flown on the LDEF were contained in some 15 experiments which utilized passive detectors to measure the radiation environment and to pursue objectives in astrophysics. The spacecraft structure became sufficiently radioactive to permit extensive measurements of induced activity. Radiation and activation measurements allowed extensive radiation mapping of the structure, independent intercomparisons, and tests of radiation environmental models. The long exposure of some 5.8 years, attitude stability and number and types of measurements produced a unique and critical set of data for low Earth orbit that will not be duplicated for more than a decade. The results have clearly shown the effects from the directional properties of the

radiation environment and have influenced some design requirements of Space Station Freedom.

Benton, E.V., Csige, I., Oda, K., Henke, R.P., Frank, A.L., Benton, E.R., Frigo, L.A., Parnell, T.A., Watts, J.W., Jr., and Derrickson, J.H. (1992) LET spectra measurements of charged particles in the P0006 experiment on LDEF. Presented at the Second LDEF Post-Retrieval Symposium, San Diego, CA, June 1-5, 1992.

Long Duration Exposure Facility, PNTD, Radiation detector, Risk assessment, CR-39, GCR, Space Station Freedom, Dosimetry

Measurements are under way of the charged particle radiation environment of the LDEF satellite using stacks of plastic nuclear track detectors (PNTDs) placed in different locations of the satellite. In the initial work the charge, energy and linear energy transfer (LET) spectra of charged particles were measured with CR-39 double layer PNTDs located on the west side of the satellite (Experiment P0006). Primary and secondary stopping heavy ions were measured separately from the more energetic particles. Both trapped and galactic cosmic ray (GCR) particles are included, with the latter component being dominated by relativistic iron particles.

The results from the P0006 experiment will be compared with similar measurements in other locations on LDEF with different orientation and shielding conditions.

The remarkably detailed investigation of the charged particle radiation environment of the LDEF satellite will lead to a better understanding of the radiation environment of the Space Station Freedom. It will enable more accurate prediction of single event upsets (SEUs) in microelectronics and, especially, more accurate assessment of the risk — contributed by different components of the radiation field (GCRs, trapped protons, secondaries and heavy recoils, etc.) — to the health and safety of crew members.

Benton, E.V., Frank, A.L., Benton, E.R., Csige, I., Parnell, T.A., and Watts, J.W., Jr. (1992) Radiation exposure of LDEF: Initial results. In: *LDEF—69 Months in Space*, Ed. A.S. Levine. NASA Conference Publication 3134, Part 1, p. 325-337.

Long Duration Exposure Facility, Radiation shielding, Radiation detector, Thermoluminescent detector, PNTD

Initial results from LDEF include radiation detector measurements from four experiments, P0006, P0004, M0004 and A0015. The detectors were located on both the leading and trailing edges of the orbiter and also at the Earthside end. This allowed the directional dependence of the incoming radiation to be measured. Total absorbed doses from thermoluminescent detectors (TLDs) verified the predicted spatial east-west dose ratio dependence of a factor ~2.5, due to trapped proton anisotropy in the South Atlantic Anomaly (SAA). On the

trailing edge of the orbiter a range of doses from 6.64 to 2.91 Gy were measured under Al equivalent shielding of 0.42 to 1.11 g/cm^2. A second set of detectors near this location yielded doses of 6.48 to 2.66 Gy under Al equivalent shielding of 0.48 to 15.4 g/cm^2. On the leading edge doses of 2.58 to 2.10 Gy were found under Al equivalent shielding of 1.37 to 2.90 g/cm^2. Initial charged particle LET (linear energy transfer) spectra, fluxes, doses, and dose equivalents, for LET in $H_2O \geq 8$ keV/μm, have been measured with plastic nuclear track detectors (PNTDs) located in two experiments. Also preliminary data on low energy neutrons were obtained from detectors containing ^{6}LiF foils.

Benton, E.V., Frank, A.L., Henke, R.P., and Benton, E.R. (1992) Dosimetric measurements on STS and the Mir space station. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

High-LET, Dosimetry, PNTD, Mir, STS-42, Radiation shielding, Radiation detector, HZE, Passive dosimetry, RME III, Biostack

High-LET dosimetry is being conducted on STS missions and the Mir space station and is further being refined. In the past 12 months 7 STS missions were supported, with a particular emphasis on STS-42. Here, passive systems were flown a) for intercomparison with the RME-III instrument, b) as part of the ESA Biostack, and c) in support of the JPL nematode experiment. Significant progress was made in the development and implementation of an automated track analysis system for the analysis of the HZE particle exposures of plastic nuclear track detectors. The system works well on detectors exposed to particle beams at accelerators and initial trials of the system on space-exposed detectors are now under way. Several packages of passive detectors were flown for four months on the Mir space station. The objectives included the measurement of the LET spectra both inside and outside the Mir, and the attenuation of dose as a function of shielding on the outside of the spacecraft. This information is being used in refining the predictive codes for the radiation environment. Intercalibrations of active and passive systems including RME-III, TEPC and PNTDs are planned, using accelerator facilities.

Csige, I., Benton, E.V., Frank, A.L., Frigo, L.A., Benton, E.R., Parnell, T.A., and Watts, J.W., Jr. (1992) Charged particle LET-spectra measurements aboard LDEF. In: *LDEF—69 Months in Space*, Ed. A.S. Levine. NASA Conference Publication 3134, Part 1, p. 339-348.

High-LET, PNTD, Radiation detector, Radiation shielding, Long Duration Exposure Facility, CR-39, GCR

The linear energy transfer (LET) spectra of charged particles has been measured in the 5-250 keV/μm (water) interval with CR-39 and in the 500-1500 keV/μm (water) interval with polycarbonate plastic nuclear track detectors (PNTDs) under different shielding depths in the P0006 experiment. The optimal processing conditions were determined for both PNTDs in relation to the relatively high track

densities due to the long-term exposure in space. The total track density was measured over the selected samples, and tracks in coincidence on the facing surfaces of two detector sheets were selected for measuring at the same position on each sheet. The short range (SR) and Galactic Cosmic Ray (GCR) components were measured separately with CR-39 PNTDs and the integral dose and dose rate spectra of charged particles were also determined. The high LET portion of the LET spectra was measured with polycarbonate PNTDs with high statistical accuracy. This is a unique result of this exposure due to the low flux of these types of particles for typical spaceflight durations. The directional dependence of the charged particles at the position of the P0006 experiment was also studied by four small side stacks which surrounded the main stack and by analyzing the dip angle and polar angle distributions of the measured SR and GCR particle tracks in the main stack.

Heinrich, W., Benton, E.V., Wiegel, B., Rusch, G., and Becker, E. (1992) Comparison of measured cosmic ray LET-spectra with models and predictions. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research***, Washington, D.C., August 28-September 5, 1992, p. 546.**

LET, Dosimetry, Model development

Radiation effects of cosmic ray nuclei are in general described as a function of the LET of these particles. Results of dosimetric measurements in space are generally presented in form of LET-spectra. Cosmic ray models considering effects of geomagnetic shielding and shielding by matter provide a more detailed information in form of energy spectra of individual elements. In this paper measured and calculated LET-spectra are compared for orbits ranging from 28° to 83° inclination and for outer space. Differences between models and experimental data are discussed and objectives for more detailed experimental investigations and improvements of the models are derived from this comparison.

Heinrich, W., Wiegel, B., and Benton, E.V. (1992) Galactic cosmic ray abundances and spectra behind defined shielding. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research***, Washington, D.C., August 28-September 5, 1992, p. 567.**

LET, Radiation detector, Model development, Radiation shielding, Lunar mission, GCR

Particle LET-spectra were measured on Apollo lunar missions and for several near-Earth orbits ranging from 28° to 83° inclination. In some cases the LET spectra is separable from contributions by GCR and by particles produced in interactions in detector material. Results of these measurements are compared with model calculations. A general agreement justifies the use of the model to calculate GCR fluxes. Systematics of the variations caused by solar modulation, geomagnetic shielding and shielding by matter are determined from calculated LET-spectra. The model additionally allows investigation in more detail of the influence of different shielding on energy spectra and elemental composition of GCR.

Nelson, G.A., Schubert, W., Kazarians, G., Richards, G., Benton, E.V., Benton, E.R., and Henks, R. (1992) Radiation effects in nematodes. Results from IML-1 experiments. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 572.

IML-1, Nematode, ESA Biorack, STS-42, HZE particles, Mutation, Genetics, CR-39, Animal models, PNTD

The nematode *Caenorhabditis elegans* was exposed to natural space radiation using the ESA Biorack facility aboard Spacelab on International Microgravity Laboratory 1, STS-42. For the major experimental objective dormant animals were suspended in buffer or immobilized next to CR-39 plastic nuclear track detectors to correlate fluence of HZE particles with genetic events. This configuration was used to isolate mutations in a set of 350 essential genes as well as in the *unc-22* structural gene. IML-1 results are compared with observations from accelerator experiments. For the secondary objectives growing populations of genetically marked animals were used to investigate chromosome mechanics and development +/- gravity. Mendelian segregation ratios from linked and unlinked double mutants were measured and anatomical comparisons of flight and ground control animals were made.

Parnell, T.A., Benton, E.V., and Armstrong, A.W. (1992) The ionizing radiation environment of the Long Duration Exposure Facility. Presented at the 22nd International Conference on Environmental Systems, Seattle, WA, July 13-16, 1992.

Long Duration Exposure Facility, Radiation detector, Space Station Freedom

The Long Duration Exposure Facility (LDEF) orbited at 28.5° between 478 and 318 km for 5.8 years. Its altitude was stable with respect to Earth and flight direction, as planned for Space Station Freedom. The accumulated radiation dose ranged from ~500 kilorads at the surface, principally from trapped electrons, to ~200 rads in the interior, mostly due to trapped protons. Cosmic rays contributed ~10 rads, and significantly influenced the linear energy transfer (LET) spectra and the production of neutrons. The radiation environment was characterized by passive detectors carried in 15 experiments which measured absorbed dose, fluence and spectra of heavy nuclei and neutrons, LET spectra, and induced radioactivity. The induced radioactivity was also measured in ~400 samples of the spacecraft structure.

Only a few effects on materials or devices have been reported as possibly due to radiation, which is consistent with the relatively low accumulated dose. However, probable genetic effects have been reported from the experiments containing seeds and biological samples. The measurements and analysis of the ionizing radiation, and the effects that may be attributed to radiation will be described.

RADIATION TRANSPORT AND SHIELDING

Conway, E.J. and Townsend, L.W. (1991) Radiation shielding in transit to Mars and on the surface. Presented at the AIAA Conference on Mars Exploration: Past, Present and Future, Williamsburg, VA, July 17-19, 1991, 9 p. AIAA Paper 91-3010.

Radiation shielding, Space radiation, Mars, Space Station Freedom, Radiation limit

This interim report on the development of deep-space radiation shielding technology provides a brief review of the radiation environment and the issues associated with radiological limits for space crews. Shielding technology development involves assessing a variety of materials and strategies for providing adequate protection through the development of accurate computer codes to estimate exposure and a materials data base to define complex shields, to improve and validate codes, and to support mission studies. Based on preliminary data, the dose accumulated behind a water shield during a 500-day mission to Mars is found to be within current Space Station Freedom exposure limits.

Miller, J. (1992) Nuclear fragmentation and the space radiation problem. Presented at the International Workshop on Biological Applications of Relativistic Nuclei (B.A.R.N. 92), Clermont-Ferrand, France, October 14-16, 1992.

GCR, HZE transport, Shielding, Fragmentation

We will discuss the role of nuclear fragmentation in the general problem of radiation risk to personnel on long-duration missions outside the geomagnetosphere. Moderately heavy nuclei ($Z \leq 26$) comprise a significant component of the dose-weight Galactic Cosmic Ray (GCR) flux, and since mean free paths for nuclear fragmentation are of the order of the ranges of primary GCR nuclei, determination of the radiation field produced by successive fragmentation of nuclei in material and tissue is essential to an accurate assessment of the high energy heavy ion contribution to space radiation effects. We will describe an iterative program for assessing and mitigating the effects of the primary and higher order heavy ion GCR flux. The physics component of this program incorporates both theory (in the form of heavy ion transport calculations) and measurements. We will summarize the existing nuclear fragmentation data for the nuclei and energies of interest and present the results of some resent heavy ion fragmentation experiments and comparisons with transport theory. Lastly, we will show some examples of the interplay between physics and biology: for example, how measured and/or simulated fragment fluences might be used to predict the biological effects of high energy heavy ions.

Shavers, M.R., Miller, J., Schimmerling, W., Wilson, J.W., and Townsend, L.W. (1992) Multi-generation transport theory as an analytical heavy-ion transport model. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding*, Pasco, WA, April 26-May 1, 1992, p. 198-210.

Transport model, LBLBEAM, Fluence, LET, Neon ions, Water, Boltzmann equation, Radiation shielding

Transport models used to describe the charged-particle radiation environment resulting from interactions of galactic cosmic ray heavy-ions with spacecraft shielding can be validated by comparing model predictions with data from experiments at particle accelerators on Earth. In this study, the one-dimensional heavy-ion transport model LBLBEAM is used to predict the fluence and linear-energy-transfer spectra of nuclear fragments emitted from interactions of 670A MeV Neon-20 incident on a thick water target. Analytical solutions of model, based on Boltzmann transport theory, are compared with experimental data using a comparison algorithm which considers detector characteristics. Reasonable agreement between the theory and data is observed. The experimental methods and the procedure for comparing accelerated heavy-ion beams with theory are shown to be quite useful for validating transport models.

Shinn, J.L. and Wilson, J.W. (1992) *An Efficient HZETRN (A Galactic Cosmic Ray Transport Code)*. NASA Technical Paper 3147.

Radiation shielding, HZE, Radiation environment, HZETRN, Transport code

To meet the challenge of the future deep-space program, which involves extended manned space missions, an accurate and efficient engineering code for analyzing the shielding requirement against the high-energy galactic heavy ions is needed. The HZETRN is a deterministic code developed at Langley Research Center that is constantly under improvement both in physics and numerical computation and is targeted for such use. One problem area connected with the space-marching technique used in this code is the propagation of the local truncation error. By improving the numerical algorithms for interpolation, integration, and grid distribution formula, the efficiency of the code is increased by a factor of eight as the number of energy grid points is reduced. The numerical accuracy of better than 2 percent for a shield thickness of 150 g/cm^2 is found when a 45-point energy grid is used. The propagating step size, which is related to the perturbation theory, is also reevaluated.

Wilson, J.W. and Badavi, F.F. (1992) New directions in heavy ion shielding. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding*, Pasco, WA, April 26-May 1, 1992, p. 205-211.

Green's function, Transport code

An analytic solution to the heavy ion transport equation in terms of Green's function is used to generate a highly efficient computer code for space applications. The code may also be applied to accelerator boundary conditions to allow code validation in laboratory experiments.

Wilson, J.W., Chun, S.Y., Badavi, F.F., Townsend, L.W., and Lamkin, S.L. (1991) *HZETRN: A Heavy Ion/Nucleon Transport Code for Space Radiations*. NASA Technical Paper 3146.

Shielding, GCRTRN, BRYNTRN, HZETRN, Heavy ions, Boltzmann equation, Radiation shielding, Transport code, Nucleon cross section

The galactic heavy ion transport code (GCRTRN) and the nucleon transport code (BRYNTRN) are integrated into a code package (HZETRN). The code package is computer efficient and capable of operating in an engineering design environment for manned deep space mission studies. The nuclear data set used by the code is discussed including current limitations. Although the heavy ion nuclear cross sections are assumed constant, the nucleon-nuclear cross sections of BRYNTRN with full energy dependence are used. The relation of the final code to the Boltzmann equation is discussed in the context of simplifying assumptions. Error generation and propagation is discussed, and comparison is made with simplified analytic solutions to test numerical accuracy of the final result. A brief discussion of biological issues and their impact on fundamental developments in shielding technology is given.

Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Khan, F., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., and Norbury, J.W. (1991) *Transport Methods and Interactions for Space Radiations*. NASA Reference Publication 1257.

Nuclear interaction, Radiation transport, Mars, Boltzmann equation, Transport code, Lunar mission, Nuclear reaction effect

A review of the program in space-radiation protection at the Langley Research Center is given. The relevant Boltzmann equations are given with a discussion of approximation procedures for space applications. The interaction coefficients are related to the solution of the many-body Schrödinger equation with nuclear and electromagnetic forces. Various solution techniques are discussed to obtain relevant interaction cross sections with extensive comparison with experiments. Solution techniques for the Boltzmann equations are discussed in detail. Transport computer code validation is discussed through analytical benchmarking, comparison with other codes, comparison with laboratory

experiments, and measurements in space. Applications to missions to the Moon and Mars are discussed.

Wilson, J.W., Townsend, L.W., Shinn, J.L., Badavi, F.F., and Lamkin, S.L. (1992) Galactic cosmic ray transport methods: Past, present, and future. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 567.

HZE particles, Transport code

The development of the theory of high charge and energy (HZE) ion transport will be reviewed. The basic solution character and approximation techniques will be described. An overview of the HZE transport codes currently available at the Langley Research Center will be given. The near term goal of the Langley program is to produce a complete set of one-dimensional transport codes. The ultimate goal is to produce a set of complete three-dimensional codes which have been validated in the laboratory and can be applied in the engineering design environment. Recent progress toward completing these goals will be discussed.

THEORY AND MODEL DEVELOPMENT

Adams, J.H., Jr., Badhwar, G.D., Letaw, J.R., Silberberg, R., and Tsao, C.H. (1992) Dose equivalent from cosmic rays in deep space. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 568.

GCR, Radiation shielding, Dose equivalent

We have calculated the dose equivalent (DE) in deep space due to Galactic cosmic rays. The DE has been calculated at depth of 5 cm in tissue within spherical aluminum shields of various thicknesses. In addition to the most probable values, upper limits on the DE are given at the 90% confidence level. Both uncertainties in the cosmic ray flux and uncertainties in the nuclear cross sections were considered in determining this upper limit. Results are given at various phases of the solar activity cycle.

Cucinotta, F.A., Wilson, J.W., and Katz, R. (1991) RBE predictions for exposure from galactic cosmic rays. Presented at the Second Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 22-23, 1991.

Track model, Cell culture, HZE, GCR, Tradescantia, RBE, Radiation shielding, Transport calculation

The parametric cellular track model is known to provide a good description of the response of mammalian cell cultures to heavy ion irradiation. Using cellular response parameters obtained from radiobiological experiments, we present predictions for the response of several cell systems to the GCR environment. Calculations are presented for C3H10T1/2 cells, V79 Chinese hamster cells, and

tradescantia. Predictions of the radiobiological effectiveness (RBE's) for these systems are discussed for exposure behind typical spacecraft shielding.

Curtis, S.B. (1993, in press) Relating space radiation environments to risk estimates. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute*, Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.

GCR, Quality factor, High-LET, Cell hit frequency, Single track effect, Radiation risk cross section

Radiation risks on extramagnetospheric manned space missions are discussed in terms of the conventional ideas of dose-LET spectra, Quality Factor, and dose equivalent. The contribution to risk due to the high-LET component is shown to be large even behind considerable aluminum shielding. A calculation of biological cell-nucleus hit frequencies from galactic cosmic rays shows that single-track heavy ion effects will dominate the high-LET contribution to risk. A new concept, the risk cross section, relating risk directly to particle fluence is shown to have merit in describing risk to travelers in deep space.

Curtis, S.B. (1991) Risk cross sections for assessing the space hazard from galactic cosmic rays. Presented at the Second Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 22-23, 1991.

Fluence-related risk coefficient, Risk cross section, GCR, Risk assessment

The idea of a risk cross section, a fluence-related coefficient, will be introduced to evaluate the radiation risk outside the magnetosphere from the galactic cosmic radiation. The risk cross section $F_i (L_i)$ is defined as the probability per unit fluence of producing the $F_i (L_i)$ $\varphi_i(L_i)$ dL_i (e.g., cancer):

$$P = \sum_i \int F_i (L_i) \, \varphi_i(L_i) \, dL_i$$

where P is the probability of effect, φ_i is the fluence of the ith particle type with LET L_i.

Orienting risk assessment in this way results in several advantages, among them:

1. Experiments with X-rays and gamma rays can be eliminated. Low-LET charged particle beam experiments [e.g., with intermediate energy (~250 MeV) protons] are still necessary, but the very demanding X- and gamma-ray experiments at low doses can be entirely bypassed.

2. Fluence-related risk cross sections orient the risk assessment problem toward single-track mechanisms, the most probable cause of important late somatic and

genetic (stochastic) effects from the very low fluences of highly ionizing particles to be encountered in deep space.

An example will be shown using tumor prevalence data from the mouse Harderian gland obtained at the Berkeley Bevalac.

Ganapol, B.D., Townsend, L.W., Lamkin, S.L., and Wilson, J.W. (1991) *Benchmark Solutions for the Galactic Heavy-Ion Transport Equations with Energy and Spatial Coupling.* **NASA Technical Paper 3112.**

Benchmark, Radiation shielding, Heavy ions, Ion flux, Transport model

Nontrivial benchmark solutions are developed for the galactic heavy-ion transport equations in the straight-ahead approximation with energy and spatial coupling. Analytical representations of the ion fluxes are obtained for a variety of sources with the assumption that the nuclear interaction parameters are energy independent. The method utilizes an analytical Laplace transform inversion to yield a closed-form representation that is computationally efficient. The flux profiles are then used to predict ion dose profiles, which are important for shield-design studies.

Lamkin, S.L., Khandelwal, G.S., Shinn, J.L., and Wilson, J.W. (1992) Numerical methods for high energy nucleon transport. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding,* **Pasco, WA, April 26-May 1, 1992, p. 165-170.**

BRYNTRN, HETC, Nucleon transport, Transport code

In the present work an approximate evaluation procedure is derived for a second order theory of high energy nucleon transport. An analytic solution to a simplified interaction model is used to verify the procedure. Effects of the improved method on transport solutions with the BRYNTRN data base are evaluated. Comparisons with HETC benchmarks are given.

Nealy, J.E., Simonsen, L.C., Wilson, J.W., Townsend, L.W., Qualls, G.D., Schnitzler, B.G., and Gates, M.M. (1991) Radiation exposure and dose estimates for a nuclear-powered manned Mars sprint mission. In: *Proceedings of Eighth Symposium on Space Nuclear Power System, Part, 2,* **Eds. M.S. El-Genk and M.D. Hoover, Albuquerque, NM, January 6-9, 1991, p. 531-536.**

Mars, Radiation shielding

A conceptual manned mission to Mars is analyzed in order to estimate potential ionizing radiation doses that may be incurred by crew members during the course of the mission. The scenario is set for a journey during the solar active period and includes a brief stay on the Martian surface. Propulsion is assumed to be provided by nuclear thermal rocket power, and estimates of the dose

contributions from the reactors are included. However, due to effective shielding of the reactors by large propellant tanks, it is found that the incurred doses are principally due to the charged particle natural environment. Recent data (August-December 1989) for large solar proton events are used to simulate the flare environment, while standard models are used for the trapped particle and galactic cosmic ray contributions. Shield effectiveness for several candidate materials are investigated.

Shinn, J.L., John, S., Tripathi, R.K., Wilson, J.W., Townsend, L.W., and Norbury, J.W. (1992) *Fully Energy-Dependent HZETRN (A Galactic Cosmic-Ray Transport Code).* **NASA Technical Paper 3243.**

GCR, Fragmentation, LET, Radiation shielding, Transport code, Risk assessment, HZETRN

For extended manned space missions, the radiation shielding design requires efficient and accurate cosmic-ray transport codes that can handle the physics processes in detail. The Langley Research Center galactic cosmic-ray transport code (HZETRN) is currently under development for such design use. The cross sections for the production of secondary nucleons in the existing HZETRN code are energy dependent only for nucleon collisions. The approximation of energy-independent, heavy-ion fragmentation cross section is now removed by implementing a mathematically simplified energy-dependent stepping formalism for heavy ions. The cross section at each computational grid is obtained by linear interpolation from a few tabulated data to minimize computing time. Test runs were made for galactic cosmic-ray transport through a liquid hydrogen shield and a water shield at solar minimum. The results show no appreciable change in total fluxes or computing time compared with energy-independent calculations. Differences in high LET (linear energy transfer) spectra are noted, however, because of the large variation in cross sections at low-energy region. The high LET components are significantly higher in the new code and have important implications on biological risk estimates for heavy-ion exposure.

Shinn, J.L., Nealy, J.E., Townsend, L.W., Wilson, J.W., and Wood, J.S. (1992) Galactic cosmic ray radiation levels in spacecraft on interplanetary missions. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* Washington, D.C., August 28-September 5, 1992, p. 567-568.

Transport code, GCR, HZETRN, Computerized anatomical model, LET, Radiation shielding

Using the Langley Research Center galactic cosmic ray (GCR) transport computer code (HZETRN) and the computerized anatomical man (CAM) model, crew radiation levels inside manned spacecraft on interplanetary missions are estimated. These radiation-level estimates include particle fluxes, LET (linear energy transfer) spectra, absorbed dose, and dose equivalent within various organs of interest in GCR protection studies. Changes in these radiation levels resulting from the use of various different types of shield materials are presented.

Shinn, J.L., Wilson, J.W., Townsend, L.W., Cucinotta, F.A., Chun, S.Y., and Badavi, F.F. (1992) Computationally efficient space radiation transport codes. In: *Proceedings of the American Nuclear Society Topical Meeting on New Horizons in Radiation Protection and Shielding*, Pasco, WA, April 26-May 1, 1992, p. 171-180.

Transport code, BRYNTRN, HZETRN, Boltzmann equation, Monte Carlo

Two engineering codes for analyzing solar proton transport (BRYNTRN) and high-energy heavy ion transport (HZETRN) are described. With the straight-ahead approximation, simple analytic-numerical stepping formulations are derived from Boltzmann equations. The propagated error from the stepping procedure are shown to have been minimized with no loss of computational efficiency. The existing physics inputs and future work required are briefly discussed. Code structure and available input/output options are outlined. Examples of verifying BRYNTRN with Monte Carlo calculation are also given.

Shinn, J.L., Wilson, J.W., Weyland, M., and Cucinotta, F.A. (1991) *Improvements in Computational Accuracy of BRYNTRN (A Baryon Transport Code)*. NASA Technical Paper 3093.

Space radiation, Numerical accuracy, High-energy transport, BRYNTRN, Radiation shielding, Nucleon transport

The extension of the baryon transport code (BRYNTRN) for use in space radiation dose analyses for very large shield thicknesses is made possible by improving the numerical algorithms. The efforts were concentrated in obtaining more accurate, yet efficient, interpolation and integration methods at each local computational step, and in optimizing the grid distributions. A brief discussion of the nucleon transport theory and propagating formula is also given in conjunction with the analysis of error propagation which reveals the need for minimizing the local truncation errors. Sample calculations were made to verify the new algorithms. An accuracy of approximately 5 percent for a shield thickness of 150 g/cm^2 was found when a minimal 30-point energy grid was used. This accuracy was far superior to the results obtained by using the old algorithms where the solutions could be an order of magnitude different when a reasonably large number of grid points were used. The propagating step size was chosen such that the perturbation theory error matched the improved numerical accuracy.

Simonsen, L.C., Nealy, J.E., and Townsend, L.W. (1992) Concepts and strategies for lunar base radiation protection: Pre-fabricated versus in-situ materials. Presented at the 22nd International Conference on Environmental Systems, Seattle, WA, July 13-16, 1992, 12 p. SAE Paper 921370.

Transport code, BRYNTRN, HZETRN, Radiation shielding, Neutron absorber

The most recently accepted environment data are used as inputs for the Langley nucleon and heavy-ion transport codes, BRYNTRN and HZETRN, to examine the

shield effectiveness of lunar regolith in comparison with commercially-used shield materials in nuclear facilities. Several of the fabricated materials categorized as neutron absorbers exhibit favorable characteristics for space radiation protection. In particular, polyethylene with additive boron is analyzed with regard to response to the predicted lunar galactic cosmic ray and solar proton flare environment during the course of a complete solar cycle.

Although this effort is not intended to be a definitive trade study for specific shielding recommendations, attention is given to several factors that warrant consideration in such trade studies. For example, the transporting of bulk shield material to the lunar site as opposed to regolith-moving and processing equipment is assessed on the basis of recent scenario studies. The transporting of shield material from Earth may also be a viable alternative to the use of regolith from standpoints of cost-effectiveness, EVA time required, and risk factor.

Townsend, L.W., Cucinotta, F.A., Shinn, J.L., and Wilson, J.W. (1991) Human exposure to galactic cosmic rays in space. Presented at the 9th International Congress of Radiation Research, Toronto, Canada, July 7-12, 1991, p. 83.

Radiation transport code, Computerized anatomical model, Risk assessment, HZETRN, Transport calculation

The Langley Research Center galactic cosmic ray transport computer code (HZETRN) and the Computerized Anatomical Man (CAM) model are used to estimate astronaut exposures from galactic cosmic rays for missions beyond Earth's magnetosphere. Conventional risk assessment in terms of total absorbed dose and dose equivalent is made for the skin, ocular lens, and bone marrow. Separate evaluations of the contributions from important incident cosmic ray ions, such as iron, are also made.

Townsend, L.W., Cucinotta, F.A., Wilson, J.W., Shinn, J.L., and Badhwar, G.D. (1992) Solar modulation and nuclear fragmentation effects in galactic cosmic ray transport through shielding. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 567.

GCR, Radiation shielding, Solar modulation, Nuclear fragmentation, Quality factor, Long-duration space mission

Crews of manned interplanetary missions may accumulate significant radiation exposures from the galactic cosmic ray (GCR) environment in space. Estimates of these dose levels are affected by the assumed temporal and spatial variations in the composition of the GCR environment, and by the effects of the spacecraft and body self-shielding on the transported radiation fields. In this work the physical processes through which shielding alters the transported radiation fields are described. We then present estimates of the effects of model calculations of (1) solar modulation, (2) variations between solar cycles, (3) nuclear attenuation

and fragmentation model uncertainties, and (4) proposed changes to the quality factors which relate dose equivalent to absorbed dose.

Townsend, L.W., Cucinotta, F.A., and Wilson, J.W. (1993, In press) HZE reactions and data-base development. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute,* **Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.**

LET, RBE, Radiation shielding, Radiation risk, Model development

The primary cosmic rays are dispersed over a large range of linear energy transfer (LET) values and their distribution over LET is a determinant of biological response. This LET distribution is modified by radiation shielding thickness and shield material composition. The current uncertainties in nuclear cross sections will now allow the composition of the shield material to be distinguished in order to minimize biological risk. An overview of the development of quantum mechanical models of heavy ion reactions will be given and computational results compared with experiments. A second approach is the development of phenomenological models from semi-classical considerations. These models provide the current data base in high charge and energy (HZE) shielding studies. They will be compared with available experimental data. The background material for this lecture will be available as a review document of over 30 years of research at Langley but will include new results obtained over the last year.

EXPERIMENTAL STUDIES

Csige, I., Benton, E.V., Frigo, L., Parnell, T.A., Watts, J.W., Jr., Armstrong, T.W., and Colborn, B.L. (1992) Three-dimensional shielding effects on charged particle fluences measured in the P0006 experiment of LDEF. Presented at the Second LDEF Post-Retrieval Symposium, San Diego, CA, June 1-5, 1992.

Radiation shielding, PNTD, Radiation detector, Long Duration Exposure Facility, Space Station Freedom, Transport calculation

Three-dimensional shielding effects on cosmic ray charged particle fluences were measured with plastic nuclear track detectors in the P0006 experiment on LDEF. The azimuthal and polar angle distributions of the galactic cosmic ray particles (mostly relativistic iron) were measured in the main stack and in four side stacks of the P0006 experiment, located on the west end of the LDEF satellite. A shadowing effect of the shielding of the LDEF satellite is found. Total fluence of stopping protons was measured as a function of the position in the main and side stacks of the P0006 experiment. Location dependence of total track density is explained by the three-dimensional shielding model of the P0006 stack. These results can be used to validate 3D mass model and transport code calculations and also for predictions of the outer radiation environment for the Space Station Freedom.

Frank, A.L., Benton, E.V., Armstrong, T.W., and Colborn, B.L. (1992) Absorbed dose measurements and predictions on LDEF. Presented at the Second LDEF Post-Retrieval Symposium, San Diego, CA, June 1-5, 1992.

Long Duration Exposure Facility, Radiation detector, Radiation shielding

The overall radiation environment of the Long Duration Exposure Facility (LDEF) was determined in part through the use of thermoluminescent detectors (TLDs) which were included in several experiments. The results given here are from four experiments (A0015 Biostack, M0004 Fiber Optics Data Link, P0004 Seeds in Space, and P0006 Linear Energy Transfer Spectrum Measurement) and represent a large fraction of existing absorbed dose data. The TLDs were located on the leading and the trailing edges and the Earth end of the spacecraft under various shielding depths (0.48 to 15.4 g/cm^2). The measured absorbed doses were found to reflect both directional dependence of incident trapped protons and shielding.

At the leading edge, doses ranged from 2.10 to 2.58 Gy under shielding of 2.90 to 1.37 g/cm^2 Al equivalent (M0004). At the trailing edge, doses varied from 3.04 to 4.49 Gy under shielding of 11.7 to 3.85 g/cm^2 (A0015), doses varied from 2.91 to 6.64 Gy under shielding of 11.1 to 0.48 g/cm^2 (P0004), and a dose range of 2.66 to 6.48 Gy was measured under shielding of 15.4 to 0.48 g/cm^2 (P0006). At the Earth end of the spacecraft, doses from 2.41 to 3.93 Gy were found under shielding of 10.0 to 1.66 g/cm^2 (A0015). The effect of the trapped proton anisotropy was such that the western side of LDEF received more than 2 times the dose of the eastern side at shielding depths of ~1 g/cm^2. Calculations utilizing a directional model of trapped proton spectra predict smaller doses than those measured, being about 50% of measured values at the trailing edge and Earth end, and about 80% near the leading edge.

Heilbronn, L., Frankel, K., Gong, W., Lampo, E., Leres, R., Miller, J., Ngo, D., Schimmerling, W., and Zeitlin, C. (1992) A detection system for measuring fluences of fragments created in collisions between GCR-like nuclei and matter. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

GCR, Heavy ion transport, Fragment fluence

The components of the Galactic Cosmic Radiation (GCR) field which may pose the greatest long-term health risk to humans in space are highly charged and energetic (HZE) nuclei. Primary HZE nuclei in the GCR not only make a significant contribution to the radiation dose received by astronauts, but they also generate a secondary field of fragments produced in nuclear interactions with human tissue and surrounding shielding materials. A series of ground-based measurements is planned to measure the fluence of fragments created in nucleus-nucleus collisions between high energy heavy ion beams (simulating components of the GCR) with targets made up of materials that simulate tissue and shielding. A detection system has been built to measure the fluences of charged particles produced near the beam axis. The system is modular in design

and can accommodate up to 16 individual silicon detectors. Each detector is automatically calibrated on-line by means of a computer-controlled onboard pulser. Fragment identification is achieved by measuring energy deposition in the silicon detectors, and in the present configuration the silicon detector stack has been supplemented by external detectors for tracking and for measuring time of flight. Because its modularity the system can be readily configured to detect a wide range of primary beam and fragment charges and velocities. We will describe the detection system in detail and present preliminary results from a test run with a beam of 600 MeV/nucleon iron nuclei.

Miller, J. (1992) Ground-based simulations of Galactic Cosmic Ray fragmentation and transport. In: _Abstracts, 29th Plenary Meeting of the Committee on Space Research_, Washington, D.C., August 28-September 5, 1992, p. 567.

GCR, HZE, Shielding, Fragmentation

Since mean free paths for nuclear fragmentation are of the order of the ranges of primary Galactic Cosmic Ray (GCR) nuclei, determination of the radiation field produced by successive fragmentations of nuclei in material and tissue is essential to an accurate assessment of GCR radiation risk to humans on long-duration missions outside the geomagnetosphere. One way to attack this problem analytically is through an iterative program incorporating both theory (in the form of heavy ion transport calculations) and measurements. We will summarize the existing nuclear fragmentation data for the nuclei and energies of interest and present the results of some recent heavy ion fragmentation experiments and comparisons with transport theory. We will discuss the role of nuclear fragmentation in the overall GCR radiation risk problem, including some examples of the interplay between physics and biology, and outline some options for an integrated, interdisciplinary experimental and theoretical program of GCR risk assessments.

Shavers, M.R., Miller, J., Schimmerling, W., Townsend, L.W., and Wilson, J.W. (1993, in press) Heavy ion fragmentation studies in thick water absorbers. In: _Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute_, Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.

Heavy ion fragmentation, Shielding, Transport model

Relatively thick shields are required on long-term manned space missions beyond the Earth's magnetosphere in order to reduce risks to crewmembers from exposure to galactic cosmic radiation. A significant portion of the dose equivalent at depth is due to nuclear interaction products produced in shielding material, including the human body. In a program designed to measure radiation fields produced by high-energy heavy ions incident on thick absorbers, detailed measurements have been made of 670A MeV accelerated neon beams interacting in water using a time-of-flight telescope to measure velocity and a set

of silicon detectors to measure energy loss of each particle. Fluence spectra of identified projectile fragment nuclei between Be(Z = 4) and Ne(Z = 10), both inclusive, were measured along the central axis of the beam-line downstream from absorbers of thicknesses between 0 and 38.5 g/cm^2. An initial comparison of the data with theoretical fluence spectra predicted by the heavy-ion transport code HZESEC, which calculates only the projectile fragments created directly from nuclear collisions of the primary beam, indicated that higher-order reaction products are important. The transport model LBLBEAM, developed at NASA-Langley Research Center, is used to calculate integral fluence and differential LET spectra of the primary neon beam, of the secondary projectile fragments created from neon interactions, and of tertiary particles created by first generation secondaries. The calculation is based on an analytical solution of a one-dimensional Boltzmann transport equation using the straight-ahead approximation, and assumes constant nuclear interaction cross sections. Multiple scattering effects on the particles emerging from the water column were separately considered for each isotope. Predicted integral fluence and LET spectra are in reasonable agreement with the data. The results demonstrate the significance of considering higher-order secondary particles, and the importance of an accurate knowledge of inclusive nuclear fragmentation parameters. The experimental methods and the procedure for comparing accelerated heavy-ion beams with theory are shown to be quite useful for validating transport models.

INSTRUMENTATION

Csige, I., Benton, E.R., Benton, E.V., and Fujii, M. (1992) Heavy ion response of SR-90 and CR-39 track detectors. Presented at the 16th International Conference on Nuclear Tracks in Solids, Beijing, China, September 7-11, 1992.

Radiation detector, PNTD

The heavy ion response of the new kind of SR-90 plastic nuclear track detector was studied in comparison with different kinds of commercially available CR-39s at the BEVALAC accelerator. The sensitivity of SR-90 (a similar material to CR-39, but longer chain length between adjacent carbonate groups) seemed to be a little bit higher than the sensitivity of the CR-39s for particles (Ne, Ar, and Fe) and energies (100-600 MeV/nuc) investigated in our study. The surface quality of SR-90, however, was not so good, and it was not possible to compare its sensitivity for very low LET particles because we could not distinguish the tracks against detector defects. The possible applications of this material are also discussed.

Hardy, K.A., Golightly, M.J., Hardy, A.C., Atwell, W., and Quam, W. (1991) RME-III: A microdosimetry based instrument for radiation dosimetry in aerospace environments. Presented at the Third Conference on Radiation Protection and Dosimetry, Orlando, FL, October 21-24, 1991.

Dosimetry, RME-III, Tissue equivalent proportional counter (TEPC), Radiation detector, Instrumentation, LET

A self-contained, portable, real-time dosimeter instrument, the RME-III has been developed by E.G.&G. Energy Measurements, inc. and the Air Force for use in aerospace operational environments such as the Space Shuttle and high altitude aircraft. The instrument is based on a tissue equivalent proportional counter (TEPC) detector which measures energy deposition by individual particles and photons in a simulated micron size target volume. The detector signals are registered as counts (or fluence) in a separate linear energy transfer (LET) bins: low, intermediate and high; which in turn are converted to dose and dose equivalent at a pre-selected time interval by microprocessor driven internal algorithms. The instrument presents the user with the cumulative absorbed dose, cumulative dose equivalent and current dose rate real-time on a liquid crystal display. In addition, the counts absorbed dose and dose equivalent per time interval are stored in an internal memory versus internal clock readings which register the coordinated universal time (UTC) and mission elapsed time. This permits time-resolved correlation of the radiation exposure with operational flight parameters such as altitude, geographic location, shielding and spacecraft orientation, etc. A description of the instrument will be provided along with some representative samples of data obtained from recent flights on the Space Shuttle.

Hardy, K.A., Golightly, M.J., and Quam, W. (1992) Radiation monitoring equipment dosimeter experiment. Presented at the NASA/DoD Space Technology Interchange Conference, Monterey, CA, October 4-9, 1992.

Risk assessment, Real-time radiation monitoring, Dosimetry, RME-III, Tissue equivalent proportional counter (TEPC), Instrumentation, LET

Spacecraft crews risk exposure to relatively high levels of ionizing radiation. This radiation may come from charged particles trapped in the Earth's magnetic field, charged particles released by solar flare activity, galactic cosmic radiation, energetic photons and neutrons generated by the interaction of primary particles with the spacecraft and crew, and on-board radiation sources (e.g., nuclear power generators). In order to more accurately define the radiological exposure and risk to the crew, active real-time radiation monitoring instrumentation must be flown capable of identifying and measuring the various radiation components. This report describes such a radiation dosimeter instrument which has successfully flown on the Space Shuttle, the Radiation Monitoring Equipment (RME)-III.

The RME-III is a portable, active (real-time) dosimeter system developed by E.G.&G. for the U.S. Air Force, which was adapted for use on the Space Shuttle. The instrument is based on a tissue equivalent proportional counter (TEPC)

detector which measures energy deposition by individual particles and photons in a simulated micrometer size target volume. The detector signals are registered as counts in three separate linear energy transfer (LET) bins, which in turn are converted to absorbed dose and dose equivalent at a pre-selected time interval by microprocessor driven internal algorithms. The instrument presents the operator with the total absorbed dose, total dose equivalent and current dose rate real-time on a liquid crystal display. In addition, the counts, absorbed dose, and dose equivalent per time interval are stored in an internal memory versus an internal clock which registers coordinated universal time (UTC) and date, and mission elapsed time. This permits time-resolved correlation of the radiation exposure with operational flight parameters such as altitude, geographic or magnetic location, spacecraft orientation, etc. Data obtained from several Shuttle missions are presented demonstrating the capabilities of the RME-III in the complex operational space radiation environment. Test data from accelerator produced heavy ions and protons are also presented.

Csige, I., Oda, K., Henke, R.P., and Benton, E.V. (1992) Identification of recoil particles using track-coincidence and multiple track etching method. Presented at the 16th International Conference on Nuclear Tracks in Solids, Beijing, China, September 7-11, 1992.

CR-39, Radiation detector, Long Duration Exposure Facility, PNTD

A new method has been developed to identify short range recoil particles — produced by energetic trapped protons (of the Earth's radiation belts) — in a two layer solid state nuclear track detector stack exposed on the Long Duration Exposure Facility (LDEF). Tracks in coincidence at the adjacent surfaces — indicating that the particle crossed the inner surfaces — are selected for measurements. Using multiple etching the growth of the etched track parameters are measured as a function of the etching time. These growth curves are analyzed to obtain the range of the particle and also to measure the etch rate ratio at some characteristic points along the particle trajectory. Then the particles are identified by these experimental data and the response curve of the detector material.

We have used this method to identify particles in a CR-39 (double layer) with charges $Z \leq 8$ and particle ranges greater than a few microns. The charge-, energy- and linear energy transfer spectra generation method of these particles is discussed. Analyzing the dip angle and the azimuth angle distribution of the measured recoil tracks, we found that some information about the anisotropy of the primary particle beam can also be obtained.

Oda, K., Csige, I., Yamauchi, T., Miyake, H., and Benton, E.V. (1992) Incident angle dependence of proton response of CR-39 (TS-16) track detector. Presented at the 16th International Conference on Nuclear Tracks in Solids, Beijing, China, September 7-11, 1992.

CR-39, Radiation detector, Etching time, PNTD

The proton response of the TS-16 type of CR-39 plastic nuclear track detector has been studied with accelerated and fast neutron induced protons in vacuum and in air. The diameters of etched tracks were measured as a function of etching time and the etch rate ratio and the etch induction layer were determined from the growth curve of the diameter using a variable etch rate ratio model. In the case of the accelerated protons in vacuum an anomalous incident angle dependence of the response is observed.

2. BIOLOGY

BIOLOGY

Nelson, G.A. (1990) Radiation biology of HZE particles. Presented at the 41st Congress of the International Astronautical Federation, Dresden, Germany, October 6-12, 1990, IAA Paper 90-548.

Nematode, High-LET, Radiation biology, Mutation

The biological effects of heavy charged particle (HZE) radiation are of particular interest to travellers and planners for long duration space flights where exposure levels represent a potential health hazard. The unique feature of HZE radiation is the structured pattern of its energy deposition in targets which may be related to charge, velocity, or rate of energy loss. There are many consequences of this feature to biological endpoints when compared to effects of ionizing photons. Dose vs response and dose rate kinetics are modified, DNA and cellular repair systems are altered in their abilities to cope with damage and, the qualitative features of damage are unique for different ions. These features must be incorporated into any risk assessment system for radiation health management.

HZE induced mutation, cell inactivation and altered organogenesis will be discussed emphasizing studies with the nematode *Caenorhabditis elegans* and cultured cells. Observations from radiobiology experiments in space will also be reviewed along with plans for future space-based studies.

MOLECULAR BIOLOGY

Coohill, T., Marshall, T., Schubert, W., and Nelson, G.A. (1988) Ultraviolet mutagenesis of radiation sensitive mutants of the nematode *Caenorhabditis elegans*. Presented at the 10th International Congress on Photobiology, Jerusalem, Israel, October 30-November 4, 1988.

Nematode, Mutant, UV radiation

A mutational tester strain of the nematode *C. elegans* was constructed. Designated JP10, this balancer strain samples a 300 gene autosomal region and measures the probability of converting a radiation interaction into a lethal mutation. Exposure of gravid young adults of this strain to 254 nm ultraviolet radiation (UV) of fluence up to 300 Jm^{-2} produced mutation rates as high as 5%. In addition, three separate radiation sensitive mutants, *rad-1*, *rad-3*, and *rad-7* were incorporated into the JP10 strain. This allowed us to measure mutation in radiation sensitive animals. JP10 +*rad-1* mutants were hypersensitive to mutation by UV, while JP10 +*rad-3* and JP10 +*rad-7* mutants proved to be hyposensitive. We also show data for the effects of UV on larval development and fecundity for each radiation mutant and its mutational tester strain corollary.

Cucinotta, F.A., Wilson, J.W., Katz, R., and Badhwar, G.D. (1992) *Katz Model Prediction of Caenorhabditis elegans Mutagenesis on STS-42.* NASA Technical Memorandum 4383.

Track structure, Nematode, Mutagenesis, IML-1, STS-42

The Katz track structure model has been applied to describe recessive lethal mutagenesis in the nematode *Caenorhabditis elegans* after exposure to heavy ions. Based on models of the cosmic-ray environment and heavy-ion transport, mutation rates for the International Microgravity Laboratory 1 (IML-1) experiment on the Space Transportation System 42 (STS-42) are predicted and the results are discussed.

Kronenberg, A. (1992) Mutation induction in human lymphoid cells by energetic heavy ions. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 548.**

LET, Mutation, Damage repair, B-lymphoblast

A series of investigations have been carried out to characterize the mutational response of human B-lymphoblastoid cells following exposure to high energy, heavy charged particle beams produced at the BEVALAC accelerator at Lawrence Berkeley Laboratory. Mutations were scored for two endogenous genetic loci: the X-linked hypoxanthine phosphoribosyltransferase (hprt) locus, and the autosomal thymidine kinase (tk) locus which is heterozygous in the TK6 cell line. Data will be presented as mutant yields vs. particle fluence for each of the two loci for particles ranging from protons to iron nuclei and across an energy range from 250 MeV/amu to 670 MeV/amu. The LET response for mutation induction differs for the two loci, both in terms of magnitude and shape. Recent molecular biological analysis of individual tk or hprt-deficient mutants suggests a bias against recovery of large deletions involving the hprt locus.

CELLULAR RADIATION BIOLOGY

Cucinotta, F.A. and Wilson, J.W. (1992) Track structure and kinetic effects in describing cell survival and transformation in mice from HZE particles. Presented at the AFRRI Physics/Biophysics Modeling Workshop, Houston, TX, April 16-17, 1992.

LET, RBE, Track structure, Cell damage, Radiation risk, HZE particles, Harderian gland, Mouse, Nuclear fragmentation, Proton, Bragg ionization curve

It is well known that the severity of biological injury in modest to low-exposure environments is related to the energy imparted to the cell nucleus by ionizing radiation. For low-energy ions, the energy released is absorbed locally to its track, and severity of injury is correlated with linear energy transfer (LET) and measured RBE is represented as LET dependent. In distinction, high-energy ions create energetic electrons which mediate the energy absorption process and

deposit the energy far from the ion track, spreading the energy over a larger volume. Furthermore, the ability of the cell to repair itself depends on the severity of the injury sustained and is likewise dependent on the spread of the energy deposit or track structure.

An understanding of track-structure effects and repair-dependent alterations of biological response for protracted exposures are essential components in risk assessment for high charge and energy (HZE) exposure. We discuss a parametric cell kinetics model which incorporates track structure which has been successfully applied in describing repair-dependent exposures with HZE beams. The importance of cell survival on modeling cell transformation rates and Harderian gland tumor prevalence is described.

The role of nuclear fragmentation on interpreting laboratory experiments with heavy ion beams is also considered. Comparisons to cell-survival experiments with ion beams along the Bragg ionization curve are made. For high-energy protons, target fragmentation effects are predicted to dominate biological response at low dose.

Results of the kinetic model for predicting maximum RBE values are discussed. The role of track structure in causing a branching of RBE as a function of LET with ion charge is also discussed. We would like to propose the use of track structure repair models as a means to design interesting experiments for model validation, improvements, and extension to other tissue systems.

Cucinotta, F.A., Wilson, J.W., Shinn, J.L., Atwell, W., and Fong, H. (1992) Dose rate and repair effects on cell damage in Earth orbit. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 573.**

Cellular repair, Track structure, Animal models

Radiobiology experiments performed in space will encounter continuous exposures to the galactic cosmic rays, as well as fractionated exposures to trapped protons and electrons which will accumulate to several hundred dose fractions for a few weeks in orbit. Models of biological response will be severely tested because of the broad range of charge and energy of the radiation fields and the complexity of the protracted exposure. Using models of track structure and cellular kinetics combined with models of the radiation environment in space and charged particle transport, we consider calculations of cell damage rates for C3H10T-1/2 and Chinese Hamster cell cultures. Analysis of the role of repair mechanisms for the continuous and fractionated exposures experienced in space flight for the endpoints of survival and transformation is emphasized.

Cucinotta, F.A., Wilson, J.W., Shinn, J.L., and Katz, R. (1992) Application of radiation transport codes to laboratory and space radiobiology. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Transport code, Track structure, Nuclear fragmentation, Cell kinetic model, Nematode

Recent progress in the development of radiation transport methods to support ground based and possible flight based radiobiology experiments are reported. Cell survival and transformation experiments with high dose exposures of protons and heavy ions have been studied using the track structure model incorporating the effects of nuclear fragmentation. A linear kinetics model is used to describe delayed plating and fractionated exposures of C3H10T 1/2 and CHO cells. Extrapolations of ground-based response to flight experiments are considered, including the role of cellular repair in multiple passes through the South Atlantic anomaly in Earth orbit. Response parameters for recessive lethal mutations in *C. elegans* have been obtained from laboratory heavy ion exposures and used to make predictions for recent experiments aboard the space shuttle.

Katz, R., Cucinotta, F.A., Wilson, J.W., Shinn, J.L., and Ngo, D.M. (1993, In press) A model of cell damage in space flight. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute*, Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.

Cell damage, LET, Track model, Fragmentation, Model development, HZE

Cell damage by high LET radiations has been described by a phenomenological model (track theory) for 20 years and more. Molecules of biological significance (dry enzymes and viruses) act as 1 hit detectors. Recent additions to the class of 1-hit detectors are E. coli B, and the creation of both single and double strand breaks in SV-40 virus in EO buffer, where indirect effects predominate. The response of cells (survival, transformation, chromosome aberration) to these radiations is typically described by a 4-parameter model whose numerical values are determined by fitting the equations of the theory to experimental data at high dose (typically above 1 Gy) with bombardments with γ rays and HZE particle beams, of the widest possible dynamic range. Once these parameters are determined the model predicts cellular response in any radiation environment whose particle-energy spectrum is known. Perhaps the central importance of the present model is the ability to estimate the response of a complex environment with many components from a limited set of laboratory data. For example, we have calculated cell survival after neutron irradiation, with mixtures of neutrons and γ rays; cell survival and transformation after irradiation with HZE ions of different energies. The model does not yet include cellular repair. Although some hopeful approaches to repair dependence are now being developed. It does not include cancer induction, for the available data neither give the number of cells at risk or the number of cancers induced, and are thus not suited to our formulation.

Most recently NASA-Langley models of HZE beams, including projectile and target fragmentation, have been joined with the biological model. This combination has been tested against ground based radiobiological data for cell survival after irradiation with protons and HZE beams with good success. Where our earlier model failed downstream of the Bragg peak (for both protons and heavy ions) for want of a proper description of fragmentation the NASA-Langley model succeeds.

Based on this experimental validation of our procedures, we have initiated calculations of cellular damage in space flight from solar protons and galactic cosmic rays. Here we incorporate NASA models of cosmic rays, beam penetration, projectile and target fragmentation with track theory. The essential radiobiological theme is that knowledge of parameters extracted at high doses makes it possible for us to calculate the response of cells at the lowest possible doses of HZE particles when only intra track (ion-kill) effects are involved for which repair is known to be minimal. Our procedures here too have ground based experimental validation in recent work of Bettega et al. where measurements made of RBE with protons and alphas of the survival of C3H10T 1/2 cells, at doses down to 0.01 Gy are consistent with our predictions based on survival measurements made at high doses with γ rays and HZE ions.

Katz, R., Cucinotta, F.A., Wilson, J.W., Shinn, J.L., and Ngo, D.M. (1992)
Track Structure Model of Cell Damage in Space Flight. **NASA Technical Paper 3235.**

Track structure, Nuclear fragmentation, Transport code, Cell survival

The phenomenological track-structure model of cell damage is discussed. A description of the application of the track-structure model with the NASA Langley transport code for laboratory and space radiation is given. Comparisons to experimental results for cell survival during exposure to monoenergetic, heavy-ion beams are made. The model is also applied to predict cell damage rates and relative biological effectiveness for deep-space exposures.

Wilson, J.W., Cucinotta, F.A., and Shinn, J.L. (1993, in press) Cell kinetics and track structure. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute,* **Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.**

Radiation risk, RBE, Cellular track model, Repair, Model development, Cell kinetic model

A major uncertainty in shield requirements for deep-space missions is establishing biological risk for high charge and energy (HZE) exposure. Estimates of biological risk in space requires an understanding of the relationship of ground-based biological experiments with intense particle beams to the low exposure rates in the space environment. We have examined the relation of a

(relatively) general cell kinetic model to the track structure theory of Katz and determined repair coefficients from the experiments of Yang et al. as a means of predicting biological response to low dose-rate exposure in the deep-space environment. The model provides repair dependent relative biological effectiveness (RBE's) which agree well with values found in ion exposure experiments and makes predictions which could be tested in future laboratory studies. The model seems to provide the necessary requirement of relating laboratory response data to space exposure conditions with the exception of the gravity environment effects.

Reitz, G., Bücker, H., Facius, R., Horneck, G., Schäfer, M., Schott, J.U., Bayonove, J., Beaujean, R., Benton, E.V., Delpoux, M., Heilmann, C., Heinrich, W., Kranz, A.R., Planel, H., Gasset, Y., Gaubin, G., Portal, G., Graul, E.H., Rüther, W., Schopper, E., Tobias, C.A., and Yang, T.C. (1992) First biological and dosimetric results of the free flyer Biostack experiment A0015 on LDEF. In: *LDEF—69 Months in Space*, Ed. A.S. Levine. NASA Conference Publication 3134, Part 3, p. 1639-1641.

HZE particles, PNTD, Biostack, Mutation, Radiation detector, Long Duration Exposure Facility

The experiment Free Flyer Biostack is part of a radiobiological research program which has been designed to get more information about the biological effectiveness of the different radiations present in space, especially on the effects of single heavy cosmic particles of high energy loss (HZE-particles), the combined effects of space radiation and other spaceflight factors, such as microgravity, and the documentation of the actual nature and distribution of the radiation field at the surface or inside spacecrafts.

Those objectives will be achieved by using hermetically sealed aluminum cannisters, which contain a series of monolayers of selected biological material, each of which is sandwiched between several types of nuclear track detectors. This arrangement - known as Biostack concept - allows localizing the trajectory of each heavy ion in the biological layer and identifying the side of penetration inside the biological object. The precision obtained for the reconstruction of the geometric relation between particle trajectory and test organism depends on the latter and could be pushed as low as 0.2 μm for the smallest object (bacterial spores, approx. diameter 1 μm) in previous Biostack experiments. These experiments comprised a widespread spectrum of biological objects, such as bacterial spores, plant seeds, shrimp eggs, and insect eggs. These species have different organization levels and different radiation sensitivity. They are well known and showed at least one typical genetic or somatic radiation effect. All objects were exposed in resting state and were tested to survive the period of experimental procedure. The radiation effects under investigation comprised changes in cellular and organic development, damages to cell nuclei and other subcellular systems, and induction of mutations leading to somatic or genetic changes of biological significance. The results of the Biostack experiments on Apollo 16 and 17, ASTP, SL1, D1, and Biocosmos 8 and 9 demonstrated for the first time with high precision and unequivocally that single HZE particles can

engender serious damages in practically all test organisms. This comprises induction of somatic mutations in plant seeds, of reduced hatching and of anomalies in insect and salt shrimp embryos, and of cell death in bacterial spores. Further quantitative results revealed that currently established physical theories modelling the reaction mechanisms cannot fully account for the observed effects.

In the Biostack experiments, complementary studies at accelerators represent a mandatory part of the program. It has been shown that, for bacterial spores, the accelerator experiments quantitatively conform with the findings from space experiments. However, in more complicated systems, not all radiobiological effects observed in space could be duplicated at accelerators.

The biological systems used in the Free Flyer Biostack experiments include spores of *Bacillus subtilis* and *Sordaria fimicola*, dry seeds of *Arabidopsis thaliana*, *Nicotiana tabaccum*, *Zea mays*, and Rice and encysted eggs of the tiny brine shrimp *Artemia salina*, one of the most primitive crustaceans. The nuclear track detectors cellulose nitrate (CN) and silver chloride (AgCl) will be used for the localization of the path of each heavy particle through each biological specimen.

Besides the radiobiological data, evaluation of the Biostack experiments will yield information on the composition of the radiation field in the path of the spacecraft. The combination of various detector systems which complement each other in their recording characteristics provided for a rather complete dosimetry. The use of thermoluminescence dosimeter (TLD), nuclear emulsions, silver chloride and plastic detectors allows measuring the absorbed dose and estimating the neutron contribution, the number of nuclear disintegrations, and the particle fluences and its spectral composition with respect to charge, energy and linear energy transfer (LET).

Although the Biostack experiment on LDEF was designed for a long-duration flight of only 9 months, most of the biological systems show a high hatching or germination rate. Some of the first observations are an increase of the mutation rate of embryonic lethals in the second generation of *Arabidopsis*, somatic mutations and a reduction of growth rates of corn plants and a reduction of life-span of *Artemia salina* shrimps. The different passive detector systems are also in a good shape and give access to a proper dosimetric analysis. The plastic detectors have been all etched and the AgCl detectors have been processed. Evaluation of the TLD gives us the total dose received in the Biostacks in different depths of the stacks. The results of the experiment on LDEF will contribute to obtain the empirical data base needed to evaluate the radiobiological consequences of space radiation.

The dominant applied aspect of the Biostack experiments concerns the problem of protection of man against radiation in space. Radiobiological and dosimetric data have to be collected in space as baseline information for estimating radiation risks to man in future space missions and for establishing radiation standards for man in space. Scientific and technical coordination of this program

constitutes a significant portion of the experimental approach which has to be realized within still restrictive constraints of space missions.

The Biostack program is performed in a multidisciplinary and international cooperation between many independent institutes and investigators. This report therefore gives the preliminary results of the LDEF Biostack in four independent reports. The results from biological objects and detector systems not presented in this report will be published later.

Four biostack reports follow this introduction; they are as follows: Preliminary Total Dose Measurements On LDEF; Total Dose Effects (TDE) Of Heavy Ionizing Radiation in Fungus Spores And Plant Seeds-Preliminary Investigations; Preliminary Results Of The *Artemia salina* Experiments In Biostack On LDEF; and Long-Term Exposure Of Bacterial Spores To Space.

TRANSFORMATION, MUTATION

Nelson, G.A., Marshall, T.M., and Schubert, W.W. (1989) Radiation-Induced mutation in the nematode *C. elegans* and the effects of radiation sensitive mutants. Presented at the Joint Meeting of the American Society for Cell Biology and the American Society for Biochemistry and Molecular Biology, San Francisco, CA, January 29-February 2, 1989.

Nematode, Genetics, Mutant, Radiation biology

C. elegans is being used as a model system for the evaluation of mutagenesis by radiation and to investigate the DNA repair pathways altered by radiation hypersensitive mutants. Fluence/dose vs response and RBE vs LET relationships have been constructed for the following endpoints using UV light, gamma rays, accelerated ions, and fission spectrum neutrons. 1) Recessive lethal mutations are being isolated in a large region corresponding to 15% of the nematode's genome using a balancer translocation *eT1(III;V)* to capture mutation as a balancer. Lethal mutants are characterized to determine the relative abundances of point mutations, deletions and chromosomal rearrangements. 2) Mutants generated in the *unc-22* gene are being analyzed by Southern hybridization to determine whether unique features are attributable to high LET radiation. 3) When newly-hatched larvae are irradiated, defects in karyokinesis of intestinal cells arise which we propose are derived from events that lead to formation of polycentric chromosomes which prevent completion of nuclear division and are seen in adult worms as nucleoplasmic bridges. 4) The induction of duplications of the right arm of the X chromosome has been quantified with kinetics suggesting that particles are efficient in producing chromosome breaks but also are likely to produce lethal mutations in the same cells. 5) Radiation hypersensitive mutants *rad-1,2,3,4* and *7* are being characterized with respect to the above endpoints. Hypo and hypermutability have been observed as well as inability to repair chromosome breaks.

Wilson, J.W., Cucinotta, F.A., and Shinn, J.L. (1992) *Multiple Lesion Track Structure Model.* NASA Technical Paper 3185.

Target fragment, Proton, Track structure, Plating, Model development, Cell kinetic model

A multilesion cell kinetic model is derived, and radiation kinetic coefficients are related to the Katz track structure model. The repair-related coefficients are determined from the delayed plating experiments of Yang et al. for the C3H10T 1/2 cell system. The model agrees well with the X-ray and heavy ion experiments of Yang et al. for the immediate plating, delaying plating, and fractionated exposure protocols employed by Yang. A study is made of the effects of target fragments in energetic proton exposures and of the repair-deficient target-fragment-induced lesions.

Yang, C.H. and Craise, L. (1992) **Development of human epithelial cell systems for radiation risk assessment.** In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* Washington, D.C., August 28-September 5, 1992, p. 571.

Radiation risk, Carcinogenesis, Cellular radiosensitivity, Human keratinocyte

The most important health effect of space radiation for astronauts is cancer induction. For radiation risk assessment, an understanding of carcinogenic effect of heavy ions in human cells is most essential. In our laboratory, we have succeeded in developing a quantitative assay for measuring the transformation frequency of human keratinocytes irradiated by low- and high-LET heavy ions. In addition, we are developing a human mammary epithelial cell system for studying the tissue specific responses to ionizing radiation. Growth variants were obtained from heavy ion irradiated immortal mammary cell line. These cloned growth variants can grow in regular tissue culture media and maintain anchorage dependent growth and density inhibition property. Upon further irradiation with high-LET radiation, transformed foci were found. Experimental results from both cell systems suggest that multiexposure of radiation is required to induce malignant transformation of human epithelial cells.

Yang, T.C., Craise, L.M., and Dutta, S. (1992) **Radiogenic transformation of human epithelial cells** *in vitro*: **Chromosome and tumor suppressor gene studies.** Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Human epithelial cell, Human keratinocyte, Cell culture, Nude mouse, Chromosome aberration, Genetic abnormality, Cell transformation

Using high-LET heavy ion radiation, we have successfully transformed human epithelial cells, which show density inhibition of growth, to various transformation stages. These cells include epidermal keratinocytes and mammary epithelial cells. The transformants of epidermal keratinocytes were isolated from foci and soft agar colonies and tested in athymic nude mice for tumorigenicity. Growth

variants and anchorage independent growth clones were obtained from immortal mammary epithelial cells (H184-B5). With these transformants, we did chromosome analysis and tumor suppressor genes checking. The G-banding technique was used for chromosome aberration analysis, and non-radioactive DNA detection method for tumor suppressor gene studies. Chromosome deletion and translocation were observed in transformants. No apparent loss of tumor suppressor genes, e.g., p53, was found in cells transformed by heavy ions.

Yang, C.H., Craise, L.M., and Mei, M. (1992) Heavy-ion induced genetic changes and evolution processes. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28- September 5, 1992, p. 549.

Mutation, Chromosome aberration, Genetic abnormality

In space, radiation environment can be very different from that on the Earth. Also on the Moon and Mars, there will be more galactic cosmic rays and higher radiation doses. Heavy ion radiation can effectively cause mutation and chromosome aberrations. Most heavy-ion induced mutants are irreversible and have DNA deletions. Chromosome translocation and deletion are common in cells irradiated by heavy particles. In addition, heavy ions are effective in causing hyperploidy through unknown mechanism(s). How important are those genetic changes in the evolution of life is an interesting question. Through evolution, there is an increase of DNA content in cells from lower form of life to higher organisms. The DNA content, however, reached plateau in vertebrates. By increasing DNA content, there can be an increase of information in the cell. For a given DNA content, the quality of information can be changed by rearranging the DNA. Because radiation can cause hyperploidy an increase of DNA content in cells, and can induce DNA rearrangement, it is likely that the evolution of life in space or on the Moon or Mars will be effected by its radiation environment.

Yang, T.C., Stampfer, M.R., and Rhim, J.S. (1991) Neoplastic transformation of human epithelial cells by ionizing radiation. In: *Neoplastic Transformation in Human Cell Culture*, Eds. J.S. Rhim, A. Dritschilo. Totowa, NJ: The Human Press, p. 103-111.

Epithelial cell, High-LET, Neoplastic transformation

Ionizing radiation can induce cancers in humans and animals and can cause *in vitro* neoplastic transformation of various rodent cell systems. There has been, however, very little studies on radiogenic transformation of human epithelial cells, especially with high-LET radiation. Using energetic heavy ions, we have been able to transform human epidermal keratinocytes and mammary epithelial cells to various stages of transformation. Both cell lines are immortal, anchorage dependent for growth, and non-tumorigenic in athymic nude mice. Experimental results indicated that radiogenic transformation of these cells is a multistep process and that a single exposure of ionizing radiation can cause only one step of transformation. Multihits may be required for transforming human epithelial cells to fully tumorigenic. Simple chromosome analysis with cells cloned at

various stages of transformation showed no consistent large terminal deletion in the transformed cells. Some changes of total number of chromosomes, however, were found in the radiation-transformed epidermal keratinocytes.

LETHALITY, SURVIVAL

Cucinotta, F.A., Katz, R., Wilson, J.W., Townsend, L.W., Nealy, J.E., and Shinn, J.L. (1991) *Cellular Track Model of Biological Damage to Mammalian Cell Cultures from Galactic Cosmic Rays*. NASA Technical Paper 3055.

Space radiation, Cell survival, Cell transformation, RBE, Track model, Transport code, Radiation shielding, GCR

The assessment of biological damage from the galactic cosmic rays (GCR) is of current interest for exploratory-class space missions where the high-energy heavy ion (HZE) particles are the major concern. The relative biological effectiveness (RBE) determined by ground-based experiments with HZE particles is well described by a parametric track theory of cell inactivation. Using the track model and a deterministic GCR transport code, we consider the biological damage to mammalian cell cultures for 1 year in free space at solar minimum for typical spacecraft shielding. Included in this study are the effects of projectile and target fragmentation. The RBE values for the GCR spectrum that are fluence dependent in the track model are found to be more severe than currently used quality factors and are seen to obey a simple scaling law with the period of exposure in free space.

Miller, J., Frankel, K., Schimmerling, W., Shavers, M.R., Townsend, L.W., and Wilson, J.W. (1992) Investigating the effects of nuclear fragmentation on the relative biological effectiveness of heavy ions. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Heavy ion transport, Fragment fluence, RBE, Cell killing, LET, Nuclear interaction

In previous work, we have compared the relative biological effectiveness (RBE) of the mixed radiation field produced by nuclear interactions of 670A MeV ^{20}Ne ions with water, calculated in three ways: from direct measurement of cell killing, from measured LET spectra for fragments with $Z \geq 4$ and from LET spectra calculated using the LBLBEAM heavy ion transport model. When the model calculation is corrected for the detector acceptance, it is in excellent agreement with the results from measured fragments; however both model and physics experiment RBE are between 10% and 40% greater than the RBE obtained from measured cell killing in a similar radiation field. The good agreement between calculated and measured fragment spectra holds out the prospect that the model could be used to investigate the relative importance of effects which are not readily detected. For example, simply extending the model calculation to $Z = 1$ indicates that only part of the discrepancy between RBE derived from cell killing and from measured fragment spectra can be attributed to undetected light fragments. Other, more subtle effects are not yet accounted for in the model

calculation, but we hope to incorporate them in the future. These include multiple particles traversing a single cell within a short time interval, track structure, and the acceptance of the biological volume of interest. Some of these effects should be more pronounced for heavier ions, and experiments presently being carried out will test this hypothesis. The ultimate objective of this work is to develop a model with both predictive and investigative power: that is, one which can be used to probe the dynamics as well as the phenomenology of the biological effects of higher energy heavy ions.

Nelson, G.A., Coohill, T.P., Marshall, T., Schubert, W.W., and Benton, E.V. (1987) Heavy Ion radiation effects in *C. elegans.* **In:** *Space Life Sciences Symposium, Three Decades of Life Science Research in Space,* **Washington, D.C., June 21-26, 1987, p. 53-55.**

Nematode, Genetics, Mutation, Reproduction, Differentiation, Gamma rays, Risk assessment, LET

The nematode *Caenorhabditis elegans,* is being used as a model system for the evaluation of high and low LET radiation effects on cell reproduction, differentiation and mutation *in vivo. C. elegans* is a small simple nematode with a variety of tissues and organs including digestive system, nervous system, muscles, and reproductive system providing a variety of target cells for radiation studies. The anatomy is invariant from individual to individual with fixed numbers of cells and fixed patterns of cell division. Organs and tissues develop from single cell primordia and the developmental timing is fixed so that whole populations of animals can be age-synchronized to produce animals with anatomical targets of precisely controlled cell number and function. Sophisticated genetic methods are available for the production and analysis of mutations, chromosomal aberrations and chromosome loss. Finally, short generation times (3-4 days) and high reproductive rates (282 progeny per worm) provide a means of collecting data on large populations in a relatively short period of time. Gamma rays from Cobalt 60 sources and accelerated particles produced at the Lawrence Berkeley Laboratory BEVALAC accelerator have been used in studies aimed at providing risk assessment data for spaceflight crews encountering cosmic rays in Earth orbit.

Wilson, J.W. and Cucinotta, F.A. (1991) *Cellular Repair/Misrepair Track Model.* **NASA Technical Paper 3124.**

Radiation injury, Repair model, Track structure, Track model, Cellular repair, Model development

A repair/misrepair cell kinetics model is superimposed onto the track structure model of Katz to provide for a repair mechanism. The model is tested on the repair-dependent data of Yang et al. and provides an adequate description of those data. Some mechanistic ambiguities are discussed.

DNA DAMAGE AND REPAIR

Dalrymple, G.V., Leichner, P.K., Cox, A.B., and Hardy, K.A. (1992) Induction of high grade astrocytoma (HGA) by protons: Molecular mechanisms and RBE considerations. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, **Washington, D.C., August 28-September 5, 1992, p. 552.**

RBE, Carcinogenesis, Rhesus monkey, Long-duration space mission

In the 1960's monkeys were irradiated with protons to simulate the space proton environment. Many survivors of 55 MeV proton exposure developed HGA (glioblastoma multiforme). In humans and monkeys, HGA are highly malignant, HGA have not been found in monkeys irradiated with other proton energies or in controls. HGA are induced in humans by radiation therapy. From this and from computer simulations, information about tumor induction dose and RBE can be derived. We will discuss the findings from the standpoint of molecular mechanisms of carcinogenesis. Projections for extended deep space missions (such as to Mars) will be made.

Lett, J.T. (1991) Damage to cellular DNA from particulate radiations and the efficacy of its repair: Emphasis on double strand breaks. Presented at the Fourth Workshop on Heavy Charged Particles in Biology and Medicine GSI, Darmstadt, Germany, September 1991.

DNA, Repair, Heavy ions, RBE, Radiation therapy

This review concerns the radiochemical events resulting from the deposition of energy in cellular systems by sparsely ionizing radiations and densely ionizing particulate radiations of the type that will be encountered during extended space missions beyond the protection of the terrestrial magnetosphere, such as the projected mission to Mars. Those relativistic charged nuclei, which are of high (H) atomic number ($Z \geq 2$) and energy (E), are galactic in origin and are believed to arise from supernovae. Of the 'ambient' spectrum of HZE particles (heavy ions) in free space within the solar system, ^{56}Fe ions are thought to be the most dangerous for astronauts in terms of fluence and probable relative biological effectiveness (RBE). Since therapeutic application of charged nuclei is also a major subject of this workshop, the importance of modern ideas and findings for heavy-ion, and more conventional forms of radiation therapy also will be examined.

Lett, J.T. and Williams, G.R. (1993, in press) Effects of heavy ions in the rabbit retina: The formation and fate of DNA damage in photoreceptor cells. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute*, Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.

DNA, Heavy ions, Gamma rays, Photoreceptor cell, Rabbit

Of the three principal risks from exposure to galactic heavy ions during extended missions beyond the magnetosphere, namely carcinogenesis, cataractogenesis and damage to the central nervous system, the latter is the least understood. To address this problem we have been studying for the past 15 years damage introduced by ^{20}Ne, ^{40}Ar, ^{56}Fe ions and ^{60}Co gamma rays into the DNA of the photoreceptor cells of the retina of the young New Zealand white (NZW) rabbit (*Orcytolagus cuniculus*), and the subsequent integrity of that DNA throughout the remainder of the post-irradiation life span. Currently, these experiments are reaching conclusion and an overview of them will be presented.

Lucas, J.N., Poggensee, M., Cox, A.B., McLean, J.R.N., and Brooks, A.L. (1992) Chromosome translocation studies in irradiated primates using fluorescence *in situ* hybridization. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Fluorescence In Situ Hybridization, Lymphocyte, Rhesus monkey, Chromosome aberration, Translocation frequency

Fluorescence In Situ Hybridization (FISH) techniques were used to "paint" chromosomes in order to measure the persistence of chromosome-4 translocations in peripheral blood lymphocytes from rhesus monkeys exposed to ionizing radiation more than 25 years ago. Human chromosome-4 has been rearranged during the course of evolution relative to the structure of the macaque chromosome-4. In the owl monkey the probe for human chromosome-4 showed partial hybridization to multiple chromosomes. However, the human probe for chromosome-4 painted the entire length of the rhesus and cynomologus monkey chromosome-4 with no cross-hybridization to other chromosomes. Thus it appears that *Macaca* monkey chromosome-4 is homologous to human chromosome-4 for applications of established FISH protocols using human whole chromosome probes. We will present examples of several chromosomal type aberrations detected in irradiated monkeys, and we will present data on translocation frequency measurements in animals irradiated 25 years ago. The ability to use human probes to obtain cytogenetic data from *Macaca* species irradiated years previously or exposed to chemical clastogens makes this primate genus an excellent model for studying genetic damage.

Williams, G.R. and Lett, J.T. (1992) Effects of heavy ions on retinal photoreceptor cells. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 551.

Heavy ions, Rabbit, Retina, Aging, DNA damage, LET

To examine risks to the central nervous system (CNS) from galactic heavy ions, retinas of New Zealand white rabbits (6-9 weeks old) were exposed *in situ* to ^{20}Ne, ^{40}Ar, and ^{56}Fe ions (LET$_\infty$: 35, 90 & 220 keV/μm, BEVALAC, Lawrence Berkeley Laboratory).

With normal aging, DNA damage accumulated in photoreceptor cells during the second half of the median lifespan (5-7 years) and preceded cell loss. Following irradiation with ^{20}Ne or ^{40}Ar ions, late accumulation of DNA damage was dependent on dose and LET$_\infty$ and most cell loss also occurred late in the lifespan. Irradiation with ^{56}Fe ions, however, caused a marked early dose-dependent loss of photoreceptor cells (25%/Gy).

Exposure to ^{56}Fe ions could cause a significant loss of photoreceptor cells and other fully differentiated, post-mitotic cells of the CNS during a Mars mission.

TISSUE, ORGANS, AND ORGANISMS

Brenner, D.J. (1991) Effects of highly fractionated low doses of fast protons. Presented at the 9th International Congress on Radiation Research, Toronto, Canada, July 7-12, 1991.

Risk assessment, South Atlantic Anomaly, Proton, Inverse dose rate effect, Fast proton, Model development, Multiple fractions, High-LET, LET, Neutron

A limiting feature of a low orbital inclination space station may be the radiation dose from fast protons trapped in the "South Atlantic Anomaly." This dose, ~5 cGy/90-day mission, will be delivered in many hourly fractions.

Considerable evidence has accumulated, both *in vivo* and *in vitro*, supported by theoretical considerations, that when neutrons are delivered in multiple fractions, their effectiveness for transformation is increased. That this "inverse" effect is real now seems clear, and a consistent pattern has emerged as to its dependence on dose, fractionation and radiation quality.

Fast protons deposit dose as a mixture of low-LET interactions (from proton-induced Coulomb interactions) and high LET interactions (from target fragments); in this sense they are similar to fast neutrons, which also deposit dose as a mixture of low and high LET interactions. For trapped-proton interactions, a significant fraction of the dose equivalent will be due to the higher LET interactions, as confirmed by recent measurements on the Soviet space station, as well as from basic cross-sectional data.

It is possible that fast protons will also exhibit an inverse dose rate effect. We suggest that, based on the best available models and data, an *upper limit* in effect enhancement of ~15-20 might be expected for 5 cGy of fast trapped protons delivered in multiple fractions.

Cucinotta, F.A., Wilson, J.W., and Katz, R. (1992) Radiosensitivity parameters for lethal mutagenesis in *C. elegans*. Presented at the Eleventh Symposium on Microdosimetry, Gatlinburg, TN, September 13-18, 1992, p. 10.

Radiation biology, Mutagenesis, Nematode, Irradiation, Track structure, Mutation, Cell survival

For the first time track structure theory has been applied to radiobiological effects in a living organism. Data for lethal mutagenesis in *Caenorhabditis elegans*, obtained after irradiation with 9 different types of ions of atomic number 1-57 and γ-rays have yielded radiosensitivity parameters (E_0, σ_0, κ, m = 68 Gy, 2.5×10^{-9} cm^2, 750, 2) comparable to those found for the transformation of C3HT10 1/2 cells (180 Gy, 1.15×10^{-10} cm^2, 750, 2) but remote from those (E_0 and σ_0 = ~2 Gy, ~5×10-7 cm^2) for mammalian cell survival. Comparisons to cross sections for mutations in mammalian cells are also discussed.

Nelson, G.A., Schubert, W.W., and Kazarians, G.H. (1992) Heavy Ion radiobiology of the nematode *Caenorhabditis elegans*. In: *Radiation Research: A Twentieth-Century Perspective, Volume II: Congress Proceedings*, Eds. W.C. Dewey, M. Edington, R.J.M. Fry, E.J. Hall, and G.F. Whitemore. San Diego, CA: Academic Press, p. 493-497.

LET, Nematode, Radiation biology, Development, Genetics, Progenitor cell, Ultraviolet light, Ionizing photon, DNA repair, Mutation, Autosomal gene, Structural gene, X-chromosome duplication, Chromosome aberration, Gonad cell, Organogenesis

The space radiation environment is a mixed field of UV, X-ray and gamma-ray photons, electrons, protons, neutrons and atomic nuclei (cosmic rays or HZE particles). Of greatest potential risk to astronauts is the charged-particle component. This high linear energy transfer (LET) ionizing radiation is characterized by structured track patterns of energy deposition. The existence of structured energy deposition may produce unique cellular lesions and may introduce errors into concepts based on dose and dose-rate which reflect only the average energy absorbed per unit target mass. An understanding of unique biological consequences of high-LET radiation is essential to a fluence-based risk assessment system for space flight crews.

We are using the nematode, *Caenorhabditis elegans*, as a model system for radiobiology studies with high-LET radiation as it possesses numerous advantages for investigation of development and genetics *in vivo*. It is a small self-fertilizing hermaphrodite with a fixed cell number and a nearly invariant developmental program that allows adult abnormalities to be directly traced to

defects in single progenitor cells. *C. elegans* is a diploid animal with six pairs of chromosomes and a haploid genome size of 8×10^7 DNA base pairs making it intermediate in scale between *Drosophila* and *Saccharomyces*. Its 3-day generation time and ease of handling combine to facilitate conventional genetic manipulation. The organism has been extensively reviewed; the most comprehensive summary is that of Wood.

Using *C. elegans* we are attempting to characterize the kinetics of production, and to identify any unique qualitative features, of cellular and genetic lesions induced *in vivo* by UV light, ionizing photons, and high-LET accelerated particles and neutrons. The effects on putative DNA repair-defective rad mutants are also being studied in this context. To this end we have concentrated our efforts on five end points. These are: 1) induction of mutations in a set of about 400 essential autosomal genes, 2) induction of mutations in a single structural gene, *unc-22*, 3) induction of X-chromosome duplications, 4) chromosome aberration leading to formation of stable anaphase bridges in the larval intestine, and 5) inactivation of gonad blast cells leading to sterility and abnormal organogenesis.

Worgul, B.V. (1992) Starry eyes: Space radiation and the visual system. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 556.

Model development, Eye, Lens, Biological dosimeter, Epithelial tissue, Retina, Central nervous system

Given its criticality in space activities the visual system should figure prominently into concerns regarding human vulnerability to the radiational environment. The placement of the eye, its anatomy, and physiology are all geared to process relatively low energy photons. These same characteristics, in turn, place the eye at considerable risk to damage from the higher energy radiations to which it is exposed. The hazards that radiation presents to the organ must be considered in terms of the unique ocular organization, including it vasculature, musculature and enervation. Of equal importance is the fact that its natural history makes the eye an excellent paradigm for determining effects of radiation on tissues less amenable to ready assay. The lens for example has served admirably as a "biological dosimeter" and, because it is a totally epithelial tissue, as a representative of epithelial cell response to radiation. The retina, an externalized portion of the brain has provided an unparalleled opportunity to gauge radiation effects on the CNS. The accessibility of the transparent ocular media and retinal function to non-invasive analyses recommend the eye for a long-term longitudinal study.

Worgul, B.V. (1991) Through the eyes of astronauts. *ASMA 62*: A43.

Eye, Lens, Biological dosimeter, Epithelial tissue, Central nervous system, Retina, Enervation

A rationale for sending man into space rests on the argument that when venturing into the unknown there is no replacement for the real-time advantage

offered by the eye/brain connection. Given its criticality in space activities the visual system should figure prominently into concerns regarding its vulnerability to the radiational environment. The placement of the eye, its anatomy, and physiology are all geared to process relatively low energy photons. These same characteristics, in turn, place the eye at considerable risk to damage from the higher energy radiations to which it is exposed. The hazards that radiation presents to the organ must be considered in terms of the unique ocular organization, its vasculature, musculature and enervation. Of equal importance is the fact that its very anatomy, physiology, and location makes the eye an excellent paradigm for determining effects of radiation on tissues less amenable to ready assay. The lens for example has served admirably as a "biological dosimeter" and, because it is totally epithelial tissue, as a representative of epithelial cell response to radiation. The retina, an externalized portion of the brain has provided an unparalleled opportunity to gauge radiation efforts on the CNS. Thus, the eye can and should be a major focus of the medical aspects of radiation exposure during manned space activities. The amenability of the transparent ocular media and retinal function to non-invasive analyses recommend the eye for a long-term longitudinal study. The opportunity for the accumulation of a database generated over the next two decades of LEO missions should be exploited. Coupled with ground-based experiments such a study promises an appreciation, to the level of predictability, of the potential damage which may be incurred during long duration deep space forays.

Worgul, B.V. (1993, In press) Heavy Ion radiobiology: Focus on the lens. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute,* Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.

Lens, Cataracts, Biological dosimeter, Risk assessment, Cytopathology, LET, Heavy ions, Cataractogenicity, RBE, Cataractotoxicity, Genotoxicity, Differentiation

Perhaps no other system has served our understanding of *in vivo* normal tissue response to radiation than has the lens and its primary pathology, cataract. Its cellular makeup, sensitivity and amenability to longitudinal noninvasive analyses recommend this ocular tissue for space radiation research. Historically the lens has proven to be extremely useful as a "biological dosimeter" for risk assessment and a means for testing theories of radiation action on biological systems.

The considerable unknowns associated with heavy ion effects have stimulated the need to fully define this critical component of the galactic cosmic radiation. While cataracts and their attendant cytopathology do not differ qualitatively from that which occur following exposure to low LET radiation they are quantitatively far more affected by heavy ions. Cataractogenecity increases with decreasing heavy particle dose when compared to X-rays. The relative biological effectiveness (RBE) for cataracts reflects a linear quadratic relationship. Cataractotoxicity is further enhanced by protracting the exposure in a dose dependent way. Taken together an inverse dose rate effect and the extreme sensitivity of the lens of low doses of heavy ions intimate that the exposures

during manned forays into deep space will be problematic as regards the eye. This is underscored by recent reassessment of the biological effects of high LET neutrons at Hiroshima/Nagasaki test work suggests RBE's for cataracts in the range observed experimentally for heavy ions of similar LET. Finally, because cataracts are the expression of genotoxicity and reflect abnormal differentiation, the findings may be diagnostic of potential damage to integrated biological systems less amenable to ready assay.

IN VIVO/IN VITRO SYSTEMS

Brenner, D.J., Geard, C.R., and Hall, E.J. (1992) Effects of dose protraction on neoplastic transformation by GCR. Presented at the NASA Space Radiation Health Program Contractors Meeting, Houston, TX.

Risk assessment, GCR, Model development, Cell cycle, Carcinogenesis, Inverse dose rate effect, Fission neutron

There is now a substantial body of evidence for endpoints such as oncogenic transformation *in vitro*, and carcinogeneis and life shortening *in vivo*, that dose protraction leads to an increase effectiveness relative a single, acute exposure - at least for radiations of medium LET. This phenomenon has come to be known as the "inverse dose rate effect," because it is in contrast to the situation at low LET, where protraction in delivery of a dose of radiation results in a decreased biological effect.

The quantity and quality of the published reports on the "inverse dose rate effect" leaves little doubt that the effect is real, but the available evidence indicates that the magnitude of the effect is due to a complex interplay between dose, dose rate and radiation quality. The available data on the inverse dose rate effect follows a consistent pattern in regard to dose, dose rate and radiation quality; we describe a model that predicts these features, and discuss the significance of the effect for radiation protection in space.

The approach, first suggested by Rossi and Kellerer, and discussed further by Brenner and Hall, and Elkind, is to postulate that cells in some period of their cycle are more sensitive to radiation (for the endpoint of interest) than cells that are not in this period. If this is the case, an acute high LET exposure of cycling sells will result in some fraction of these sensitive cells receiving (on average) very large depositions of energy - much greater than required to produce the changes that may lead to oncogenic transformation. On the other hand, if the exposure is protracted or fractionated, a larger proportion of sensitive cells will be exposed, though to smaller (on average) numbers of energy depositions; however, because we are considering high LET exposures, it is postulated that the total energy deposited in the sensitive cells by these smaller number of energy depositions will still be large enough to produce the change in the cell which may ultimately lead to a transformation. This postulate amounts to suggesting that the response function (i.e. the probability that a sensitive cell will show an effect after absorbing a given amount of energy) saturates, becoming constant, for large total energy depositions. Based on general biophysical

considerations this is not an implausible suggestion. At low LET, on the other hand, the response function would be expected to change with a change in total energy deposition and so no inverse dose-rate effect would be expected. Thus a differential sensitivity to low LET radiation through the cell cycle would not be expected to produce an inverse dose-rate effect at low LET, although it might be an indicator of an effect at high LET.

In a direct test of the model, Miller exposed $C_3H10T_{1/2}$ cells to 40-keV/μm deuterons, both in plateau phase, and whilst exponentially growing. No inverse dose rate effect was seen with plateau-phase cells, but a significant effect was seen with cells that were exponentially growing. Direct support for the model also comes from preliminary experiments by Hill who observed a differential sensitivity for transformation of synchronized $C_3H10T_{1/2}$ cells by fission neutrons.

For GCR, we would expect inverse dose-rate effects to disappear at very high LET because of a reduction in the number of cells being hit, and to disappear at low LET because most of the dose is deposited at low specific energy. However, the medium LET range is where the majority of GCR dose is deposited, and so enhancement effects might well be expected, and have indeed been observed.

Lindgren, A.L., Riley, E.F., Miller, R.C., Austin, B.T., and Ainsworth, E.J. (1992) Recovery from G_0/G_1 block in lens cells following X-, ^{56}Fe, and neutron irradiations. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Lens, Wounding, Neutron, Cataracts, Mitotic abnormality

Cells in the quiescent region of the lens epithelium were stimulated to enter cell cycle progression by mechanical wounding. [^{3}H]-thymidine was used to label cells in DNA synthesis at hours 12 to 20 following stimulation. The DNA synthesis responses of irradiated epithelia were compared to those for control epithelia after recovery intervals of 3, 7, 14, and 28 days. A G_0/G_1 block was demonstrated after 0.5 to 10 Gy X-rays, 0.5 to 2 Gy ^{56}Fe, and 2 Gy neutrons. By 14 days, recovery was complete in all radiation treatment groups except the 10 Gy X-ray group. Dose response curves showed a shoulder after X-irradiation with D_q being time-dependent to t < 14 days. The D_0 remained constant from days 3 to 28. A time dependent D_0 was demonstrated for ^{56}Fe and neutron dose response curves. RBE values ranged from 6.6 to 1.7 from 3 to 14 days following ^{56}Fe irradiation. An RBE of 4.4 was shown for neutrons at 3 days. The demonstrated recovery from radiation-induced G_0/G_1 block is in contrast to the absence of recovery shown with cataracts and mitotic abnormalities.

CARCINOGENESIS AND LIFE SHORTENING

Ainsworth, E.J. (1992) Life span studies in irradiated animals. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 559.**

Life span, Aging, Stem cell, Risk assessment, Cancer, Rodent, Canine

Studies on radiation-induced cancer involves many approaches that span molecular, cellular and animal experiments. Information derived from life span studies, primarily on rodents, includes dose-response relationships for tumorgenesis, life shortening, non-neoplastic diseases, and physiological changes associated with aging or radiation injury. A brief review is provided of the major life span studies on rodents, canines and non-human primates. Information from prior murine life span studies on photons, protons and neutrons represents a critical baseline for comparison with recent result from and extensive collaborative study on the effects of single or fractionated doses of 600 MeV/amu ^{56}Fe particles, given over six weeks, on life shortening and tissue damage in mice. The available life span data on heavy charged particles will be presented and interpreted in the context of what additional data are needed for a variety of model systems in support of risk assessment.

Alpen, E., Powers-Risius, P., DeGuzman, R., and Fry, R.J.M. (1992) The Harderian gland model for tumorigenesis. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 558.**

Harderian gland, Risk coefficient, HZE particles, Prolactin, LET, RBE, Tumorigenesis, Dose fractionation

The murine Harderian gland has been used as a test system for estimation of the risk coefficient for HZE particle radiations. The system has the advantage of a low normal incidence of tumors, allowing the detection of increases resulting from doses as low as 0.05 Gy of HZE radiation. The development can be modulated by promotion by pituitary isografts, and presumably the promotion is caused by prolactin. The emphasis has been on measuring the initial slope of the prevalence vs. dose curve for ions ranging from 250 MeV protons to 600 MeV lanthanum ions, with LET values up to 1000 keV/μm. The initial slope RBE values range from slightly above 1.0 to nearly 35 for ^{56}Fe. Fractionation of ^{56}Fe exposures dramatically increases effectiveness of the radiation.

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Alpen, E.L., Powers-Risius, P., Fry, R.J.M., and DeGuzman, R. (1992) Fractionation of high energy ^{56}Fe ions and Harderian gland carcinogenesis in the mouse. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Tumorigenesis, Fractionation, Harderian gland, HZE particles, Animal models, Mouse

It has been shown for a number of endpoints that some high LET radiations appear to be biologically more effective when the dose is delivered in multiple fractions than when the dose is given in a single session. In particular, Ullrich has shown enhancement of the response by fractionation of the exposure to fast neutrons for mammary tumor induction and lung tumor induction. The mechanism and generality of this response is not well understood. We have collected extensive data on tumorigenesis in the mouse Harderian gland after single dose, high energy, high Z charged particle radiations, and, in particular for 600 MeV/ iron particle beams. The system is sensitive enough to detect increased tumor incidence after as little as 0.05 Gy. We have compared tumor prevalence in the mouse Harderian gland after 0.40 Gy given in a single exposure to 0.42 Gy given in six fractions of 0.07 Gy and an interfraction interval of two weeks. In 60 animals receiving the single exposure the prevalence of tumors at 16 months was 29.4%. In 67 animals receiving the six fractions the prevalence was 43.3%. The calculated risk ratio is highly significant, indicating appreciable enhancement of the neoplastic endpoint by fractionation of the exposure. A comparison with the fast neutron data on enhancement by fractionation will be offered.

Joseph, J.A., Rabin, B., Dalton, T., Kandasamy, S., and Hunt, W. (1992) Accelerated brain aging, induced by putative space radiation (^{56}Fe particles): Implications for motor behavioral changes. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 555.

Aging, Space radiation, Rat

Future astronauts may be exposed to particles of high charge and energy (HZE's; e.g., ^{56}Fe) from cosmic rays. Present experiments showed that ^{56}Fe HZE's (0.10 - 1.0 Gy), had deleterious effects [similar to those seen previously in old (24 mo)] in young (3 mo) rats [e.g., decrements in wire suspension motor behavior, reductions in agonist sensitivity of muscarinic cholinergic receptors (mAChR). Subsequent experiments indicated that in both conditions (aging and radiation) mAChR signal transduction is compromised as a result of decrements in mAChR-G-protein coupling/uncoupling. The findings suggest exposure to space radiation may accelerate central indices of aging.

Wilson, J.W., Townsend, L.W., Nealy, J.E., Hardy, A.C., Atwell, W., and Schimmerling, W. (1991) *Preliminary Analysis of a Radiobiological Experiment for LifeSat.* NASA Technical Memorandum 4236.

Radiation biology, Tumorigenesis, LifeSat, Dosimetry, Mouse, Harderian gland, RBE

With the possibility of performing radiation life science experiments on a dedicated satellite (LifeSat) in space, a combined effort in radiation physics and radiation dosimetry, in addition to radiation biology, is clearly required to ensure that meaningful biological experiments can be performed. To better understand the relationship of these disciplines, we examine some possible LifeSat missions. As a trial biological system, we consider tumorigenesis in the Harderian gland of mice, a system of sufficient radiosensitivity for which the relative biological effectiveness (RBE) is well-defined by laboratory experiments.

Wood, D.H. (1992) **Head and neck tumors after energetic proton irradiation in rats. In:** *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* Washington, D.C., August 28-September 5, 1992, p. 561.

Rat, Mortality, Cancer, Proton, Aging, Animal models

This report summarizes mortality and cancer incidence among 1000 male Fischer-344 rats that were exposed to head-only spread Bragg-Peak proton irradiation at a dose rate of approximately 1.25 Gy per minute in July, 1989. Dose groups were 0.0 (sham), 2, 4, 8.5 and 18 Gy absorbed dose from a 138-MeV beam attenuated by Lucite filters to provide a uniform dose distribution throughout the head of the subjects. The primary cause of death in the 18-Gy group during the first 75 weeks was obstructive squamous metaplasia of the nasopharynx, a precancerous condition that has been observed in nearly all of the subjects in this group. Pituitary adenomas are also a common finding in the irradiated rats. Glial cell tumors of the type that were associated with proton irradiation in rhesus monkeys in earlier studies have been uncommon, and the only malignant glioma has occurred in a control animal. The final report is expected to include analysis of data collected through 1 February, 1992.

CATARACTOGENESIS

Blakely, E.A., Daftari, I.K., Gillette, E.L., Lee, A.C., Lett, J.T., Castro, J.R., and Char, D.H. (1992) **Helium-ion induced human cataractogenesis. In:** *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* Washington, D.C., August 28-September 5, 1992, p. 557.

Uveal melanoma, Helium ion, Cataractogenesis, Tumor, RBE, Risk assessment, Aging

We have begun an analysis of the medical records of 332 patients treated at LBL since 1979 with accelerated helium ions for uveal melanoma. A preliminary examination of 261 patients who were treated before 1986 showed that 74

individuals (28%) had developed asymmetric, clinically significant lens opacifications. Lens doses were determined by the location of the tumors. A total dose range of 50 to 80 Gray-equivalent to the tumor was used assuming an RBE of 1.3. All patients received the total dose in 5 fractions over a 10-14 day period. The lens dose varied from 10% to 100% of the tumor dose, so that cataractogenic responses from a wide range of fractionated doses can be evaluated. We will report our initial results of the dose-dependent latency for the development of cataract among these patients. We believe these data are relevant to estimating the human risk for cataract in space flight.

Carr, K.E., McCullough, J.S., Brennan, P., Hayes, T.L., and Ainsworth, E.J. (1992) Heavy ion induced changes in small intestinal structural parameters. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 557-558.

Heavy charged particles, Time dependence, Crypt cell

Numbers of structural parameters present per circumference of small intestine were used to prepare a graphical and tabular Morphological Index data display, summarizing the changes after irradiation with neon, iron, and niobium ions. Collared crypts are dose and time dependent structures seen after neon and iron ion irradiation. Histological changes are seen clearly in the epithelial compartment after all three treatments. There is also obvious change in the submucosal plexus after neon ion irradiation and subtle alterations in the neuromuscular compartment after iron or niobium ion treatment. The current conclusion is that, although there are some broad principles summarizing the effects of heavy ion treatment as opposed to photon irradiation, many changes are characteristic to the type of particle used and to dose and time.

Cox, A.B., Lee, A.C., Williams, G.R., and Lett, J.T. (1992) Late radiogenic cataracts from high-energy particles in selected animal species: A comparative study. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 557.

Cataracts, Cataractogenesis, High-LET, Rat, Rabbit, Dog, Monkey, Animal models

Late cataracts caused by particulate radiations are among the risks to be considered for astronauts undergoing long-term sojourns in space. We have examined late radiation cataractogenesis following exposure to low- and high-LET (linear energy transfer) radiations in animal models including the rat, the rabbit, the dog and the rhesus monkey. We will present information on radiogenic cataracts in the four species and discuss extrapolation of those data between and among the models studied as well as to the human situation. Implications of these data for accurate determinations of risk factors for any long-term ocular damage which might be expected in astronauts following completion of a trip to Mars will be discussed as well.

Lett, J.T. and Cox, A.B. (1992) Risks of radiation cataracts from interplanetary space missions. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Risk assessment, Vision, Aging, Cataractogenesis

Ionizing radiations represent an acknowledged hazard for astronauts on extended missions in interplanetary space. Protracted exposures to cosmic and solar radiations beyond the protection of the geomagnetic field during the projected Mars mission can induce vision-impairing levels of lenticular opacification but only *after* the proposed mission careers of astronauts are over. Risks of clinically significant cataracts developing *during* an extended mission through acute exposures to protons from large solar particle events (SPEs) can be obviated by effective satellite warning systems.

Stationary cataracts, the magnitudes of which depend upon dose, dose rate, radiation quality and *age* at *exposure*, arise in longer-lived mammalian species after an induction period, and usually change little until the final third of subsequent lifespan. The, lenticular opacification increases progressively and blindness can result even after low radiation doses. Tissue degeneration concomitant with such *late* radiation cataractogenesis is of particular concern because it may jeopardize surgical remediation of the impairment of vision.

Human radiation cataractogenesis can be simulated in lifespan studies of such longer-lived animal models as the monkey and rabbit. Lenticular opacification caused in those animals by important components of the galactic heavy ion spectrum, and protons of SPE energies, have been examined over the past 20-25 years in ground-based experiments. Analysis, including collaborative use of the NASA Langley cosmic ray shielding code (HZETRN), of stationary opacifications caused in young animals by ^{20}Ne, ^{40}Ar, and ^{56}Fe ions, protons (10-2300 MeV) and ^{60}Co γ-photons has generated provisional estimates of risks of *stationary* cataracts for the Mars mission. For *mature* humans those risks are likely to *decrease*, but formal estimation will require additional information on the effect of age at exposure that should become available in about five years.

Qualitative assessments of *late degenerative* opacification during the final third of the human lifespan, the real danger from lenticular radiation damage, will be made from the responses of young animals to heavy ions and high energy protons. Those risks are likely to *increase* for *mature* humans.

Radiosensitive, short-lived, rodents are not good models with which to simulate late radiation cataractogenesis in humans. Use of rodent data can result in exaggerations of human cataractogenic risk that might arise unwarranted concerns about the safety of manned missions in interplanetary space.

Medvedovsky, C., Ainsworth, J., Brenner, D.J., Huang, Y., and Worgul, B.V. (1992) The influence of dose, dose-rate and particle fragmentation on cataract development. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 557.

Cataracts, Heavy charged particles, Mouse, Single vs. fractionated doses, Fragmentation

Because activities in space necessarily involve chronic exposure to a heterogeneous charged particle radiation field it is important to assess the influence of dose-rate and the possible modulation role of heavy particle fragmentation on biological systems. Using the well studied cataract model mice were exposed to 600 MeV/amu ^{56}Fe iron ions either as acute or fractionated exposures at a variety of doses. Additional groups of mice received 20 cGy behind 5 cm of polyethylene. Animals were examined by slit lamp biomicroscopy over their year life spans. Fractionation of a given dose did not reduce the cataractogenecity of the radiation compared to the acute regimen. Fragmentation of the beam in the polyethylene did not alter the cataractoxicity of the ions either when administered singly or in fractions.

Medvedovsky, C., Worgul, B.V., Brenner, D.J., Huang, Y., and Ainsworth, J. (1992) The effects of dose, dose rate and charged-particle fragmentation on cataractogenesis in the mouse lens. *Radiation Research* 40: 93.

Single vs. fractionated doses, Cataractogenesis, Heavy charged particles, Fragmentation, Mouse

Crucial to an appreciation of the hazard that radiation might present to those frequenting the space environment is an understanding of the effects of heavy-ions on higher order biological systems such as tissues and organs. Inasmuch as manned space activities involve a low-dose rate exposure to a heterogeneous charged-particle field, consideration must be given to the influence of dose-rate and the possible modulating role of fragmentation of heavy particles. In order to address the problem male mice were exposed to 600 MeV/amu ^{56}Fe iron ions at total doses of 5, 10, 20, and 40 cGy administered singly or as six fractions over 12 weeks. In addition, groups receiving a single and fractionated dose of 20 cGy behind a 5 cm polyethylene shield were also studied. The animals were examined by slit lamp biomicroscopy at intervals of two to three months over their three year life spans. The experiments indicate that the fragments which arise as the iron particles traverse the 5 cm of unit density material have a cataractogenic potential which is similar to the pristine (unshielded) beam. Fractionation of these ions in the unshielded of shielded regimen does not produce a "sparing" effect. The details and implications of the data will be discussed.

Medvedovsky, C., Worgul, B.V., Brenner, D.J., Huang, Y., and Merriam, G.R. (1992) Cataractogenesis: Low-dose and low dose rate high-LET radiation exposure. *Investigative Ophthalmology and Visual Science* 33(4): 1171.

Single vs. fractionated doses, LET, Cataractogenesis, Rat, RBE, Argon ions, Iron ion, Cataracts

High-LET radiation effects are generating a heightened sense of urgency due to the consequences of the DS86 re-evaluation of the Japanese A-bomb dosimetry and plans for increased manned space activities. Therefore we examined the effect of single and fractionated doses of plateau 450 MeV/amu (LET = 195 keV/μm) ^{56}Fe ions on cataractogenesis in a 28 day old ($\pm$ 1 day) Columbia Sherman rats. For the acute exposure study doses of 1, 2, 5, 25 and 50 cGy were evaluated. The fractionated regimens involved total doses of 2, 25 and 50 cGy. The reference radiation consisted of 50, 100, 200 and 700 cGy of 250 kVp X-rays. The animals were examined on a weekly or biweekly basis for two years. Using non parametric techniques the RBE's for the single doses versus X-rays were estimated. In accordance with previous rat findings using 570 MeV/amu ^{40}Ar ions, the RBE increased rapidly with decreasing dose. In addition, fractionated doses of ^{56}Fe ions result in a dose dependent enhancement. The details and significance of these findings as they relate to current theories of radiation cataractogenesis and risk assessment will be discussed.

Shinn, J.L., Wilson, J.W., Cox, A.B., and Lett, J.T. (1991) A study of lens opacification for a Mars mission. Presented at the 21st International Conference on Environmental Systems, San Francisco, CA, July 15-18, 1991, 5 p. SAE Paper 911354.

Risk related cross section, Risk assessment, Cataractogenesis, Rabbit, HZETRN, Radiation shielding, Fragmentation, Animal models, Lens, Optical tissue, Optical model

Risk assessment in an environment of mixed radiation quality has been addressed in the past by use of the experimental parameter "relative biological effectiveness" (RBE) or the related "quality factor" (Q), which is defined for purposes of radiation protection. Herein, an alternative method which is based on risk-related cross sections, is used to estimate risks of "stationary" cataracts caused by radiation exposures during extended missions in deep space. Estimates of the even more important risk of late degenerative cataractogenesis are made on the basis of the limited data available. Data on lenticular opacification in the New Zealand white rabbit, an animal model from which such results can be extrapolated to humans, are analyzed by the Langley cosmic ray shielding code (HZETRN) to generate estimates of stationary cataract formation resulting from a Mars mission. The effects of the composition of shielding material and the relationship between risk and linear energy transfer (LET) are given, and the effects of target fragmentation on the risk coefficients are evaluated explicitly. The needs for further experimental lens opacification studies are discussed.

Tao, F., Khorrami, A., Medvedovsky, C., David, J., Broglio, T., Powers-Risius, P., Alpen, E.L., and Worgul, B.V. (1992) Effects of heavy ions on cellular parameters in the lens. *Investigative Ophthalmology and Visual Science* 33(4): 1170.

Cataractogenesis, Heavy ions, Micronuclei

A critical factor for manned missions into deep space is the heavy charged particle flux to which the astronauts will be exposed. Cataract formation is among the possible consequences of such exposure. Cataract related epithelial damage, such as abnormal mitoses, micronuclei (MN), and meridional row (MR) disorganization have been studied in the lenses of mice irradiated with 670 MeV/amu ^{20}Ne, 600 MeV/amu ^{56}Fe and ^{93}Nb ions. The LET's ranged from 25 KeV/μm to 464 KeV/μm, and the particle fluence (dose) from 1.46×10^3/mm^2 to 2.6×10^4/mm^2. Our studies show that the number of abnormal mitotic figures, nuclear fragmentation and micronuclear frequency increases at a given dose as the LET rises, however, MR disorganization goes up to an estimated level and remains constant. For particles of the same LET, the severity of MR disorganization and MN number goes up with the increasing fluence. These observations demonstrate that cosmic heavy charged particles have strong cataractogenesis effects and the contribution of the different particle components to cataractogenesis depends on their LET and fluence. We also found that both LET and particle fluence changed neither the number nor the density of cells in the epithelial population at 64 weeks post irradiation, although there was an early modulating effect on cell numbers. These findings are consistent with the generally held view that radiation cataractogenesis is tied to early events in the epithelium.

Tao, F., Khorrami, A., Medvedovsky, C., David, J., Broglio, T., Powers-Risius, P., Alpen, E., and Worgul, B.V. (1992) The effect of dose and LET on cytological parameters in the rodent lens. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 557.

Opacification, Micronucleation, Mouse, Cataractogenesis

A limiting factor for manned missions into deep space is the heavy charged particle flux to which the astronauts will be subject. Cataract is among the possible consequences of such exposure. However, associated with and often presaging the opacification of the lens are effects on the cell population at risk, the lens epithelium. Alterations in growth fraction, micronucleation and meridional row organization have been examined following exposure of mouse lenses to particles of a wide range of LET and fluence. The findings indicate that dose and LET modulate the effects on those cellular parameters thought to be associated with the cataractogenic process. The number of cells surviving at late times post-irradiation were comparable to controls and their density was independent of the exposure. These observations are consistent with the current theory of the mechanism of radiation cataractogenesis.

Tao, F., Medvedovsky, C., David, J., Broglio, T., Powers-Rislus, P., Alpen, E.L., and Worgul, B.V. (1992) Accelerated heavy ion effects in the murine lens. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Cataracts, Micronuclei, Cataract load hypothesis, HZE, Mouse

Radiation cataracts arise from a primary effect on the lens epithelium mediated by aberrant differentiation. The epithelial damage is reflected in altered cellular dynamics and division-based pathologies such as abnormal mitoses and micronuclei (MN). Meridional row (MR) disorganization has been demonstrated in experimental animals and humans to be an indicator of abnormal differentiation and diagnostic of cataract. These and a number of other parameters have been studied in the lenses of mice irradiated with 670 MeV/amu ^{20}Ne, 600 MeV/amu ^{56}Fe and 600 MeV/amu ^{93}Nb ions. The LET's ranged from 25 keV/μm to 464 keV/μm and the particle fluences from 5×10^3/mm^2 to 2×10^5/mm^2. Our studies show that MR disorganization and MN frequency are related not only to the fluence (number of heavy particles/unit area) but also to the LET of the heavy-ions. At a given dose as the LET rises the number of abnormal mitotic figures, micronuclear frequency, and disorganization of the MR also increases. For particles of the same LET the severity of MR disorganization and MN number go up with increasing fluence (dose).

These observations are consistent with the cataractotoxic load hypothesis. Furthermore the data taken together support the contention that radiation cataractogenesis is the result of genomic injury to the lens epithelial cells.

Worgul, B.V. (1992) The cataractotoxic load hypothesis: A model for an exogenous basis for cortical cataract development. *Investigative Ophthalmology and Visual Science* 33(4): 1167.

Cataract load hypothesis, Cataracts, Opacification, Cataractogenic potential

The cataractotoxic load hypothesis (see Worgul et al., 1989, *Lens and Eye Tox. Res.* 6(4):559-571) was first broadly formulated to address the possibility of an exogenous basis for senescent cortical cataract development. Although a number of clinical and experimental observations seem to run counterintuitive to the general experience with biological systems and the very premise of the hypothesis on a close examination the general experience has not only been consistent with, but predicated by, the model. Central to the model is its dependence on primary genotoxic damage, expressed by abnormal differentiation and driven by growth kinetics. In it cataract latency (the time between the insult and the clinical signs of opacification) is tied to the necessity for a critical mass of abnormal fibers to accumulate. The refined model takes into account that the latent period is heavily modulated by growth kinetics which in

turn reflects the age of the individual, the accumulated damage to date, and finally the severity of the damage (on a population basis) currently incurred. Together these all define whether or not an "event" would be cataractogenic but suggest that perturbations in any one alone may be insufficient to lead to cataract. Such disparate data as the inverse dose-rate effect for certain types of radiation and heretofore inexplicable age modulating dose effect of radiation are in accordance with the model as is the synergy, or lack thereof, of certain other cataractogens. The hypothesis may not only be useful in suggesting experiments to test its veracity but also, if proven, had a role in policy decisions regarding relative risk and the manner in which to best test the efficacy of purported anticataractogenic drugs. The model and the data supporting it will be discussed in detail.

Worgul, B.V., Medvedovsky, C., Brenner, D.J., Huang, Y., and Merriam, G.R., Jr. (1992) Low-dose heavy-ion cataractogenesis. *Radiation Research* 40: 93.

Single vs. fractionated doses, Cataractogenesis, Rat, X-ray, High-LET, RBE

Radiation cataract analysis in the rodent model has a proven track record as a means to assess the effects of flow-dose and low-dose rate radiation on *in vivo* systems and has been particularly useful for assessing the biological effects of high-LET radiation. High-LET radiation effects are generating a heightened sense of urgency due to the consequences of the DS86 reevaluation of the Japanese A-bomb dosimetry and plans for increased manned space activities. Therefore we examined the effect of single and fractionated doses of plateau 450 MeV/amu (LET = 195 keV/μm) [56]Fe ions on cataractogenesis in 28 day old ($\pm$ 1 day) Columbia Sherman rats. For acute exposure study doses of 1, 2, 5, 25, and 50 cGy were evaluated. The fractionated regimens involved total doses of 2, 25 and 50 cGy. The reference radiation consisted of 50, 100, 200 and 700 cGy of 250 kVp X-rays. The animals were examined on a weekly or biweekly basis for two years. Using non parametric techniques the RBE's for the singly doses versus X-rays were estimated. In accordance with previous rat findings using 570 MeV/amu [40]Ar ions, the RBE increased rapidly with decreasing dose. In addition, fractionated doses of [56]Fe ions result in a dose dependent enhancement.

Worgul, B.V., Medvedovsky, C., Brenner, D.J., Huang, Y., and Merriam, G.R., Jr. (1992) Low dose/low dose-rate heavy ion cataractogenesis. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 559.

Single vs. fractionated doses, Iron ion, Cataractogenesis, Rat lens, X-ray, RBE

Plans for a greater presence of man in space coupled with the DS86 reevaluation of the Japanese A-bomb survivors has set the stage for an intense effort to fully

define the risk from high-LET radiation exposure. We, therefore, have compared the effect of single and fractionated doses of plateau 450 MeV/amu (LET = 195 KeV/μm), ^{56}Fe ions on cataractogenesis in 28 day old (± 1 day) Columbia Sherman rats. The doses which ranged from 1-50 cGy and were compared to doses of 250 kvp X-rays ranging from 50-700 cGy. Using nonparametric techniques the RBE's for the single doses verses X-rays were estimated. Consistent with earlier observations following 570 MeV/amu argon ions, the RBE's increased rapidly with decreasing dose. Fractionating the heavy ion dose produced a dose dependent augmentation of the response.

Worgul, B.V., Brenner, D., Medvedovsky, C., Merriam, G.R., Jr., and Huang, Y. (1991) The cataractogenic potential of low doses of high LET radiation. *Investigative Ophthalmology and Visual Science* **32(4): 851.**

LET, RBE, Rat lens, Opacification, Argon ions, X-ray, Cataracts, Quality factor, Protection standard

Recent dosimetric reanalysis (DS86) of the Hiroshima/Nagasaki data has stimulated a reevaluation of the risk from high LET radiation exposure in humans. We therefore studied the prevalence, hazard and relative biological effectiveness (RBE) for various stages of lens opacification in rats induced by very low doses of fast (570 MeV/amu) argon ions (LET ≈ 88 keV/μm), compared to those for 250 kVp X-rays. Doses of argon ions from 0.01 to 0.25 Gy were used and the RBE's of these ions were estimated using a non-parametric technique. At the end of the 67 week follow-up period, 90% confidence intervals for the RBE of the argon ions relative to X-rays were 4-8 at 0.25 Gy, 10-40 at 0.05 Gy and 50-100 at 0.01 Gy. The results are in reasonable accord with an RBE varying as:

$$RBE = (25/D_A)^{1/2}$$

where D_A is the dose of argon ions in Gy. This relationship is consonant with a linear quadratic formulation as predicted by the Dual Radiation Theory.

Our results are consistent with those RBE's for cataracts generated from the DS86 analysis of the Japanese A-bomb survivors. Furthermore when extrapolated to higher doses our findings are also consistent with previous high dose data for argon-ion cataractogenesis in rats, mice and rabbits. We conclude from these results that at very low doses the quality factor (Q) of 20 currently being suggested for radiation protection standards is inadequate and a Q of at least 50 should be considered.

GENETICS/DEVELOPMENTAL

Coohill, T., Marshall, T., Schubert, W., and Nelson, G. (1988) Genetic and developmental responses of radiation sensitive mutants of the nematode, *C. elegans*, to ultraviolet, high and low radiation. In: *Terrestrial Space Radiation and Its Biological Effects*, Eds. P.D. McCormack, C.E. Swenberg, and H. Bucker. New York: Plenum Publishing Corporation, p. 265-276.

Nematode, Ultraviolet light, High-LET, Mutation, Development

Some responses of the nematode *C. elegans* to ultraviolet (UV) high and low LET ionizing radiation are reported. This animal will be part of a dosimetric stack that will fly on a future space shuttle mission. Ten million larval worms will be sent into orbit to measure the effects of the space radiation environment on both the genetic and developmental processes in this biological test system. Here we report on some of the lethal, developmental, and mutational responses of wild type (N2) and five radiation sensitive mutants (*rad-1, rad-2, rad-3, rad-4* and *rad-7*) to UV (254 nm), ^{60}Co γ-rays, protons, and various high energy sub-atomic ions (HZE's) generated at the BEVALAC facility. An ideal candidate for studies involving UV is identified (*rad-3*). Radiation mutant sensitivity, compared to wild type, was not evident for experiments conducted with HZE's. A suitable mutational tester strain (JP10) has been developed for flight. Whether, in addition, a mutant hypersensitive to HZE's can be incorporated into this strain before launch is still questionable. *C. elegans* progeny, produced during the shuttle mission, will be conceived, born, and developed in the space environment.

Nelson, G.A., Coohill, T.P., Marshall, T.M., and Schubert, W.W. (1987) Genetic and developmental effects of heavy ion radiation in the nematode *C. elegans*. In: *Abstracts, Third Workshop on Heavy Charged Particles in Biology and Medicine*, Darmstadt, Germany, July 13-15, 1987, Abstract No. D6.

Nematode, Genetics, Mutation, LET, Differentiation, Cell reproduction, Chromosome aberration, Damage repair, Gamma rays

The nematode, *Caenorhabditis elegans*, is being used as a model system for the evaluation of high and low LET radiation effects on cell reproduction, differentiation and mutation *in vivo*. *C. elegans* is a small, simple nematode with a variety of tissues and organs including digestive system, nervous system, muscles, and reproductive system providing a variety of target individual to individual with fixed numbers of cells and fixed patterns of cell division and differentiation. Organs and tissues develop from single cell primordia and the developmental timing is fixed so that whole populations of animals can be age-

synchronized to produce animals with anatomical targets of precisely controlled cell number and function. Extensive genetic methods are available for the production and analysis of mutations, chromosomal aberrations and chromosome loss. Finally, short generation times (3-4 days) and high reproductive rates (280 progeny per self fertilizing hermaphrodite) provide a means of collecting data on large populations in a relatively short time.

Gamma rays from Cobalt-60 and accelerated particles produced at the Lawrence Berkeley Laboratory BEVALAC accelerator have been used in studies aimed at understanding the structures and repair of genetic lesions produced by ionizing radiation and providing risk assessment data for spaceflight crews encountering cosmic rays in earth orbit.

Nelson, G.A., Marshall, T.M., and Schubert, W.W. (1989) Genetic and developmental effects of high-LET radiation on the nematode *Caenorhabditis elegans.* **In:** *Multilevel Health Effects Research: From Molecules to Man,* **Eds. J.F. Park and R.A. Pelroy. Columbus, OH: Battelle Memorial Press, p. 61-66.**

Nematode, High-LET, Mutation, Radiation-sensitive mutant, Reproduction, Differentiation, Cell inactivation, Nucleoplasmic bridge formation, Chromosome aberration

Caenorhabditis elegans is being used as a model system for the evaluation of high and low linear-energy-transfer (LET) radiation effects on cell reproduction, differentiation, and mutation *in vivo.* Fluence/dose versus response and relative biological effectiveness (RBE) versus LET relationships have been constructed for the following end points using accelerated ions, gamma rays and fission spectrum neutrons.

Cell inactivation. Radiation damage to a four-cell gonad primordium interferes with the developmental program that constructs a functional adult gonad whose normal function is to produce 282 offspring by self-fertilization.

Mutation. Recessive lethal mutations are being isolated in a large region corresponding to 15% of the nematode's genome using a strain (JP10) containing the reciprocal translocation *eT1* (*III;V*) as a balancer. A set of 29 mutants generated by ions is being characterized to determine the relative abundances of point mutations, deletions, and chromosomal rearrangements.

Nucleoplasmic bridge formation. When newly hatched larvae are irradiated, defects in karyokinesis of intestinal cells arise; we propose that these defects are derived from events that lead to formation of polycentric chromosomes, which prevent completion of nuclear division and are seen in adult worms as nucleoplasmic bridges.

Duplications of unc-3. The production of duplications of the right arm of the X chromosome has been quantified with interesting kinetics, which suggests that particles are very efficient in producing chromosome breads but also are likely to produce second-site lethals.

Radiation-sensitive mutants. Rad mutants *rad-1,2,3,4* and *7* are being characterized with respect to the foregoing end points. Hypo- and hypermutability have been documented as well as inability to repair chromosome breaks.

Nelson, G., Marshall, T., and Schubert, W. (1989) Heavy Ion genetic studies with the nematode *C. elegans.* Presented at a Workshop on Biomedical and Space-Related Research with Heavy Ions at the BEVALAC, Berkeley, CA, March 16-17, 1989.

Nematode, Mutation, Damage repair, Chromosome aberration, Ultraviolet light, Gamma rays, LET, Gonad cell, Reproduction, Differentiation

We are interested in the mechanisms by which various forms of radiation induce genetic lesions and how such damage is repaired. The model system used for these studies is the nematode *Caenorhabditis elegans.* Our overall approach is to induce mutations or other lesions in cells whose environment or genotype is manipulated to alter the activity of DNA repair systems, the spatial pattern of energy deposition in the cells, and the relative contributions of direct ionization versus indirect damage by reactive chemical species. The five principal biological endpoints used in our analyses are: (1) induction of recessive lethal mutations in a genetic region balanced by the translocation *eT1*, (2) induction of anaphase bridges in intestinal nuclei, (3) induction of mutations in the *unc-22* gene, (4) duplication of the X-chromosome right arm and, (5) inactivation of gonad blast cells. Using this approach we have learned the following about *C. elegans'* response to radiation.

Fluence and dose versus response curves for each of the foregoing endpoints have been measured for UV light, ^{60}Co gamma rays, fission spectrum neutrons and accelerated ions. From these measurements, inactivation cross sections have been derived as functions of linear energy transfer. However, LET alone was insufficient to account for the kinetics.

Using mutagenesis in a set of 300 to 400 essential autosomal genes it was determined that different repair capacities defined by the genes *rad-1, rad-2, rad-3, rad-4* and *rad-7* can distinguish between classes of damage caused by UV light, gamma rays, accelerated charged particles and neutrons. Similar results were obtained for the kinetics of chromosome aberration in somatic intestinal cells. The spectrum of lethal mutation was found to be grossly similar for gamma

rays and accelerated ions using conventional mapping and complementation analysis; however, the class of chromosome rearrangements may be less frequent with ions.

The spectrum of mutations generated in the *unc-22* gene, which codes for a large muscle protein, is being analyzed by DNA hybridization to detect systematic differences in mutation structure as a function of properties of the inducing radiation species.

We have assessed the probability of cell inactivation using developing gonad cells and have concluded that the likelihood of complete cell inactivation (loss of reproductive capacity) is rather low whereas alterations to the states of differentiation of blast cells and their daughters are substantial.

Manipulation of physical parameters of accelerated particles and the level of available oxygen was used to control ion track structure and the proportion of damage induced by direct ionization. For a given LET value, tracks from slower particles were biologically more effective. Oxygen enhancement ratios have been measured as a function of LET and maximum values of approximately 3 were measured for mutagenesis.

Nelson, G.A., Marshall, T.M., and Schubert, W.W. (1989) The nematode *C. elegans*. A model animal system for the detection of genetic and developmental lesions. Presented at the 19th Intersociety Conference on Environmental Systems, San Diego, CA, July 24-26, 1989, 3 p. SAE Paper 891488.

Nematode, Mutation, Ultraviolet light, Gamma rays, Accelerated particle, Cell inactivation, Chromosome rearrangement, Damage repair

Caenorhabditis elegans is being used as a model system for the evaluation of ionizing and nonionizing radiation effects on cell reproduction, differentiation and mutation *in vivo*. Fluence/dose vs response and quality factor (RBE) vs LET (linear energy transfer) relationships have been constructed for the following biological effects using gamma rays, accelerated particles and ultraviolet light.

Cell inactivation. Radiation damage to a four-cell gonad precursor interferes with the normal development program that constructs an adult gonad whose normal function is to produce 280 offspring be self fertilization. This provides a measure of altered gene expression and cell inactivation.

Mutation. Recessive lethal mutations in a set of over 300 essential genes are being isolated using a balancer chromosome technique and the spectrum of mutant structures is being evaluated as a function of radiation type.

Chromosome Rearrangement. The production of duplications of the right arm of the X chromosome has been measured. The kinetics indicate that the production rate is the result of competing processes of sperm inactivation and chromosome damage. The formation of polycentric chromosomes in intestinal nuclei has also been evaluated.

Damage Repair. Radiation and mutagen hypersensitive mutant strains have been tested. The patterns of sensitivity with respect to radiation type and biological effect indicate 1) that a complex repair pathway is present in the nematode and 2) that such mutants can be successfully used to "tune" the sensitivity of the system to specific mutagens/radiation types.

Nelson, G.A., Schubert, W., Marshall, T., Benton, E.V., and Coohill, T. (1987) Heavy ion radiobiology of the nematode *C. elegans*. In: *Radiation Research*, Vol I, Eds. E.M. Fielden, J.F. Fowler, J.H. Hendry, and D. Scott. London: Taylor & Francis, p. 352D.

Nematode, Mutation, Reproduction, Gonad primordia, Chromosome aberration, Differentiation, Genetics, Gamma rays, Ultraviolet light

The nematode *C. elegans* is being used to characterize a variety of genetic and developmental lesions induced by heavy ion radiation. These include: 1) forward autosomal lethal mutations, 2) formation of dicentric and ring chromosomes, 3) duplications of the X chromosome right arm and 4) loss of reproductive and developmental integrity in a set of 4 gonadal blast cells.

The Lawrence Berkeley Laboratory BEVALAC accelerator has been used to irradiate nematodes with ions of Z=1 to 57. Fluence vs response and RBE vs LET relations have been established for the above endpoints and the probability of generating the lesions in single particle - single cell interactions has been measured.

The structures of a set of 60 ion-induced mutants are under study to determine the relative abundances of deletions, rearrangements and point mutations. Finally, a set of four radiation hypersensitive mutations is being used to explore the pathways by which ion-induced lesions are processed relative to X-ray, gamma ray or UV-induced lesions.

*Nematode, Genetics, Mutation, Risk assessment, Gonad primordia, Larva,
Chromosome aberration, Development*

Heavy ion radiation is a unique component of the space environment which
presents a hazard to astronauts and such particles generated at accelerators
have features which are useful for certain tumor treatment protocols. We have
used *C. elegans* as a model system for characterizing various biological lesions
induced by heavy ions in order to identify basic features of the interaction of such
high energy particles with cells and to aid NASA in risk assessments for
astronauts. Dose vs response and relative biological effectiveness relations have
been derived for several assays. In each case, heavy ions proved to be
significantly more effective than X-rays of gamma rays at equal dose and
optimum particle characteristics were identified. The following biological
endpoints have been investigated as functions of particle charge, energy and
fluence.

Developmental integrity of N2 gonad primordia was characterized by measuring
the reduction of fertility in hermaphrodites irradiated as larvae with different
gonad cell number. Damage to or loss of X-chromosomes was scored by
appearance of F1 males. Forward lethal mutation rate was assessed by
irradiation of an *eT1* (*III;V*) balancer strain (JP10) which samples a 300 gene
autosomal region (Rosenbluth et al. Mutation Res. 110:39, 1983). The
probability of converting a single particle - single gamete interaction into a lethal
mutation in this region has been measured for various ions and reaches 5%. The
structures of a set of ion-induced mutants have been described.

Chromosomal breakage and reannealing have been investigated in intestinal
nuclei where karyoplasmic bridges are efficiently produced by heavy ions in the
In cells of L1 larvae.

Duplications of the *unc-3* regions of LG X have been produced by several ions
with kinetics that differ dramatically from X-rays.

Schubert, W.W., Marshall, T.M., and Nelson, G.A. (1989) Genetic effects of high LET radiation on the nematode *C. elegans*: Ground-based studies for International Microgravity Laboratory. *ASGSB Bulletin* 2: 50.

Nematode, Genetics, Mutant, Animal models

The nematode, *Caenorhabditis elegans*, is being used as a model animal for the investigation of genetic lesions caused by high linear energy transfer (LET) forms of radiation such as accelerated ions and neutrons comparable to those species found in Earth orbital space. The following endpoints have been characterized with respect to fluence or dose vs response, LET dependence, and the presence of unique qualitative features: 1) induction of recessive lethal mutation in a set of 400 essential genes balanced by the translocation *eT1*, 2) induction of mutations in the gene *unc-22*, 3) duplication of the right arm of the X chromosome, and 4) induction of nucleoplasmic bridges in intestinal syncytia. These kinetics have been modified by the presence of radiation hypersensitive mutations. These measurements will be used as calibrations for a Spacelab/Biorack experiment on IML-1. Physiological studies and radiation simulations are in progress with flight-like hardware for IML-1 in which nematodes will be flown immobilized next to nuclear track detectors or free in suspension to measure the effects of mixed radiation fields in space.

RADIOPROTECTANTS

Ledney, G.D., Elliott, T.B., Landauer, M.R., and Vigneulle, R.M. (1992) Survival of irradiated mice treated with synthetic Trehalose Dicorynomycolate (S-TDCM) or WR-151327 (WR). In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 559.

Immune system, Neutron, Radioprotectant, Mouse, Irradiation, Gamma rays, Survival rate

Space flight requires that personnel be provided treatment agents that enhance survival after a variety of radiations from various sources and that have minimal side effects. Groups of mice were treated i.p. with the immunomodulator S-TDCM (8 mg/kg, 22 h) or the phosphorothioate WR (200 mg/kg, 30 min) before irradiation. Treatment doses were selected on the results of 30-day survival studies and behavioral (locomotor activity) tests. Groups of S-TDCM, WR, and saline-treated mice were irradiated at 0.4 Gy/min with mid-line LD80/30's of reactor-generated mixed-field radiations (fission neutrons and γ-rays: 5.6 Gy $n/\gamma=1$) or ^{60}Co γ-rays (10.25 Gy). Survival at 6 months for $n/\gamma=1$ and γ-irradiated mice was 20% and 80% respectively after S-TDCM, 85% and 90% respectively

after WR, and 10% and 15% respectively after saline. Thus, preceded by WR than by S-TDCM. The differences in survival produced by these agents may be related to their unique actions on proliferative cells.

PLANTS

Yang, T.C., Craise, L.M., and Mei, M. (1991) Biological effects of heavy ion radiation in plants. Presented at the 20th Japan Conference on Radiation and Radioisotopes, Tokyo, Japan, November 12-14, 1991.

Plant, Mutation, Doses, Photon, Fertility, Heavy ions

Earlier studies with Arabidopsis seeds indicated that low energy heavy ions can be effective in producing various biological effects, including growth inhibition, mutation, and tumor induction. The effectiveness of heavy ions in causing somatic mutation was further suggested by the results of space flight experiments, using Zea mays seeds. After the completion of BEVALAC at Lawrence Berkeley Laboratory, several investigators took the unique opportunity to study biological effects of heavy ions with various charges and energies in plants. Although there are only limited studies, interesting results have been obtained. Systematic studies with various heavy ions demonstrated that the frequency of somatic mutation in Zea mays seeds increased linearly with dose and that high-LET heavy ions were many times more effective than photons in inducing mutation. More recent studies with rice seeds showed exciting results. Although both seedling survival and fertility of plants decreased with an increase of dose of argon beam, interesting mutants, such as semi-dwarf, early maturity, and large grain, were found. In general, the mutation frequency increases with dose. However, there appeared to be an optimal range of doses for certain types of mutation. The potential use of heavy ions in crop improvement appears to be promising and warrants further research. In addition to seeds studies, preliminary experiments with cultured plant tissues were performed and various developmental effects of heavy ions were observed. Experimental studies on the biological effects of heavy ions in plants are only at beginning stage and much remain to be explored.

OTHER EFFECTS

Ainsworth, E.J. (1992) Acute radiation effects in animals: Relevance to space radiation scenarios. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 561.

Heavy charged particles, Solar flare, Acute radiation injury, Neutron, Shielding

Large solar particle events (SPE's) and nuclear weapons detonations in space provide doses such that acute radiation responses are of concern. Shielding is critical because composition and thickness determine the dose, influences target and incident particle fragmentation, and particle charge and velocity. This presentation considers dose-response relationships for animal lethality, the

effects of exposure time, instantaneous dose rate or dose fractionation on lethality and damage to tissues at risk for acute radiation damage such as marrow, intestine and skin. Physiological responses such as emesis and performance degradation will also be considered. The role of primary particle fragmentation on biological response is illustrated with survival curves for mouse marrow CFU-S inactivation by 600 MeV/amu ^{56}Fe particles transported through 0, 2, 5 or 8.4 cm of polyethylene. Acute biological responses to heavy charged particles will be compared with neutrons of various energies.

Rabin, B.M., Joseph, J.A., Hunt, W.A., Kandasamy, S.B., and Ludewigt, B. (1992) Behavioral endpoints for radiation injury. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 556.

Heavy charged particles, Radiation injury, Rat

The relative behavioral effectiveness of heavy particles was evaluated. Using the taste aversion paradigm in rats, the behavioral toxicity of most types of radiation (including ^{20}Ne and ^{40}Ar) was similar to that of ^{60}Co photons. Only ^{56}Fe particles and fission neutrons were significantly more effective. Using emesis in ferrets as the behavioral endpoint, ^{56}Fe and neutrons were again the most effective; however, ^{60}Co photons were significantly more effective than 18 MeV electrons. These results suggest that LET does not completely predict behavioral toxicity. Additionally, exposing rats to 10 cGy of ^{56}Fe particles attenuated amphetamine-induced taste aversion learning. This behavior is one of a broad class of behaviors which depends on the integrity of the dopaminergic system and suggests the possibility of alterations in these behaviors following exposure to heavy particles in a space radiation environment.

Shavers, M., Poston, J.W., Atwell, W., Hardy, A.C., and Wilson, J.W. (1991) *Preliminary Calculation of Solar Cosmic Ray Dose to the Female Breast in Space Missions*. NASA Technical Memorandum 4235.

Human geometry, Solar cosmic ray, Risk assessment, Female, Mammary gland, Dose equivalent, Model development, Radiation shielding

No regulatory dose limits are specifically assigned for the radiation exposure of female breasts during manned spaceflight. However, the relatively high radiosensitivity of the glandular tissue of the breasts and its potential exposure to solar-flare protons on short- and long-term missions mandate a priori estimation of the associated risks. In this report, a model for estimating exposure within the breast is developed for use in future NASA missions. The female breast and torso geometry is represented by a simple interim model. A recently developed proton dose-buildup procedure is used for estimating doses. The model considers geomagnetic shielding, magnetic-storm conditions, spacecraft

shielding, and body self-shielding. Inputs to the model include proton energy spectra, spacecraft orbital parameters, STS orbiter-shielding distribution at a given position, and a single parameter allowing for variation in breast size.

Stone, W.H. and Miller, M.L. (1990) *Late Immunobiological Effects of Space Radiation.* Brooks AFB, TX: USAF School of Medicine, USAF-AM-Technical Report 90-39, p. 32.

Proton, Aging, Immune system, Monkey

The objective of this investigation was to obtain profiles of immune competence in primates more than 25 years following exposures to protons. The availability of irradiated animals provided a unique opportunity to study immune defects which could be relevant to astronauts and high-flying pilots. The Delayed Radiation Effects Colony at Brooks Air Force Base provided blood samples. Antibody-mediated immune function (associated with B-cell function) was assessed by measuring immunoglobulin levels, hemolytic complement activity and autoantibodies; cell-mediated immune function (associated with T-cell function) was evaluated by measuring selected T- and B-cell activity plus response to mitogens and interleukin production. There were no significant differences between control and irradiated animals for most parameters measured in this preliminary survey, but lymphocyte proliferation tended to decrease as radiation dosage increased. Survivors of low and intermediate dose of proton irradiation apparently show few late immunobiological effects, which is encouraging. Additional monkeys will be measured in future confirmatory studies.

Stone, W.H. and Miller, M.L. (1992) *Effects of Space Radiation on Humoral and Cellular Immunity In Rhesus Monkeys.* Brooks AFB, TX: USAF School of Medicine. Armstrong Laboratory Technical Report 1992-0101.

Aging, Monkey, Immune system, Proton

The objective of this study was to complete profiles of immune competence in rhesus monkeys more than 25 years after single exposures to protons of different energies. Access to irradiated animals provided a unique opportunity to study late effects on the immune systems of nonhuman primates; late immunological defects could be relevant to astronauts and high-flying pilots. Working with the primate model allowed us to assess the possible late effects of ionizing radiations on parameters associated with B-cell and T-cell functions. Antibody-mediated immune (AMI) function was investigated by measuring immunoglobulin (Ig) levels, hemolytic complement activity, and autoantibodies. Cell-mediated immune (CMI) function was evaluated by measuring selected T- and B-cell activities as well as responses to mitogens and interleukin production. There were no significant differences between control and irradiated animals for most

parameters measured in this survey, but some reduction in spontaneous proliferation was noted in irradiated primates. With regard to late risks for humans following exposure(s) to ionizing radiations, it is encouraging that few late immunbiological effects were exhibited by primate survivors of low and intermediate doses of protons.

Vazquez, M.E., Broglio, T.M., and Worgul B.V. (1992) Effects of single and fractionated radiation doses on retinal neuritogenesis. *Investigative Ophthalmology and Visual Science* 33(4): 1061.

Model development, Chicken embryos, Retina, Neural cell, Non-mitotic, Irradiation, Cell culture, X-ray, Morphology, Image analysis, Inverted microscopy, Neuritogenesis, Doses, Dose rate effect, Radiation damage

Evidence for CNS damage among the A-bomb survivors and the promise of increased human activity in space has stimulated concern for the potential effects of High-LET radiations on differentiated tissues. To date the majority of studies on radiation damage emphasize simple end-points such as growth related events, which, while useful to understand the nature of primary cell injury, have poor predictive value for extrapolation to more complex tissues as the CNS. We developed a model for assaying the effects of radiations on neuritogenesis which provides the opportunity to assess radiation damage on a non-mitotic neural cell population. Retinal explants were taken from E6 chick donor embryos (White Leghorn), cultured in hydrated collagen (Type I) lattice, covered with nutrient medium (Eagle's Basal Medium enriched with optic lode extract, 500 µg/ml) and incubated for five days (37.5°C, 5% CO_2, and 80% of relative humidity). They were then irradiated 24 hours post explantation with a series of single and fractionated doses of X-rays in a range of 40-1200 cGy. The fractionated protocol consisted of four exposures equally distributed over nine hours. Neurite number, length, and growth index were determined daily with an inverted microscope coupled to an image analyzer. The irradiated explants showed a marked alteration of neuritogenesis regulation, expressing changes in the vitality and functional integrity of retinal cells as a function of dose and dose-rate.

Vazquez, M. and Worgul, B.V. (1992) Neuritogenesis: A model for space radiation effects on the CNS. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 556.

Neuritogenesis, High-LET, Central nervous system

Pivotal to the astronauts' functional integrity and survival in long space flights are the strategies to deal with space radiations. The majority of the *in vitro* studies in this area emphasize simple endpoints such as growth related events, which while useful to understand the nature of primary cell injury, have poor predictive value for extrapolation to more complex tissues as the CNS. A recently developed

model for assaying the effects of radiation on neuritogenesis provides the opportunity to assess radiation damage on a non-mitotic neural cell population. Neurite formation is essential in neuroplasticity (rewiring, learning, and long term memory) in the CNS, a failure of which results in functional decrements. The methodology exploits the effects of radiation on neuritogenesis employing retinal explants of embryos from different species. Our studies on the effects of low- and high-LET radiation on neuritogenesis are useful and relevant to space radiation exposure.

3. RISK ASSESSMENT

RISK ASSESSMENT

Curtis, S.B. (1992) Single track effects, Biostack and risk assessment. Ceremonial Address presented at "20 Years of BIOSTACK," the Colloquium honoring Professor Dr. Horst Bücker at DLR, Köln-Porz, Germany, October 9, 1992.

Biostack, High-LET, Risk assessment, Single hit, HZE, Bacteria, RBE, Inactivation cross section

The scientific career of Prof. Bücker has spanned a very exciting period in the fledgling science of Space Radiation Biology. The capability for placing biological objects in space was developed, and the methods for properly packaging, retrieving, and analyzing them were worked out. Meaningful results on the effects of radiation were obtained for the first time. In fact, many of the successful techniques and methodologies for handling biological samples were developed in Prof. Bücker's laboratories, as attested by the extensive Biostack program. He was the first to suggest and successfully carry out experiments in space directly aimed at measuring effects of single tracks of high-energy heavy galactic cosmic rays by specifically identifying whether or not the object had been hit by a heavy particle track . Because the "hit" frequencies of heavy galactic cosmic rays to cell nuclei in the bodies of space travelers will be low, it is expected that any effects to humans on the cellular level will be dominated by single-track cell traversals. This includes the most important generally recognized late effect of space radiation exposure: radiation-induced cancer.

This paper addresses the single-track nature of the space radiation environment, and points out the importance of single "hits" in the evaluation of radiation risk for long-term missions occurring outside the Earth's magnetic field. A short review is made of biological objects found to show increased effects when "hit" by a single heavy charged-particle in space. A brief discussion is given of the most provocative results from the bacterial spore *B. subtilis*: experimental evidence that track can affect biological systems at much larger distances from the trajectory than previously suspected, and the resultant inactivation cross section in space calculated for this system is very large. When taken at face value, the implication of these results, when compared to those from experiments performed at ground-based accelerators with beams at low energies in the same LET range, is that high-energy particles can exert their influence a surprising distance from their trajectory and the inactivation cross sections are some twenty times larger than expected. Clearly, beams from high-energy heavy-ion accelerators should be used to confirm these results.

For those end points that can also be caused by low-LET beams such as high energy protons, it is important to measure their action cross sections as well. The ratio of the cross sections for a high-LET beam to that of a low-LET beam is an interesting experimental ratio and, we suggest, of more intrinsic interest than the RBE. It is a measure of the "biological" importance of one particle type relative to another particle type. This ratio will be introduced and given the name RPPE (*Relative Per Particle Effectiveness*). Values of RPPE have appeared in

the literature and will be discussed. A rather well-known value of this quantity (13,520) has been suggested for the RPPE of high-energy iron ions to high-energy protons. This value was suggested by Letaw *et al.*; we will call it the Letaw limit. It will be discussed in terms of the importance of the heavy-ion component vs. the light-ion component of the galactic cosmic rays. It is also pointed out, however, that there may be unique effects from single tracks of heavy ions that do not occur from light-ion tracks. For such effects, the concepts of both RBE and RPPE lose their meaning.

Curtis, S.B. (1992) Single-track effects and new directions in GCR risk assessment. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 568.

Single track effect, Fluence-related risk coefficient, Risk cross section, Single particle traversal, Risk assessment

Light flashes in the eye as recorded by astronauts on missions outside the geomagnetosphere are presumably caused by single particle traversals of galactic cosmic rays traversing the retina. Although these flashes are not considered to have deleterious short- or long-term effects on vision, they are testimony that the body can detect single particle traversals. The frequencies of the flashes implicate ions in the charge range of 6 to 8 (i.e., carbon and/or oxygen ions). Other particles with higher charge and causing more ionization are present at lower frequencies. The possibility of the importance of such single-track effects in radiation carcinogenesis and other late effects suggest that a risk assessment system based on particle fluence rather than absorbed dose might be useful for assessing risk on long-term space missions. Such a system based on the concept of a *risk cross section* is described. Human cancer risk cross sections obtained from recently compiled A-bomb survival data are presented, and problems involving the determination of the LET-dependence of such cross sections are discussed.

Schimmerling, W. (1992) Problems of radiation in space. Presented at the International Workshop on Biological Applications of Relativistic Heavy Nuclei (B.A.R.N. 92), Clermont-Ferrand, France, October 14-16, 1992.

Space radiation hazard, Radiation research

Human space exploration in the 21st century holds exciting prospects for the advancement of science and the expansion of our experience. Projected missions include an outpost on the Moon and a piloted mission to Mars. However, for space exploration to proceed, adequate protection of crew members must be ensured against the hazards presented by the harsh environment of space; in particular, against the hazards of ionizing radiation. While much still remains to be learned in all aspects of radiobiology, major unresolved issues for human activities in space are: radiation protection against large fluxes of high energy protons from solar energetic particle (SEP) events; the possible existence of new qualitatively different biological effects, either not seen, or not seen at comparable radiation levels, for conventional (low-LET)

radiation such as X-rays, γ-rays; and the uncertainties associated with predicting biological effects, even when these are known, based on extrapolations from low-LET data and sparse high-LET data.

Schimmerling, W. (1991) The NASA Radiation Health Program. Presented at the 21st International Conference on Environmental Systems, San Francisco, CA, July 15-18, 1991, SAE Paper 911371, p. 5.

HZE, Radiation theory, Space radiation hazard, Radiation exposure, Radiation environment, Solar particle event, Proton, Ionizing radiation, Free-flyer, LifeSat, Lunar mission, Shielding thickness, Energy deposition, Risk assessment

Protection from the hazards of ionizing radiation in the space environment has been identified as critical to human exploration, and is of the utmost importance both for journeying to and living on other planetary bodies. The major radiation hazards for exploration class missions outside of the Earth's magnetosphere are due to protons from solar particle events and to the highly charged, energetic (HZE) particles constituting galactic cosmic rays. The mean free path for nuclear interactions of HZE particles is comparable to shielding and tissue thicknesses present in human interplanetary exploration, resulting in a significant fraction of nuclear reaction products at depth. The energy deposition of HZE particles, on the microscopic scale of cells, is extremely non-uniform. Since the physics and biology of HZE particles have been studied for a much shorter time than that of other types of radiation, current knowledge about the biological effects of space radiation cannot predict astronaut health hazards with acceptable precision. Such predictions are required in order to define acceptable risk levels for space exploration and specify shielding for the lunar base, lunar vehicles, and Mars spacecraft. Attempts to deal with present uncertainties by making worst case assumptions may overestimate the required shielding thickness by as much as a factor of 10 and lead to inordinate vehicle masses. Major sources of these uncertainties will be illustrated. The NASA Life Sciences program to resolve the critical problems posed by ionizing radiation in interplanetary space, which consists of an expanded ground-based research effort and space-based validation using the LifeSat satellite, will be described.

Schimmerling, W. and Sulzman, F.M. (1992) The NASA Space Radiation Health Program. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 573.

Space radiation hazard, Radiation protection, Radiation limit, Radiation risk

The goal of the NASA Space Radiation Health Program is the establishment of the scientific basis for radiation protection of humans in space, with emphasis on lunar and Mars exploration. The end product of the research required to accomplish this goal is the accurate prediction, for a given architecture, of the probability that a crew will experience well-defined health effects (mainly, but not exclusively, cancer) following a successful return to Earth. The scientific data required for these predictions will be obtained in ground-based research using high-energy accelerator beams to simulate the interplanetary radiation. The

extent to which spaceflight significantly changes the irradiation parameters must be investigated in space. The strategy pursued by the NASA Space Radiation Health Program to achieve these goals will be described.

RADIATION HEALTH AND EPIDEMIOLOGY

Curtis, S.B. (1992) Fluence-related criteria for simulating HZE-particle exposures to animals in ground-based experiments. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Dose rate effect, Single track effect, Experimental strategy, Galactic cosmic ray simulation, High-LET, Model development

HZE particles in space hit areas the size of cell nuclei very infrequently. For example, at solar minimum under 4 g/cm^2 Al shielding, the number of ions with Z ≥ 3 (i.e., HZE particles) that pass through a 100 $\mu m2$ area is less than 1.5 per year, or the mean time between HZE hits is greater than 240 days. More shielding will only decrease the hit frequency and increase the mean time between hits. In simulating this exposure situation in the laboratory, the time between fractions should be long compared with the mean times governing important radiation-related cellular processes. These include mean repair and/or recovery times and mean turnover times of proliferating cell compartments. One-week fractionation intervals are suggested. To simulate a two-year mission outside the geomagnetosphere, a *conservative* suggestion is to give fractionated exposures of iron ions at weekly intervals for 30 weeks with a fluence of 105 per cm^2 per fraction (on average, 0.1 hit per cell nucleus per fraction). For iron ions with LET of 200 keV/μm, this translates to a dose of 3.2 cGy per fraction or 96 cGy total dose of iron ions. This simulates the total mean number of HZE particles through a cell nucleus in two years (3 per cell nucleus per 2-year mission) with an iron ion beam given in weekly fractionated doses over 30 weeks. Over one week's time, we are replacing a mean hit rate of 0.03 hits per cell nucleus with a one-fraction mean hit rate of 0.1 hits per cell nucleus. The dose is also seen to be conservatively high.

To simulate a "low-LET background" at solar minimum, the number of hits per year from protons and helium ions is less than 180 per cell nucleus in free space and is roughly constant as a function of shielding thickness. This translates into one hit per cell nucleus every two days. One fraction every two days for 30 weeks (105 fractions) gives 3.43 x 10^6/(cm^2. fraction) to simulate a 2-year mission. Using helium ions with LET of 1 keV/μm yields a dose of 0.55 cGy per fraction or 58 cGy over 105 fractions (30 weeks). This is also seen to be conservatively high, but simulates in fluence the total number of low-LET particles traversing cells in a two-year mission.

Gupta, R.C. (1992) *Survival Analyses of Radiated Animals Incorporating Competing Risks and Covariates.* Final Report for: Summer Research Program, Armstrong Laboratory, 1992.

Model verification, Model development, Survival analysis, Delayed Bio-Effects Colony, Radiation exposure

The effects of radiation, taking into account the cause of death (cancer or heart disease) along with the covariates such as sex, age, type of exposure, and dose, are examined. A general log linear hazard model approach is studied. The model estimates the cause specific hazard rates, assuming piecewise exponential distribution and exhibits the survival function for each of the covariate groups and the probability of death due to each cause. A data set called "Delayed Bio-Effects Colony," of radiated animals, is analyzed and some conclusions are drawn.

Reeves, G.I., Ainsworth, E.J., McCarthy, K.F., and Gaiter, S.L. (1992) **Design study for life span experiments on carcinogenesis and late effects from heavy charged particles. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.**

Life span, Heavy charged particles, Carcinogenesis, HZE, Proton, Risk assessment, Model development

The project entitled "Design Study for Life Span Experiments in Mice on Carcinogenesis and Biological Effects of Heavy Charged Particles" is well under way. The Scientific Advisory Committee (SAC) met 10 January 1992 to set up the initial plan of attack. Briefly, we will have three workshops, each of which will involve preparation and collation of written abstracts as part of a meeting summary. The SAC will then meet and review the final product, using the workshop summaries and other pertinent materials. This final report will offer prioritized recommendations to NASA staff on experiments that should provide, over the next ten years, a definitive data base useful for assessing the risk of carcinogenesis and other late effects from HZE particles.

Dr. Peter Groer will chair the first workshop, which will focus on Physics/Biophysics Models as they relate to radiation transport and damage in environments where persons will be exposed. The overall goal of this workshop is to identify and discuss physical and biophysical considerations that should merit attention in the design of experiments that support generation of a database relevant to estimation of carcinogenic risks for protons or heavy charged particles. It will be held immediately after this meeting.

The second workshop will focus on experimental options and design considerations on model systems, including the biological endpoints that should be evaluated. This will be held in the May-June time frame. The third workshop, in August or September, will focus on definitions of what cellular or molecular studies should be done in parallel with animal experiments. Chairs, members, dates and places for these workshops will be determined shortly.

The SAC will then meet with the workshop chairs at AFRRI to advise on the final written report. Our projected completion date is the end of October.

SPACE FLIGHT RADIATION HEALTH PHYSICS

Badhwar, G.D., Hardy, A.C., Robbins, D.E., and Atwell, W.A. (1992) *Radiological Assessment for Space Station Freedom.* **NASA Technical Memorandum.**

Space radiation, Space Station Freedom, Risk assessment, Male vs. female, Orbit, NCRP, Radiation environment, Radiation hazard

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

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

Cucinotta, F.A., Atwell, W., Weyland, M., Hardy, A.C., Wilson, J.W., Townsend, L.W., Shinn, J.L., and Katz, R. (1991) *Radiation Risk Predictions for Space Station Freedom Orbits.* **NASA Technical Paper 3098.**

Space Station Freedom, Radiation shielding, Radiation risk, LET, Cellular track model, RBE, Quality factor, Mutation

Risk-assessment calculations are presented for the preliminary proposed solar minimum and solar maximum orbits for Space Station Freedom (SSF). Integral linear energy transfer (LET) fluence spectra are calculated for the trapped-proton and galactic cosmic ray (GCR) environments. Organ-dose calculations are discussed using the Computerized Anatomical Man model. The cellular track model of Katz is applied to calculate cell survival, transformation, and mutation rates for various aluminum shields. Comparisons between relative biological

effectiveness (RBE) and quality factors (QF) for SSF orbits are made, and fluence-dependent effects are discussed.

Golightly, M. and Hardy, A.C. (1992) Results of time-resolved radiation exposure measurements made during U.S. Shuttle missions with a tissue equivalent proportional counter. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 546.

RME-III, Dose equivalent, High-LET, Radiation detector, Dosimetry, Fluence, Tissue equivalent proportional counter (TEPC)

Time-resolved radiation exposure measurements inside the crew compartment of the Shuttle have been made during ten recent missions. The measurements were made with the USAF Radiation Monitoring Equipment-III, a portable battery-powered three-channel tissue equivalent proportional counter. Half of the missions had orbital inclinations of at least 57° and the remaining missions had orbital inclinations of 28.5°; altitudes ranged from 200-600 km. The determined dose equivalent rates ranged from 40-5300 mSv/dy. The peak average dose and dose equivalent rates within the South Atlantic Anomaly were found to be not geographically coincident. Particle count measurements indicated that medium- and high-LET particles contributed less than 2% of the total particle flux for all missions, but up to 40% of the total dose equivalent, depending on the spacecraft's altitude and orbital inclination.

Hardy, K.A., Atwell, W., Golightly, M.J., Hardy, A.C., and Quam, W. (1990) Real-time and time-resolved dose measurements on space shuttle missions with the Radiation Monitoring Equipment (RME)-III. Presented at the 35th Annual Meeting of the Health Physics Society, Anaheim, CA, June 24-28 1990, Abstract No. TAM-B9.

RME-III, Dosimetry, Fluence, Dose equivalent, STS-27, STS-28, STS-33, Proton

The RME-III is a self-contained portable active dosimeter system developed by EG&G for the US Air Force adapted for use on the Space Shuttle. It features a three-channel tissue equivalent proportional counter which measures particle fluence and computes dose and dose equivalent at operator selected time intervals. The total accumulated dose and dose equivalent are displayed real time on a liquid crystal display while the data and time of the interval dose readings are stored in memory modules for future analysis. Analysis of the time-resolved data permits correlation of the radiation exposure with Shuttle position and altitude.

The RME-III was flown in a middeck locker aboard STS-27, STS-28, and STS-33. STS-27 and -28 featured 57° inclination circular orbits at 448 kM (242 nm) and 296 kM (160 nm), respectively, while STS-33 featured a 28° inclination elliptical orbit [perigee: 231 kM (125 nm); apogee: 563 kM (304 nm)]. Total dose and dose equivalent measured were 1580 micro-Gy/2473 micro-Sv (STS-27), 636 micro-Gy/1094 micro-Sv (STS-28), and 3706 micro-Gy/4827 micro-Sv (STS-

33). Analysis of the time-resolved data indicated that doses on STS-27 and -33 were dominated by the trapped Van Allen Belt protons, while the dose on STS-28 was primarily due to galactic cosmic rays. A solar proton event also occurred on STS-28 which was measured with RME-III. Time resolved data from each mission are presented.

Hardy, K.A. and Leavitt, D.D. (1992) Experimental simulation of proton space radiation environments: A dosimetric perspective. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 545.

Primate, Proton, Irradiation, Tumor, Solar flare, Omni vs. unidirectional irradiation, Dose calculation

Three-dimensional dose calculation techniques developed for radiotherapy treatment planning were used to calculate dose distributions from unidirectional, planar rotational and omnidirectional incident radiation (proton beams/solar flares). The calculations predicted regions of high dose within primate heads exposed to 55 MeV protons, supporting the postulate of radiation-induced brain tumors within this population. Comparisons among predicted doses to the human head from solar flares of 3 different energies demonstrated differences between unidirectional and omnidirectional irradiation in the space environment. The results can be used to estimate dose distributions based on a) limited phantom measurements, or b) non-uniformly incident radiations in orbit; both situations are difficult to replicate under laboratory exposure conditions.

Konradi, A., Badhwar, G.D., Hardy, A.C., Cash, B.L., Golightly, M.J., Atwell, W., and Hardy, K.A. (1992) Space Shuttle radiation measurements and the radiation models. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 544.

Radiation detector, Doses, Active radiation detector, LET, Model verification

Total dose measurements from passive detectors flown on the Shuttle Orbiter have been used for comparison with predictions from an omnidirectional, isotropic flux model. The results indicate a significant overestimate by the model during solar minimum, and an underestimate during solar maximum. The model ignores the highly non-isotropic nature of the trapped radiation and assumes that different altitudes of the Space Shuttle average out the anisotropy of the incident flux. Active instruments flown recently on the Shuttle include two tissue equivalent proportional counters and a proton and heavy ion detector whose measurements support these findings. The measurements also allow direct determination of linear energy transfer (LET) spectra. Comparison between measured LET values and model calculations shows disagreement which reaches factors of 2 at low values of the LET.

Leavitt, D.D. (1990) *Proton Depth Dose Distribution: 3-D Calculation of Dose Distributions from Solar Flare Irradiation.* **USAF School of Aerospace Medicine Report TP-90-17.**

Depth dose distribution, Proton, Dosimetry, Uni vs. omnidirectional radiation, Isodose distribution, Solar flare

Relative depth dose distribution to the head from 3 typical solar flare proton events were calculated for 3 different exposure geometries: (1) single directional radiation incident upon a fixed head; (2) single directional radiation incident upon head rotating axially (2-D rotation); and (3) omnidirectional radiation incident upon head (3-D rotation). Isodose distributions in the transverse plane intersecting isocenter are presented for each of the 3 solar flare events in all 3 exposure geometries. In all 3 calculation configurations the maximum predicted dose occurred on the surface of the head. The dose at the isocenter of the head relative to the surface dose for the 2-D and 3-D rotation geometries ranged from 2% to 19%, increasing with increasing energy of the event. The calculations suggest the superficially located organs (lens of the eye and skin) are at greatest risk for the proton events studied here.

Leavitt, D.D. (1990) *Proton Arc Doses to the Primate Head.* **USAF School of Aerospace Medicine Report TP-90-24.**

Proton, Space radiation, Dose distribution, Phantom, Dosimetry

The radiation dose distributions to the primate head are calculated for 10 MeV, 55 MeV, and 110 MeV protons incident on the primate. Rotation of the primate in the field is simulated by summing a 360-degree arc in 1/2 degree increments. Representative anatomy is determined by Computerized Tomography scans of primate head phantom. Dose-volume histograms are used to compare the dose to the brain for each of the four irradiation techniques. Surface dose and depth dose calculation are made to evaluate the dosimetric effects to the primate eye. Estimates are made of the effects of irradiation with the primate eyes open versus closed. A focusing effect is described to explain the localized high doses seen with 32 MeV and 55 MeV proton exposures. Doses to the eye are calculated and tabulated by animal identification key for a series of irradiated primates. These calculations demonstrate significant departures from the dose predictions based on simple cylindrical phantoms, suggesting that careful review of the primate dosimetry must accompany any evaluation of radiation effects on these animals.

Yang, C.H. (1992) Potential health effects of space radiation. Presented at the Sixth Annual Space Operations, Applications, and Research Symposium, Houston, TX, August 4-6, 1992.

Radiation hazard, High-LET, Radiation risk

Crewmembers on missions to the Moon or Mars will be unavoidably exposed to ionizing radiation as they pass through the Van Allen belts and the galactic

cosmic rays (GCR) of interplanetary space. In addition, outside of the Earth's magnetosphere, there is the possibility for exposure to high dose of proton and heavy particles from Solar Particle Event (SPE). The potential health hazards due to these space radiation must be considered carefully to ensure the success of space exploration. Unlike photons, such as X and gamma rays, there is no human radioepidemiological data for acute and late effects of high-LET radiation, and the biological risks of energetic charged particles have to be estimated from experimental results on animals and cultured cells. Experimental data obtained todate indicate that charged particle radiation can be much more effective than photons in causing various biological effects, including DNA damages, chromosome aberrations, cell killing, mutation, cataract formation, and tumor induction. The relative biological effectiveness (RBE) varies with biological endpoints and depends on linear-energy-transfer (LET) of heavy ions. Most lesions induced by low-LET radiation can be repaired in mammalian cells. Energetic heavy ions, however, can produce large complex DNA damages, which may lead to large deletions and are irreparable. For high-LET radiation, therefore, there is less or no dose rate effects. Physical shielding may not be effective in minimizing the biological effects of energetic heavy ions, since fragments of the primary particles can be effective in causing biological effects. At present the uncertainty of biological effects of heavy particles is still very large. With further understanding of the biological effects of space radiation, the career doses can be kept at acceptable levels so that the space radiation environment need not be a barrier to the exploitation of the promise of space.

INTER- AND INTRASPECIES EXTRAPOLATION

Broerse, J.J., Wagemaker, G., van Bekkum, D.W., Zurcher, C., Lee, A.C., Williams, G.R., and Cox, A.B. (1992) Late effects of high-dose total body Irradiation in rhesus monkeys and the extrapolated risk to man. Presented at the European Society for Radiation Biology, Erfurt, Germany, October, 1992.

Monkey, X-ray, Neutron, Aging, Tumor, Eye, Proton, Animal models, Cataractogenesis

Presently, many thousands of patients are treated each year with high dose total body irradiation followed by autologous or allogeneic bone marrow transplantation. These patients mostly suffer from haematological malignancies and severe congenital or acquired disorders of the haemopoietic system. It is of importance to assess in experimental animals the late radiation effects that can be expected in such patients in order to take timely preventive measures and minimize morbidity as much as possible.

Studies on detrimental effects in primates are of relevance since the response to radiation of primate species does not seem to be significantly different from that in man. The risks of total body irradiation with large doses of X-rays and fission neutrons are investigated by keeping long-term surviving monkeys from an experiment on acute effects under continuous observation for a period in excess of 25 years. Rhesus monkeys of a comparable age distribution are maintained

under identical conditions of housing and nutrition to serve as a control group. On the basis of the number of animals developing tumors per group as a function of the total observation period and the average absorbed dose, risk factors of 56 x 10^{-4} year^{-1} Gy^{-1} and 216 x 10^{-4} year^{-1} Gy^{-1} were derived for the X- and neutron-irradiation, respectively.

The lens of the eye is among the tissues with a high susceptibility for deterministic effects. Cataract induction has been studied in rhesus monkeys exposed to photons, neutrons and protons. The latency period for cataract induction decreases with increasing dose levels. In the group of X-irradiated monkeys exposed to doses of 4 Gy signs of cataract were not observed over a period of 8 years post-irradiation. For higher dose levels of X-rays, around 8 Gy, cataracts were produced in about 20 percent of the monkeys within three years after exposure, and increased to 100 percent after 10 to 15 years.

Cox, A.B., Salmon, Y.L., Lee, A.C., Lett, J.T., Williams, G.R., Broerse, J.J., Wagemaker, G., and Leavitt, D.D. (1993, in press) Progress in the extrapolation of radiation, cataractogenesis data across longer-lived mammalian species. In: *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Proceedings of the NATO Advanced Study Institute,* **Eds. C.E. Swenberg, G. Horneck, and E.G. Stassinopoulos. New York: Plenum Press.**

Risk assessment, Lenticular opacity, Cataractogenicity, Animal models, Proton

Induction of cataracts from exposure of astronauts to "ambient" galactic and episodic solar particulate radiations is considered to be one of the primary risks of extended missions beyond the protection of the terrestrial magnetosphere. Exposures to high fluxes of solar protons during the projected mission to Mars, for example, could result in vision-impairing lenticular opacities late in the life span after the career missions of the astronauts are over (Lett *et al.*, 1991).

Quantitative assessments of cataractogenic risks for astronauts from both densely and sparsely ionizing radiations requires extrapolation across species of results from mammalian models that simulate humans. Such models do not include short-lived rodents when late degenerative cataractogenesis is concerned. Data obtained from such longer-lived species as the New Zealand white (NZW) rabbit (*Oryctolagus cuniculus*, median life span in captivity = 5-7 years), the beagle dog (*Canis familiaris*, median life span in captivity = 13-14 years) and the rhesus monkey (*Macaca mulatta*, median life span in captivity = ~24 years), which have been normalized for differences in subjective scoring indices, will be used to simulate cataractogenic profiles for humans.

Proton-induced cataracts in the Fischer-344 rat (*Rattus norvegicus*, median life span = ~2 years) also have been studied by our group. From the standpoint of radiation cataractogenesis, the fundamental objective of the rodent project was to examine the validity of our scoring system with a short-lived animal model that exhibits a very high incidence of senile cataracts.

The most recent data on radiation cataractogenesis in New Zealand white rabbits have been published by Cox et al. (1992), and are not shown here. Our primary purpose now is to present data from additional animal models to illustrate the potential for cross-species extrapolation from present and future data bases.

Fanton, J.W. and Golden, J.G. (1991) Radiation-induced endometriosis in Macaca mulatta. Presented at the Workshop on Basic Pathophysiology of Endometriosis, Washington, D.C., September 1991.

Endometriosis, Environmental toxin, Rhesus monkey, Pathophysiology, Women's health, Animal models

A summary of the outcome of discussions appeared in a recent issue of the Endometriosis Association Newsletter (13(2), 1992). It seems that investigators on several unpublished studies noted that environmental toxins (polychlorinated biphenyls (PCB's) and mycotoxin deoxynivalenol (DON) induced elevated *severity* of endometriosis in rhesus and cynomolgus monkeys while TCDD (2, 3, 7,8-tetrachlorodibenzo-p-dioxin) caused statistically significant increases in the *numbers* of monkeys which developed endometriosis. The research discussed has exposed a link between endometriosis and environmental pollutants/radiation which was not anticipated. Moreover, the issue of women's health, which has received a lot of attention lately, is served well by all these studies, both published and unpublished, because of the possible link between environmental toxins and loss of reproductive function in the primates under investigation. Finally, the results of all these investigations underscore the importance of long-term studies of toxic agents in primate models.

Lett, J.T. (1992) Radiation cataracts: Extrapolation across species. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Cataractogenesis, Animal models, Risk assessment, Model development, Photon, Doses, Species comparison

Terrestrial experiments with animals models have been used to examine cataractogenesis induced by radiations of types that will be encountered on exploratory flights in interplanetary space, e.g., the Mars mission. The data obtained are useful for the evaluation of the human risks to astronauts from radiation cataracts only if they can be extrapolated across species to humans. Six main variables must be considered for such extrapolations: basic cataractogenic radiosensitivity; linear energy transfer; post irradiation development of lenticular opacification; lifespan; age at exposure; exposure rate.

In an initial attempt to explore means for consolidation, the various factors will be considered in terms of the investigations with photons and relativistic charged particles that have been funded by NASA. Other extant data from the literature, especially those for survivors from radiation exposure at Hiroshima and Nagasaki, will also be considered.

McCarthy, K.F. and Hale, M.L. (1992) Extrapolation of rodent LD50/30 data to humans. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 559.

Hematopoiesis, Radiation injury, Stem cell, Animal models, Rodent, Radiation protection

LD50/30 data for mice and rats has been re-evaluated based on the concept of an "age structure" within the hematopoietic stem cell (HSC) compartment. Those cells conferring radioprotection (RPC) were determined, by Poisson statistics, to be distinct from the cells capable of long-term reconstitution (LTRC) of hematopoietic tissues post-irradiation. Larger animals require more RPC to survive lethal irradiation than do small animals; but even in larger animals, one or a few LTRC are sufficient to repopulate the entire hematopoietic system. This model implies that humans could survive irradiation doses well in excess of 3 to 4 Gy if therapies could be designed to replace or supplement RPC function post-irradiation.

Worgul, B.V. (1992) Rationale for studies on integrated biological systems: A biologist's viewpoint. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 553.

High-LET, Cell damage, Cell repair

A rationale for the man in space program rests on the argument that when venturing into the unknown there is no substitute for the presence of a sentient primate. Due to the potential depredations of the heavy ion component of cosmic rays, manned exploration into deep space demands an examination of high-LET radiation effects on tissues and organs critical to mission success and survival. *In vitro* data, while invaluable for understanding fundamental radiological phenomena, do not extrapolate readily to multifunctional cell systems characteristic of tissues and organs. They also fail to provide sufficient insights into the translation of primary biological damage into more remote, higher order, integrated functions. There currently exists a ground-based research infrastructure which promises the essential data in this regard. In addition, the opportunity for the accumulation of a database generated over the next two decades of LEO missions should be fully exploited. The ultimate goal is an appreciation, to the level of predictability, of the potential damage which may be incurred *during long duration deep space forays.*

RADIATION LIMITS AND STANDARDS

Cucinotta, F.A., Wilson, J.W., Townsend, L.W., Shinn, J.L., and Katz, R. (1991) LET analyses of biological damage during solar particle events. Presented at the 21st International Conference on Environmental Systems, San Francisco, CA, July 15-18, 1991, 8 p. SAE Paper 911355.

Solar particle event, RBE, Track model, Radiation shielding, Cell culture, LET, BRYNTRN, Proton, Fragmentation

Solar particle events (SPE) are typically dominated by high-energy, low-linear energy transfer (LET) protons. Biological damage to astronauts during an SPE is expected to include a large contribution from high LET target fragments produced in nuclear reactions in tissue. We study the effects of nuclear reactions on integral LET spectra, behind typical levels of spacecraft and body shielding, for the historically largest flares using the high-energy transport code, BRYNTRN in conjunction with several biological damage models. The cellular track model of Katz provides an accurate description of cellular damage from heavy ion exposure. The track model is applied with BRYNTRN to provide an LET decomposition of survival and transformation rates for solar proton events. In addition, a fluence-based risk coefficient formalism is used to estimate Harderian gland tumor induction in rodents and cataractogenesis in rabbits from solar flares, and a LET analysis is used to assess the relative contribution from target fragments on these biological endpoints.

Curtis, S.B. (1992) Development of the risk cross section concept for human carcinogenesis induced by low- and high-LET radiations. Presented at the 40th Annual Meeting of the Radiation Research Society, Salt Lake City, UT, March 14-18, 1992.

Risk cross section, Risk assessment, Model development

In the development of the risk cross section concept, it is important to link the cross sections at low LET to the epidemiological carcinogenesis data being obtained from the A-bomb survivors at high dose rates. This can be done by separating the overall risk into its component parts by tissue or organ. The risk cross sections are obtained for each tissue/organ separately, the risks are then calculated and added assuming independence of risks from one tissue/organ to the next. At this point, the DDREF (dose and dose rate effectiveness factor) is applied. If, on the other hand, high-LET radiation is considered, the cross section at low LET for each tumor as derived from the A-bomb survivor data must be divided by the DDREF first and an LET dependence for the cross section must be determined in some manner. Lacking experimental data, various methods have been studied. Such analysis leads to the development of a list of necessary laboratory experiments. Risk determination by this method circumvents use of absorbed dose, RBE, Quality Factors, and equivalent dose. Also low dose and/or dose-rate gamma- and X-ray experiments can be avoided.

Curtis, S.B. (1992) Importance of dose rate and cell proliferation in the evaluation of biological experimental results. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 544.

Single particle traversal, Radiation hit, Dose threshold, Cell proliferation, Radiation risk

The nuclei of cells within the bodies of astronauts traveling on extended missions outside the geomagnetosphere will experience *single traversals* of particles with high LET (e.g., one iron ion per one hundred years on average) superimposed on a background of tracks with low LET (~one proton every 3 days, one helium ion per month, etc.). In addition, some cell populations will be proliferating, thus possibly providing increasing numbers of cells with "initiated" targets for subsequent radiation hits. These temporal characteristics are not generally reproduced in laboratory experimental protocols. Implications of the differences in the temporal patterns of radiation delivery between conventionally designed radiation biology experiments and the pattern to be experienced in space will be examined and the importance of dose rate and cell proliferation will be evaluated in the context of radiation risk assessment on long missions in deep space.

Curtis, S.B. (1992) Developing risk cross sections for human carcinogenesis. Presented at the Third Annual Investigators Meeting on Space Radiation Research, Houston, TX, April 14-15, 1992.

Risk cross section, Separate organ risk, Risk assessment

In developing the risk cross section concept, the cross sections at low-LET must be linked to the epidemiological carcinogenesis data obtained from the A-bomb survivors at high dose rates. This can be done by separating the overall risk into its component parts by tissue or organ. The risk cross sections are obtained for each tissue/organ separately, the risks are calculated and added assuming independence of risks from one tissue/organ to the next. The DDREF (dose and dose rate effectiveness factor) is applied if the risk at low dose rate is desired. For high-LET radiation, the low-LET risk cross sections for each tissue/organ must be divided by the DDREF first an LET dependence for the cross section must be determined. Such analysis leads to suggestions for critical experiments to measure the LET dependence.

Curtis, S.B. (1992) Risk from relativistic heavy ions on manned space missions. Presented at the International Workshop on Biological Applications of Relativistic Heavy Nuclei (B.A.R.N. 92), Clermont-Ferrand, France, October 14-16, 1992.

GCR, Risk assessment, High-LET, Solar particle event

The risk of relativistic nuclei to space travellers outside the geomagnetosphere has not yet been adequately quantified. The major identified risk is radiation-induced cancer, but other possible risks include accumulation of damage to the

central nervous system resulting in degradation of function of the brain and/or neuroreceptors elsewhere in the body. Single particle effects from the galactic cosmic rays dominate in an interplanetary or lunar radiation environment, assuming that enough shielding is available to protect from the more intense but spectrally softer solar particle events. A review of present uncertainties in our understanding of the biological effects of such relativistic nuclei will be presented. It is suggested that our lack of understanding presently results in an uncertainty in biological effects leading to an uncertainty in risk of factor between 2 and 5.

Curtis, S.B., Townsend, L.W., and Wilson, J.W. (1991) Effects of HZE particles on astronauts. Presented at the American Nuclear Society Winter Meeting, San Francisco, CA, November 10-14, 1991.

Single track effect, Risk assessment, Risk cross section, High-LET, GCR

Outside the effective shielding provided by the Earth's magnetic field, space travelers will experience penetrating high-energy galactic cosmic-ray particles, which permeate the solar system isotropically. Over an eleven-year interval that is related to the eleven-year cycle of solar activity, the fluxes of galactic cosmic rays vary smoothly in time by factors on the order of two, depending on particle energy. Minimum fluxes occur during the years of maximum solar activity and maximum fluxes occur during the interval of minimum solar activity. This radiation consists of protons (with nuclear charge $Z=1$) up to uranium (with nuclear charge $Z=92$). There is an excess of even over odd Z-nuclei, with several local peaks in abundance. A prominent peak occurs in the iron abundance ($Z=26$) and is presumably related to the richness of iron in the galactic cosmic ray sources. An integral fluence rate in number of particles per cm^2 per steradian per year with Z greater than the value on the abcissa. The iron component is particularly important in biological assessment of risk due to its highly ionizing power.

Fry, R.J.M. (1992) Deep space missions: Radiobiological research needs. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research*, Washington, D.C., August 28-September 5, 1992, p. 547.

Space radiation, Animal models, Radiation risk, Stochastic effect, Long-duration space mission

A number of questions about the exposure to radiation during deep space missions and the subsequent effects remain to be answered. In the case of stochastic effects the information about the relationship of the carcinogenic effect to the linear energy transfer (LET) and the energy of the galactic cosmic rays, especially heavy ions is inadequate. Such information must come from experimental animals and therefore methods of extrapolation must be available to estimate risks for humans. Also required is information about the effects of protracted exposure to protons on the reproductive organs. Because of the characteristics of the energy deposition with heavy charged particles, it is not known how well the late effects, especially in the brain and the lens of the eye,

can be predicted from the effects of low-LET radiation. Can the necessary risk estimates be obtained from ground-based research?

Robbins, D.E. (1992) Radiation health in space. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 568.**

Radiation risk, Lunar mission, Mars, LifeSat, LET, RBE, Space Station Freedom

Exposure of humans to the serious hazard of ionizing space radiation has been recognized by a number of studies on exploration class missions including the Synthesis Group. It will be necessary for NASA to initiate a new program to assess the risk from radiation on future lunar and Mars missions. When LifeSat was eliminated from the FY92, NASA budget funding for this research was lost, including the critical ground-based research. The only data base from which radiation risks can be determined addresses only low, linear energy transfer (LET) radiation gamma rays from Japanese atomic bomb survivors. The biological effectiveness of high-LET space radiation appears to pose a greater risk than equal absorbed doses of low-LET radiation. It is, therefore, important that means of minimizing the exposure of humans to ionizing radiation in space be developed. The exposure limits adopted for low Earth orbit (LEO) flights will constrain duty assignments of astronauts to about 250 days. If Space Station Freedom is to be the laboratory where critical life sciences research on the physiological effects of zero gravity is conducted, then duty assignments of a year or more will be required. For space missions outside the Earth's magnetic field, the exposure from galactic cosmic rays inside a typical spacecraft exceeds the annual LEO exposure limits. Thus, part of the radiation health program, especially the ground-based research, must be reinstated.

Sinclair, W.K. (1992) Radiation protection issues in galactic cosmic ray risk assessment. In: *Abstracts, 29th Plenary Meeting of the Committee on Space Research,* **Washington, D.C., August 28-September 5, 1992, p. 567.**

Radiation risk, Radiation shielding, Cancer, LET, Radiation limit, Radiation weighting factor, ICRP, NCRP

Radiation protection involves the limitation of exposure based on a knowledge of the risk. The principal risk associated with low dose rate galactic cosmic rays is the increased risk of cancer. Estimates of this risk depend on two factors (a) estimates of cancer risk for low-LET radiation and (b) the value of the radiation weighting factor, w_R, for the high-LET radiation of galactic cosmic rays. Both factors are subject to considerable uncertainty. The low-LET cancer risk derived from the late effects of the atomic bombs is especially vulnerable to uncertainty from projection in time, and from extrapolation from high to low dose rate. However, recent low dose studies tend to confirm these estimates. w_R, relies on biological effects studied mainly in non-human systems. Additional laboratory studies could reduce the uncertainties in w_R and thus produce a more confident estimate of the overall risk of galactic cosmic rays.

Townsend, L.W., Cucinotta, F.A., Shinn, J.L., and Wilson, J.W. (1991) Human exposure to galactic cosmic rays in space. Presented at the 9th International Congress of Radiation Research, Toronto, Canada, July 7-12, 1991.

HZE, GCR, LET, Risk assessment, Radiation shielding, HZETRN, Computerized anatomical model, Space radiation

As the era of manned exploration of the solar system unfolds, cumulative exposure of astronauts to space radiations, especially the high-energy heavy ion (HZE) component of galactic cosmic rays (GCR), becomes a major concern of mission planners, spacecraft designers, and the crews themselves. These GCR ions, classified as high-LET (linear energy transfer) radiations, deposit large quantities of energy per unit pathlength in tissue. Thus, they may be much more damaging than conventional low-LET radiations, such as x-rays. Reliable estimates of risk to the astronauts, and concomitant shielding requirements necessary for crew protection, require methods currently being developed which accurately describe the interactions and transport of these radiations through matter. In this work, the Langley Research Center GCR transport computer code (HZETRN) and the Computerized Anatomical Man (CAM) model are used to estimate astronaut exposures, from GCR particles, for missions beyond Earth's magnetosphere. Conventional risk assessments in terms of total absorbed dose and dose equivalent are made for the skin, ocular lens, and bone marrow. Evaluations of relative contributions from incident protons, iron nuclei, and their secondary reaction products are presented for each organ.

Townsend, L.W., Cucinotta, F.A., Shinn, J.L., and Wilson, J.W. (1991) Risk analyses for the solar energetic particle events of August through December 1989. Presented at the 1991 Aerospace Medical Association Annual Meeting, Cincinatti, OH, May 5-9, 1991.

Radiation risk, Radiation shielding, BRYNTRN, Solar particle event

The solar particle events (SPE) of August through December 1989 were among the largest ones ever recorded. To assess the potential hazards to humans on interplanetary missions from events of these types, risk estimates for exposures to the skin, ocular lens, and bone marrow behind nominal thicknesses of spacecraft aluminum shielding are made using the Langley space radiation transport code BRYNTRN. Risk assessment in terms of absorbed dose and dose equivalent is discussed for each SPE. Also presented are estimates of cumulative organ exposures for the complete August through December 1989 period.

KEYWORD INDEX

KEYWORD INDEX

KEYWORD INDEX

KEYWORD INDEX

KEYWORD INDEX

KEYWORD INDEX

Stem cell 2-54, 2-90
Stochastic effect 2-93
Structural gene 2-49
STS-27 2-84
STS-28 2-84
STS-33 2-84
STS-42 2-14, 2-16, 2-35
Survival analysis 2-82
Survival rate 2-71

Target fragment 2-42
Thermoluminescent detector 2-13
Time dependence 2-57
Tissue equivalent proportional counter
    (TEPC) 2-6, 2-30, 2-84
Track model 2-20, 2-37, 2-44, 2-45,
    2-91
Track structure 2-35, 2-36, 2-37, 2-38,
    2-42, 2-45, 2-49
Tradescantia 2-20
Translocation frequency 2-47
Transmission function 2-8
Transparency 2-3
Transport calculation 2-4, 2-20, 2-25,
    2-26
Transport code 2-10, 2-11, 2-18, 2-19,
    2-20, 2-22, 2-23, 2-24, 2-37, 2-38,
    2-44
Transport model 2-4, 2-18, 2-22, 2-28
Triangle graph model 2-3
Tumor 2-56, 2-85, 2-87
Tumorigenesis 2-54, 2-55, 2-56

Ultraviolet light 2-49, 2-65, 2-67, 2-68,
    2-69
Uni vs. omnidirectional radiation 2-86
UV radiation 2-34
Uveal melanoma 2-56

Vision 2-58

Water 2-10, 2-18
Women's health 2-89
Wounding 2-53

X-chromosome duplication 2-49
X-ray 2-63, 2-64, 2-75, 2-87

AUTHOR INDEX

AUTHOR INDEX

Adams, J.H., Jr. 2-5, 2-6, 2-20
Ainsworth, E.J. 2-53, 2-54, 2-57, 2-59,
    2-72, 2-82
Alpen, E.L. 2-54, 2-55, 2-61, 2-62
Armstrong, T.W. 2-8, 2-12, 2-16, 2-26,
    2-27
Atwell, W.A. 2-6, 2-9, 2-10, 2-11, 2-30,
    2-36, 2-56, 2-73, 2-83, 2-84, 2-85
Austin, B.T. 2-53

Badavi, F.F. 2-19, 2-20, 2-24
Badhwar, G.D. 2-5, 2-6, 2-20, 2-25,
    2-35, 2-83, 2-85
Bayonove, J. 2-39
Beaujean, R. 2-39
Becker, E. 2-15
Benton, E.R. 2-5, 2-12, 2-13, 2-14,
    2-16, 2-29
Benton, E.V. 2-5, 2-7, 2-8, 2-12, 2-13,
    2-14, 2-15, 2-16, 2-26, 2-27, 2-29,
    2-31, 2-32, 2-39, 2-45, 2-69
Blakely, E.A. 2-56
Braby, L.A. 2-6
Brennan, P. 2-57
Brenner, D.J. 2-48, 2-52, 2-59, 2-60,
    2-63, 2-64
Broerse, J.J. 2-87, 2-88
Broglio, T.M. 2-61, 2-62, 2-75
Brooks, A.L. 2-47
Bücker, H. 2-39

Carr, K.E. 2-57
Cash, B.L. 2-85
Castro, J.R. 2-56
Char, D.H. 2-56
Chun, S.Y. 2-19, 2-24
Colborn, B.L. 2-12, 2-26, 2-27
Conway, E.J. 2-17
Coohill, T. 2-34, 2-45, 2-65, 2-69
Cox, A.B. 2-46, 2-47, 2-57, 2-58, 2-60,
    2-87, 2-88
Craise, L.M. 2-42, 2-43, 2-72

Csige, I. 2-5, 2-12, 2-13, 2-14, 2-26,
    2-29, 2-31, 2-32
Cucinotta, F. A. 2-3, 2-6, 2-9, 2-10,
    2-11, 2-19, 2-20, 2-24, 2-25, 2-26,
    2-35, 2-36, 2-37, 2-38, 2-42, 2-44,
    2-45, 2-49, 2-83, 2-91, 2-95
Curtis, S.B. 2-21, 2-78, 2-79, 2-81,
    2-91, 2-92, 2-93

Daftari, I.K. 2-56
Dalrymple, G.V. 2-46
Dalton, T. 2-55
David, J. 2-61, 2-62
DeGuzman, R. 2-54, 2-55
Delpoux, M. 2-39
Derrickson, J.H. 2-8, 2-12, 2-13
Dutta, S. 2-42

Elliott, T.B. 2-71

Facius, R. 2-39
Fanton, J.W. 2-89
Fishman, G. 2-12
Fong, H. 2-36
Frank, A.L. 2-12, 2-13, 2-14, 2-27
Frankel, K. 2-27, 2-44
Frigo, L.A. 2-13, 2-14, 2-26
Fry, R.J.M. 2-54, 2-55, 2-93
Fujii, M. 2-29

Gaiter, S.L. 2-82
Ganapol, B.D. 2-22
Gasset, Y. 2-39
Gates, M.M. 2-22
Gaubin, G. 2-39
Geard, C.R. 2-52
Gillette, E.L. 2-56
Golden, J.G. 2-89
Golightly, M.J. 2-9, 2-30, 2-84, 2-85
Gong, W. 2-27
Graul, E.H. 2-39
Gupta, R.C. 2-82

AUTHOR INDEX

AUTHOR INDEX

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13. ABSTRACT (maximum 200 words) The present volume is a collection of 227 abstracts of radiation research sponsored by the NASA Space Radiation Health program for the period 1991-1992. Each abstract has been categorized within one of three discipline areas: Physics, Biology and Risk Assessment. Topic areas within each discipline have been assigned as follows: Physics - Atomic Physics, Theory, Cosmic Ray and Astrophysics, Experimental, Environments and Environmental Models, Solar Activity and Prediction, Experiments, Radiation Transport and Shielding, Theory and Model development, Experimental Studies, and Instrumentation. Biology-Biology, Molecular Biology, Cellular Radiation Biology, Transformation, Mutation; Lethality, Survival; DNA Damage and Repair; Tissue, Organs, and Organisms; In Vivo/In Vitro Systems, Carcinogenesis and Life Shortening; Cataract-ogenesis, Genetics/Developmental, Radioprotectants, Plants, and Other Effects: Risk Assessment - Risk Assessment, Radiation Health and Epidemiology; Space Flight Radiation Health Physics, Inter- and Intraspecies Extrapolation and Radiation Limits and Standards. Section I contains refered journals; Section II contains reports/meetings. Keywords and author indices are provided. A collection of abstracts spanning the period 1986-1990 was previously issued as NASA Technical Memorandum 4270.

14. SUBJECT TERMS
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