National Aeronautics and Space Administration

Space Radiation Environment and Human Exploration

Marianne B. Sowa, Ph. D.

Chief, Space Biosciences Research
NASA Ames Research Center
Moffett Field, CA 94035
Marianne.sowa@nasa.gov

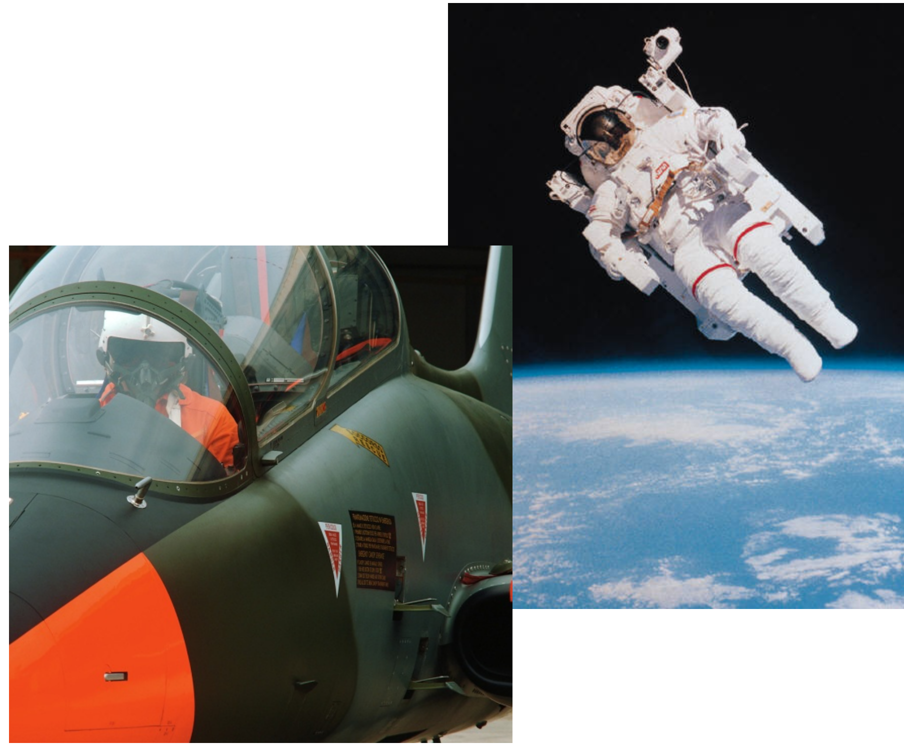
Radiation Exposure

Background

Cosmic rays
Air (radon)
Building material
Water
Food
Earth

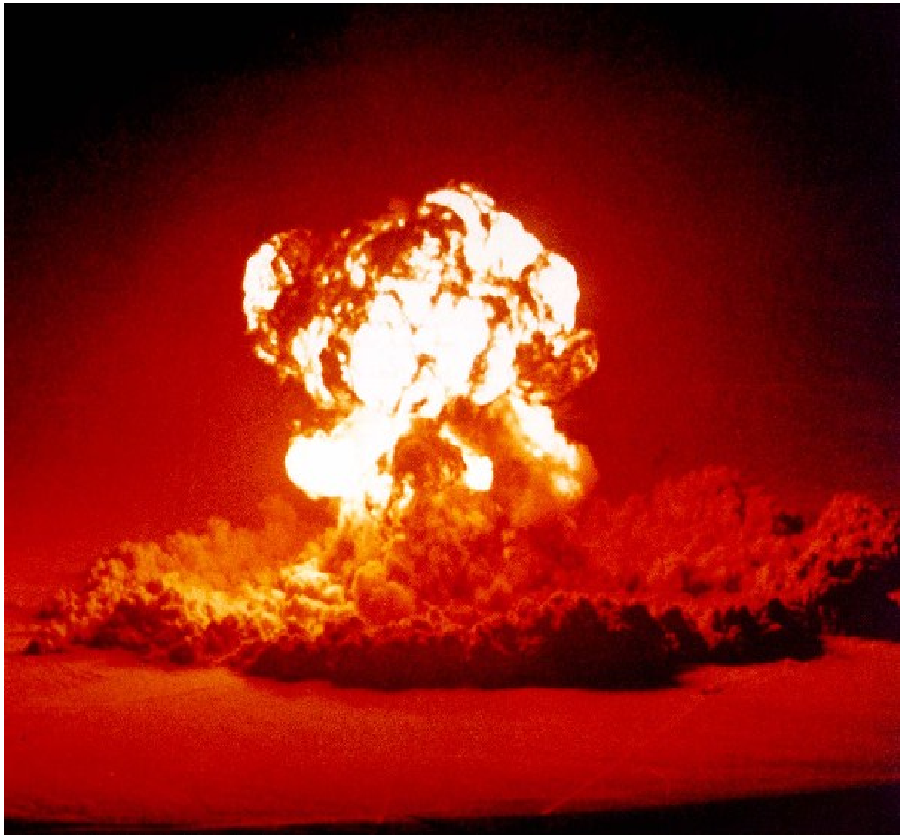
Occupational and Other

Air and Space travel
Testing fallout /contamination
TV & luminous watches
Nuclear power plants (20%)
Radioactive waste
Diagnosis & therapy*



*Diagnostic radiology > 200 million procedures/year (USA). Two billion procedures world-wide. High dose/partial body.

Most of our understanding of radiation effects comes following a single acute exposure



Hiroshima, 1945

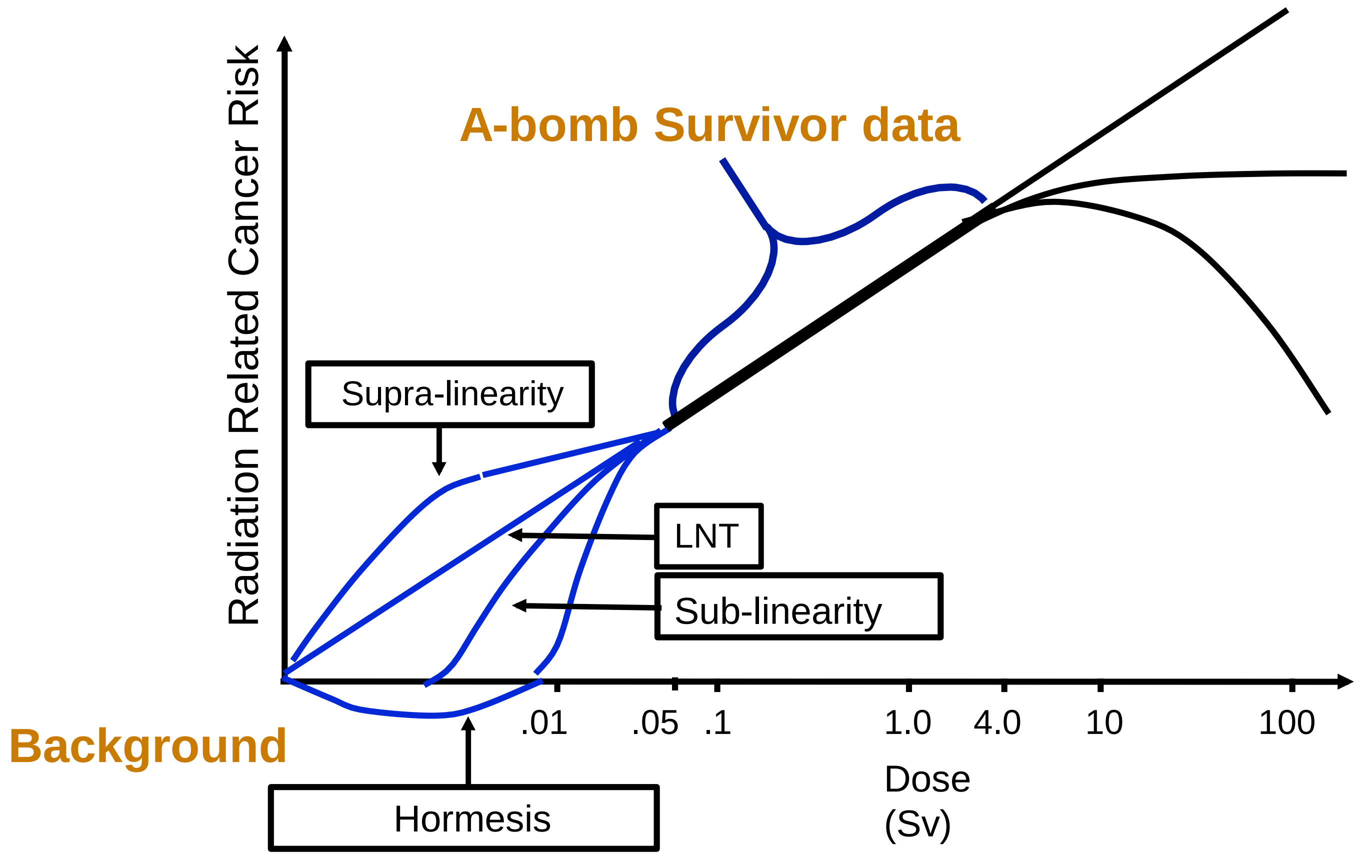
Killed outright	100,000
Survivors studied	86,572
Expected cancers (no bomb)	21,643
Observed cancers	22,064*
Increase	421*

Increased non cancer deaths: Circulatory, digestive and respiratory diseases

*Data not updated

What is the issue?

The shape of the dose response at low radiation doses (< 100 mGy) and low dose rates for radiation-induced cancer is a critical judgement for radiation policy and risk assessment.



Specific Questions being Addressed

Are the mechanisms of action the same for low and high doses of radiation?

Do we need to change current paradigms in radiation biology?

Is the LNT hypothesis an accurate scientific description for the dose-response relationship for cancer (or other risks) in the low dose region?

How do non-targeted effects influence cancer and non-cancer risks after irradiation?

How does this translate to space radiation exposures?

The Space Radiation Environment

Solar particle events (SPE) (generally associated with Coronal Mass Ejections from the Sun):

- medium to high energy protons
- largest doses occur during maximum solar activity
- not currently predictable
- MAIN PROBLEM: develop realistic forecasting and warning strategies

Trapped Radiation:

- medium energy protons and electrons
- effectively mitigated by shielding
- mainly relevant to ISS
- MAIN PROBLEM: develop accurate dynamic model

Galactic Cosmic Rays (GCR)

- high energy protons
- **highly charged, energetic atomic nuclei (HZE particles)**
- not effectively shielded (break up into lighter, more penetrating pieces)
- abundances and energies quite well known
- MAIN PROBLEM: biological effects poorly understood but known to be most significant space radiation hazard

GCR High Energy

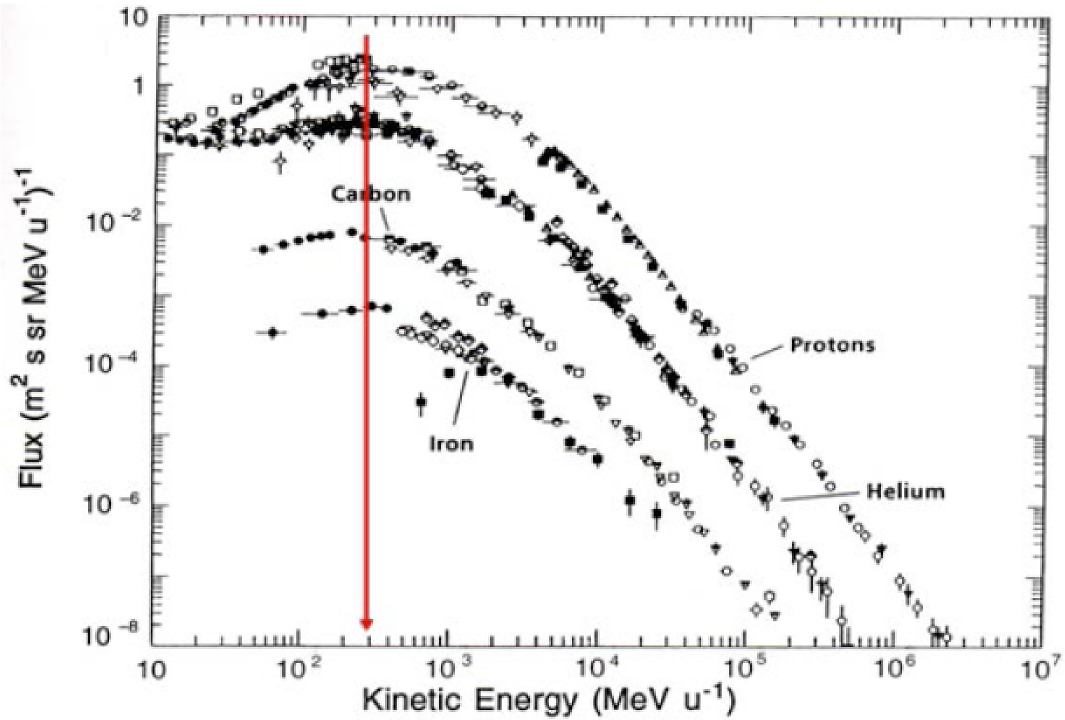
Space radiation problem

GCR (primary) composition

- 98% nuclei, 2% $e^+ e^-$
- Nuclear component:
  87% Hydrogen
  12% Helium
  1% heavy nuclei

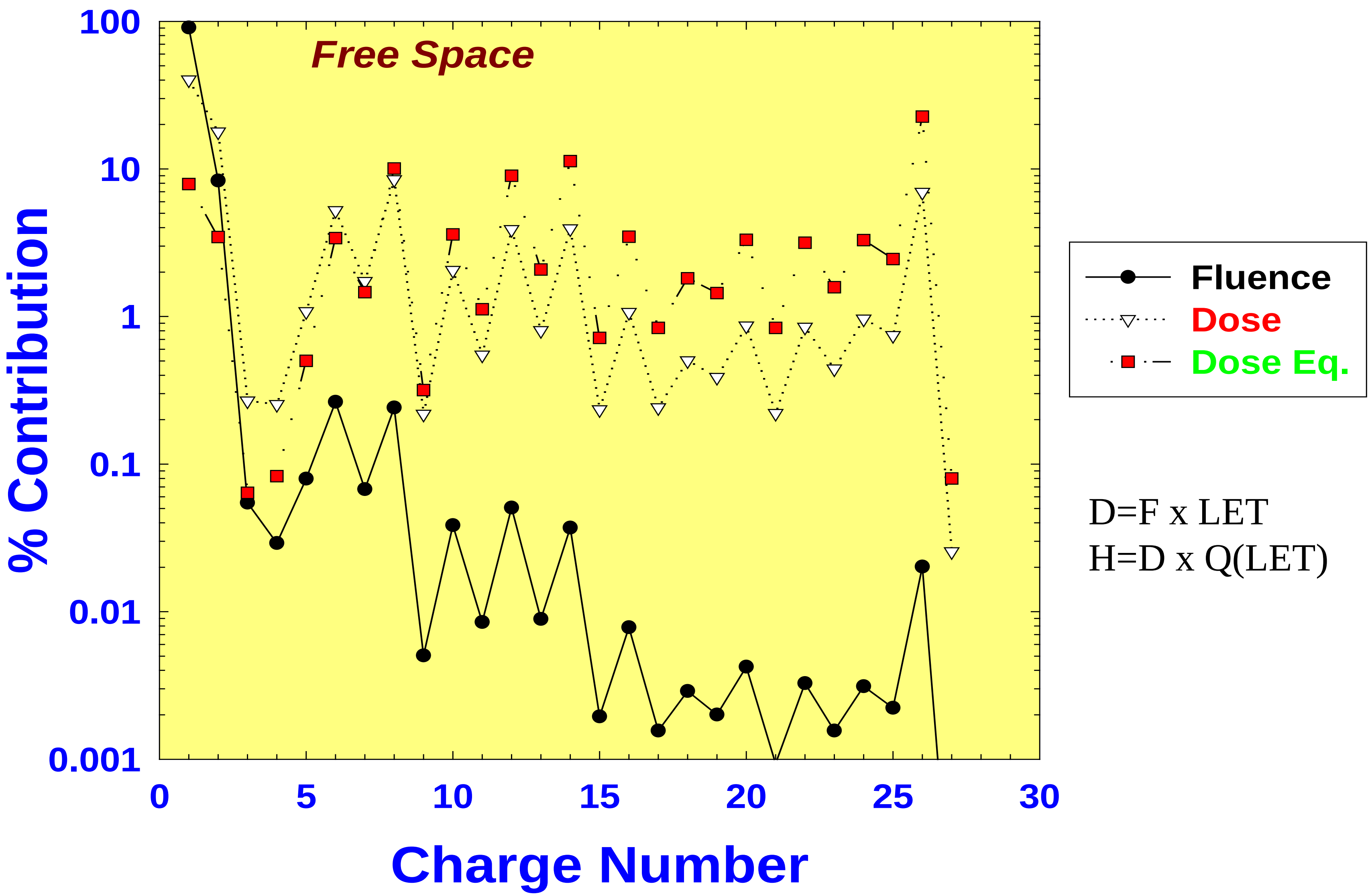
GCR origin

- Emitted in stellar wind & flares & accelerated by supernova shock waves (within our Galaxy)



[Simpson, Ann. Rev. Nucl. Part. Sci. 33, 323, 1983]

GCR Charge Contributions

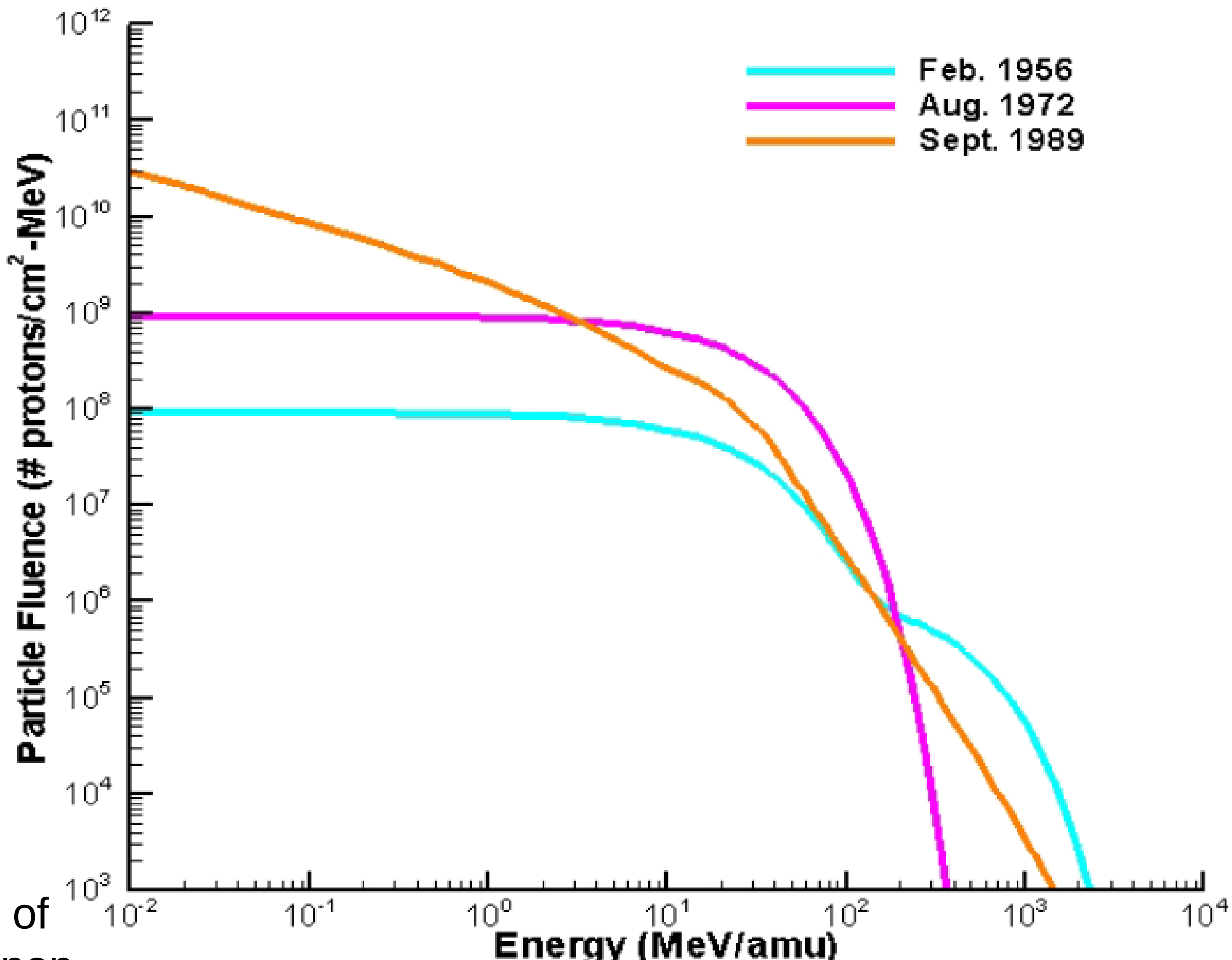


D=F x LET

H=D x Q(LET)

Solar Particle Events

e, p & some heavy nuclei < 1 GeV/N $(v \sim 0.9c)$



SPE Proton spectra [Clowdsley et al., AIAA, 2006]

Energy/dose deposition of protons in tissue highly non-linear

The Space Radiation Problem

- The space radiation environment in unique
  - High energy protons and heavy ions (HZE)
  - Secondary protons
  - Neutrons
  - Heavy ions produced in shielding
- Unique damage to biomolecules, cells, and tissue
- No human data to estimate risk from heavy ions
- Solar particle events cannot currently be predicted with sufficient warning
- Shielding not practical (weight, cost, will not eliminate HZE due to fragmentation)

Primarily a low dose/low dose rate problem

Adapted from Cucinotta

Biological Temporal and Spatial Scales

- Biological time and spatial scales as well as linear or non-linear response modes must be known relative to GCR fluxes (type and rate) to properly simulate:
  - **protracted exposures are essential**

- Temporal:
  - Initial damage and radiation chemistry per nucleus <1 sec
  - DNA Damage repair 10 minutes to ~1 day
  - Apoptosis and differentiation ~0.5 to several days
  - Cell turn-over rates- Tissue specific from ~1 to 30 days
  - Tumor latency (post initial damage) in humans 2 to 30 yrs
  - Tumor latency in mice 100 to 800 days
  - CNS Adaptation time to GCR insult??
  - Lifespan in astronauts ~80 yrs
  - Lifespan in mice ~1000 days
  - Mars mission 1000 days

Spatial Scales- continued

- Space Radiation (GCR proton hits/day ; HZE)
  - DNA damage repair foci ~0.5 μm^2 (0.002 per day / $1x10^{-6}$)
  - Chromosome cross sections ~ 2 μm^2 (0.01 per day / $2x10^{-4}$)
  - Cell Nucleus ~200 μm^2 ` (1 per day/ 0.02)
  - Interacting cell matrix ~1000 μm^2 (>5 per day/ >0.1)
  - Whole Tissue >Many per day

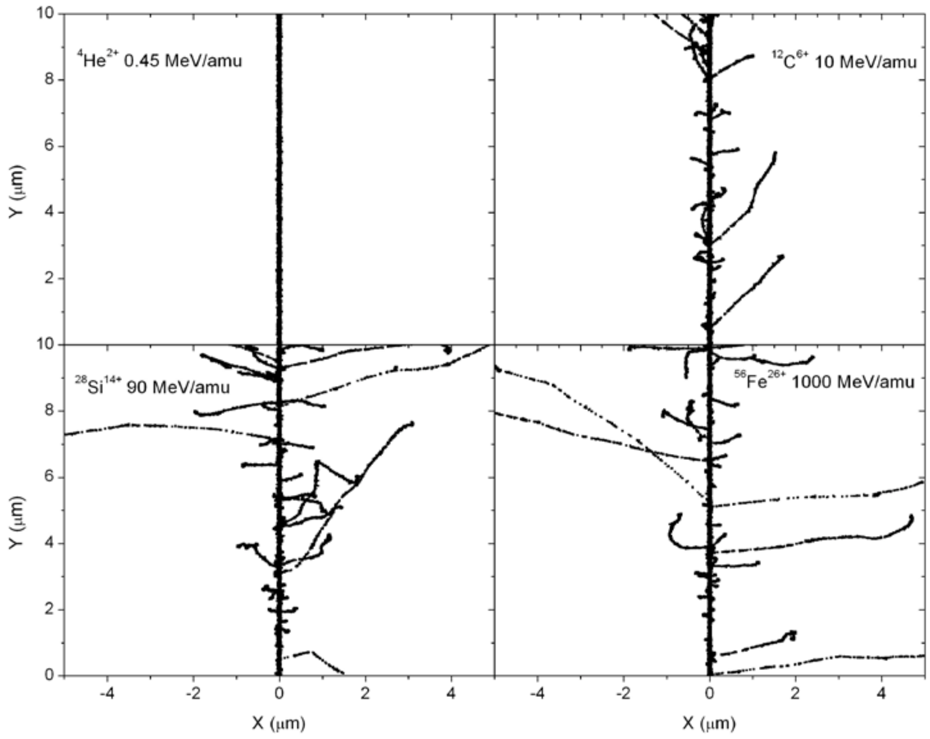
- Space radiation simulation is anchored in knowing space conditions relative to scientific question being addressed
  - A "low dose" for certain biological questions, may be a "high dose" for another: Microdosimetry

- Most ground based experiments to date have been performed in "track segment mode" where samples are irradiated with largely a single species with constant LET across sample

Track Structure of Space Radiation

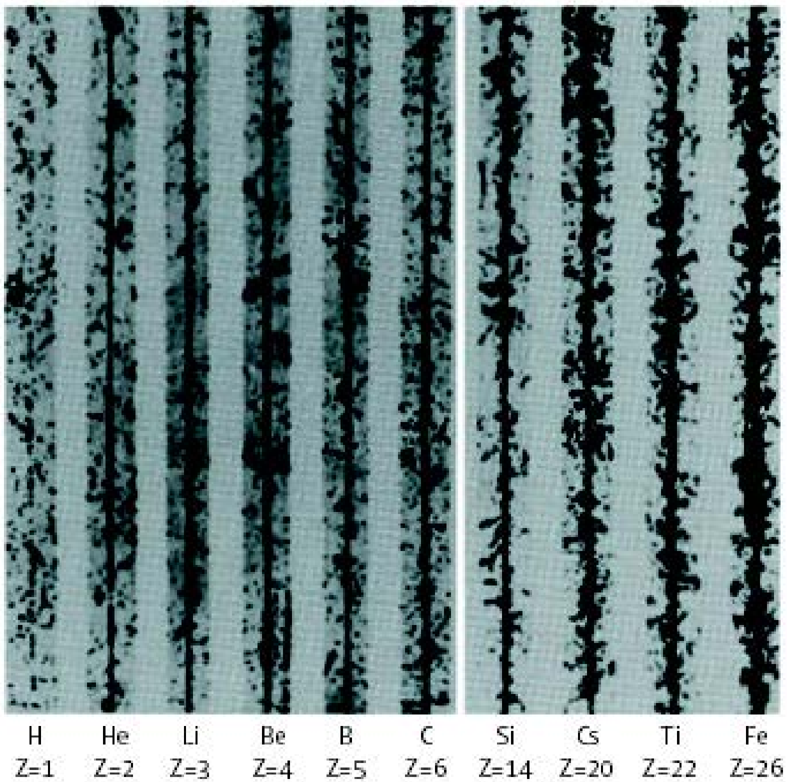
- Linear energy transfer (LET) does not adequately describe energy deposition at biomolecular or cellular scales
- Full characterization of HZE nuclei-
  - Charge, Z defines density of ionization along track (Z^2 dependence)
  - Kinetic energy of β defines width of track corresponding to maximum distance of energy deposition laterally from track

Nuclei of LET = 150 keV/μm



Monte-Carlo simulation of ionization patterns (He 0.45 MeV/u; C (10 MeV/u), Si (90 MeV/u) and Fe (1 GeV/u)

Charged particle tracks in nuclear emulsions

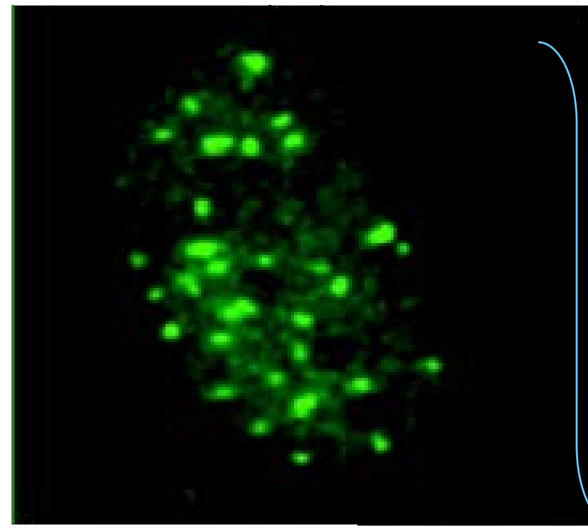


100 µm

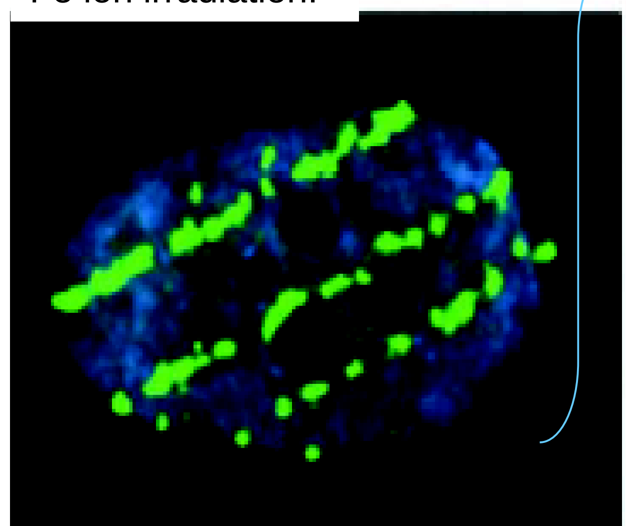
(Cucinotta & Durante, Lancet Oncol 2006)

Fluorescent foci marking DSB in cell nuclei

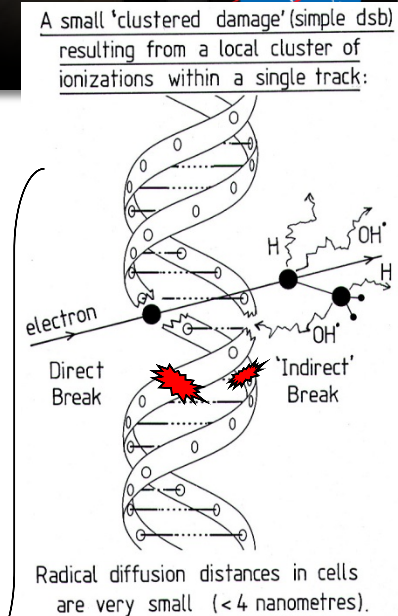
Gamma-ray irradiation:

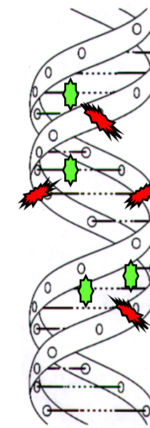


Fe ion irradiation:



10 µm





Complex Clustered damage in DNA

2 nm

Magnification X 20 X 1600

DTG 13.5.10

Understanding Radiation Risk

Current radiation health effects assume:

1) the primary mode of action is linearly related to dose and
2) that the individual cell is the unit of risk.

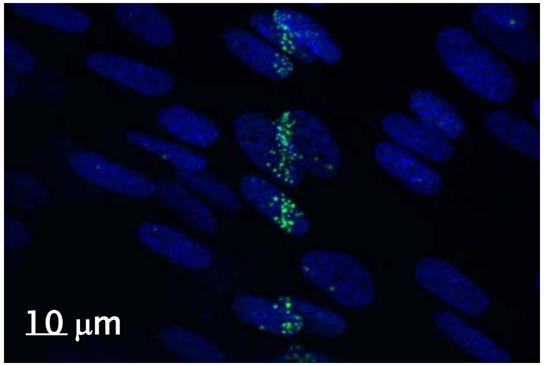
Non-targeted effects and other low dose effects suggest responses occur non-uniformly over time at the multi-cellular scale

Not all radiation is equal: RBE

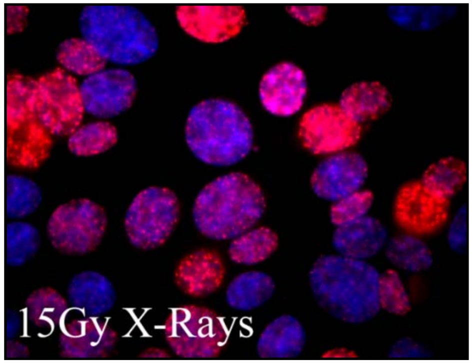
Space Radiation - High-LET

- Galactic cosmic rays (HZE)
- Solar Particle events
- Trapped radiation

Role of radiation quality and track structure?



High-LET



Low-LET

Dose Equivalents

	Dose Equivalent (mSv)
Chest x-ray	0.1
USA annual background	4
Public annual limit (above background)	1
International Airline crews	4
Radiation worker annual limit	20
No observed effects (Abomb)(instant)	200
Blood count changes	$>$200
Acute Radiation Syndrome (ASR)	1,000
Death (instantaneous dose)	3,000
Mir, ISS (with shield) annual	150
Large solar flare (free space)	10,000

ICRP cancer risk estimate: 5% per Gy $\sim$ 5% per Sv (for Q=1)

1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)

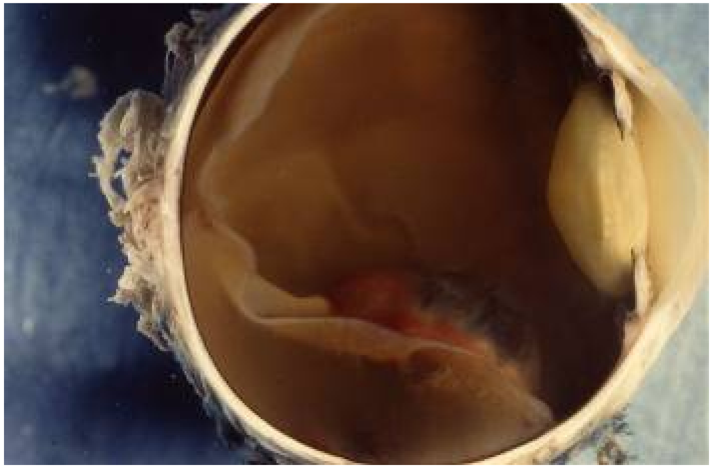
Categories of Space Radiation Risks

Four categories of risk of concern to NASA:

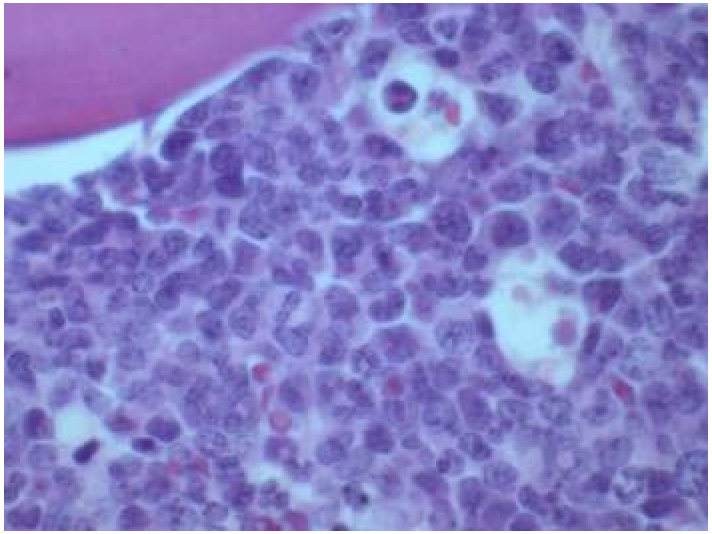
- ***Carcinogenesis (morbidity and mortality risk)***
- ***Acute and Late Central Nervous System (CNS) risks***
  - ✓ immediate or late functional changes
- ***Chronic & Degenerative Tissue Risks***
  - ✓ cataracts, heart-disease, etc.
- ***Acute Radiation Risks*** – sickness or death

Differences in biological damage of heavy nuclei in space with x-rays, limits Earth-based data on health effects for space applications

- **New knowledge on risks must be obtained**



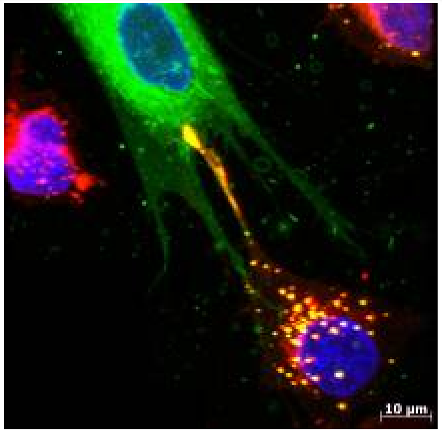
Lens changes in cataracts



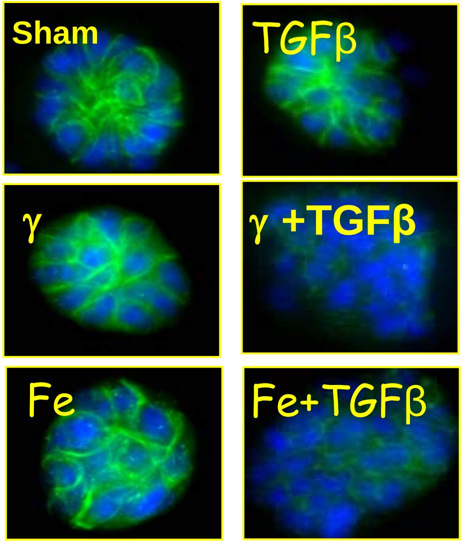
First experiments for leukemia induction with GCR

Space Safety Requirements

- Congress has chartered the National Council on Radiation Protection (NCRP) to guide Federal agencies on radiation limits and procedures
  - NCRP guides NASA on astronaut dose limits
- Crew safety
  - limit of 3% fatal cancer risk
  - prevent radiation sickness during mission
  - new exploration requirements limit brain and heart disease risks from space radiation
- Mission and Vehicle Requirements
  - shielding, dosimetry, and countermeasures
- NASA programs must follow the ALARA principle to ensure astronauts do not approach dose limits



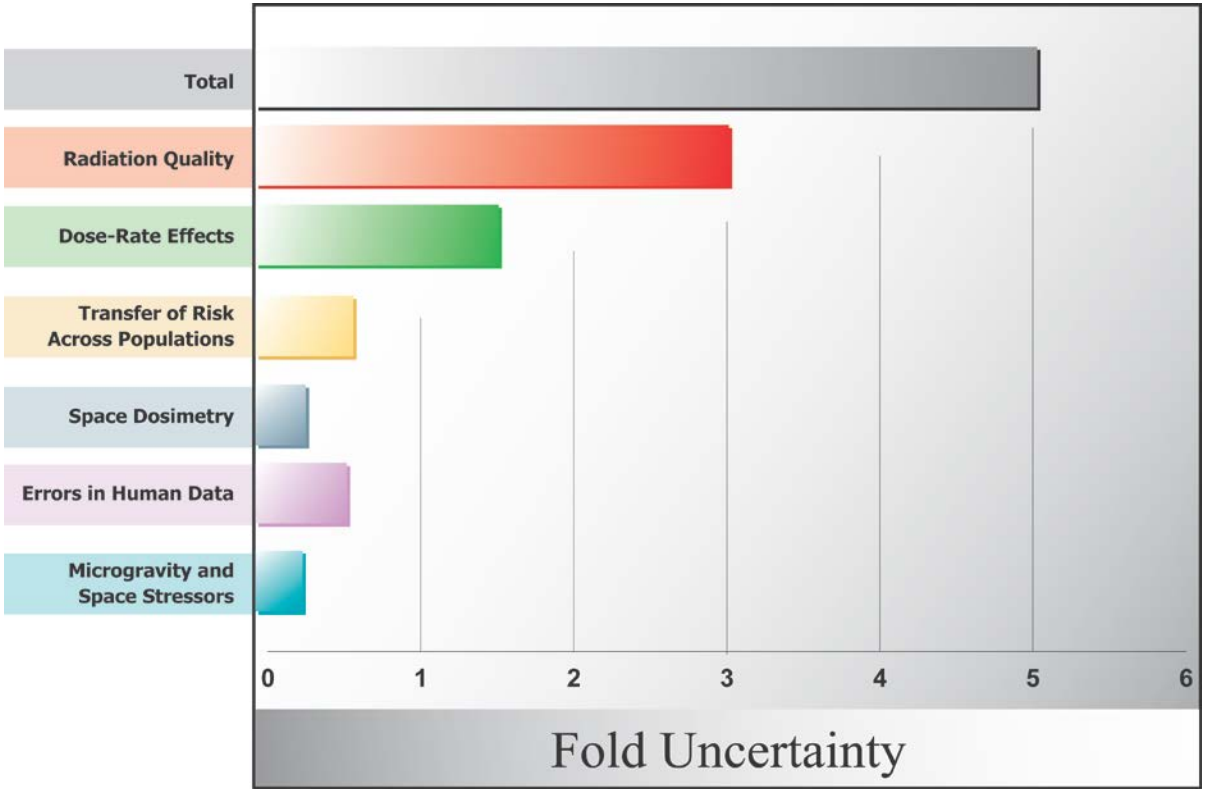
Cell fusion caused by radiation

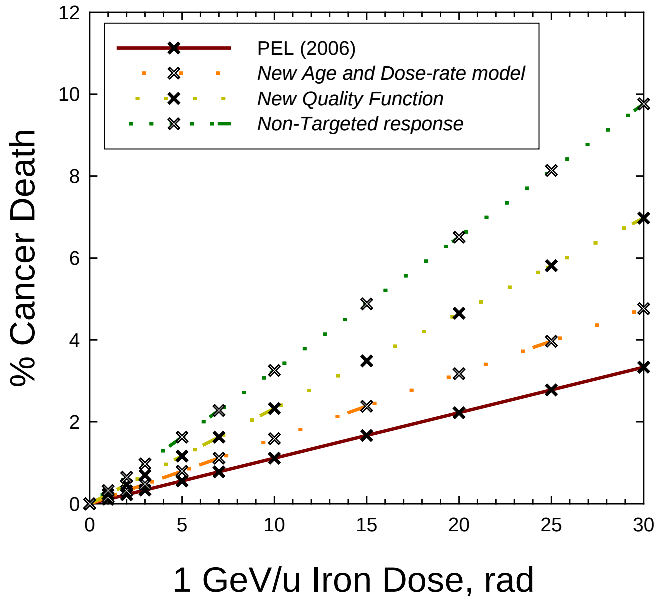


Space Radiation in breast cancer formation

Cancer Uncertainty Assessments

- Uncertainties assessments use probability distribution functions (PDF) to represent range of data of different factors in risk model
- NASA is Unique amongst government agencies in that Uncertainty assessments are part of radiation protection program





Risk per unit Dose from HZE nuclei will potentially be assessed higher in near future:
- Age, RBE, dose-rate, and latency for solid tumors

Estimates of “Safe Days” in Space for GCR

Research progress shows significant increase in “Safe Days” to be within acceptable risks for a Mars mission

- Uncertainties are being reduced through ground based research

Table: Estimates of “Safe Days” in deep space under heavy shielding where NASA limit is not exceeded

Age, yr	Females		Males	
	Previous (2001)	Current (2006)	Previous (2001)	Current (2006)
30	54	112	91	142
35	62	132	104	166
40	73	150	122	186
45	89	182	148	224
50	115	224	191	273

Note: missing reference for this table

Dose Rate effects

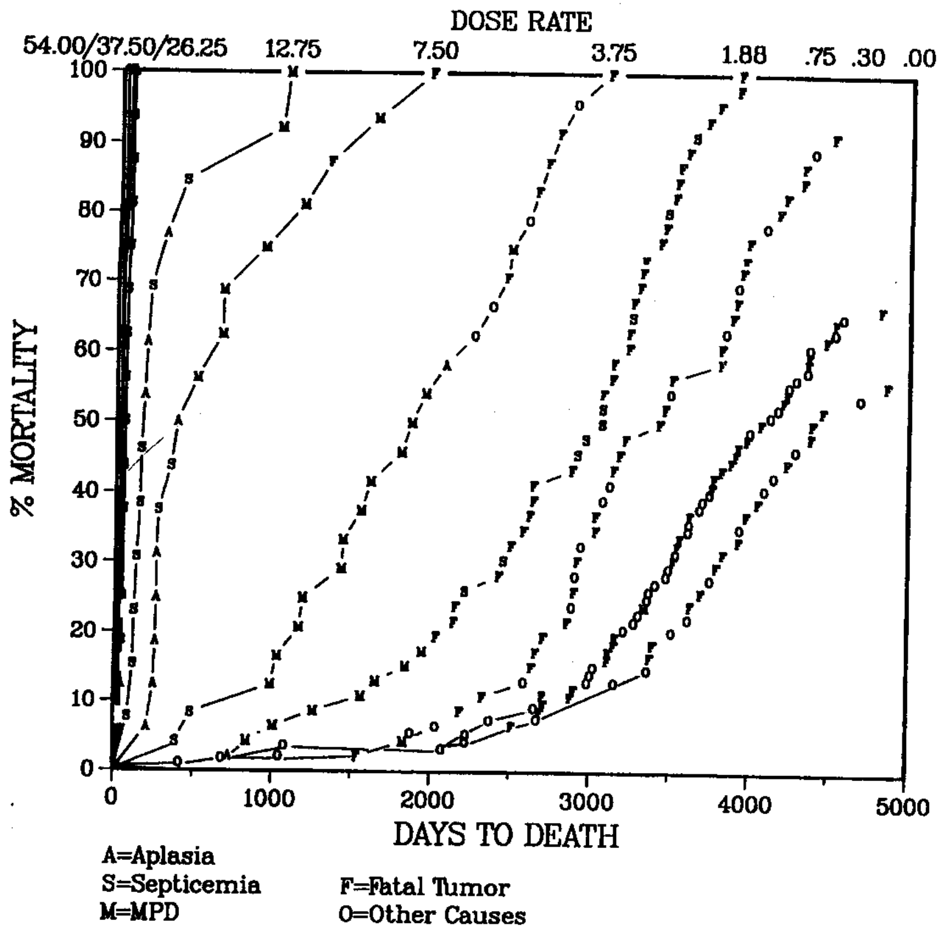


Figure 2. Relationship between dose rate, time to death and causes of death in adult beagles continuously irradiated (22 h day^{-1}) at several dose rates (rads day^{-1}; average absorbed dose).

Fritz T. (2002) BJR Supplement 26, 103-111.

Conclusions and Questions?

- Relative to low LET exposures, we know comparatively little about the ultimate health risks of HZE and SPE exposures.
  - Relevant doses and dose rates
  - Protracted exposures
  - Combined exposures (microgravity)

- How does the heterogeneous nature of the energy distribution effect the response? Can microdosimetry predict response?
- Much of the past emphasize was on cancer risk but at low dose are other risk more important?
  - CNS – low dose (0.1 cGy) induced cognitive impairment
  - Cardio vascular risk, visual impairments
- Does microgravity act synergistically, antogonistically or they are uncoupled?
- Role of ground, LEO, and BLEO, the integration of large data sets and systems approaches in defining mechanisms of response.

Acknowledgments

Many of the slides presented were shared by colleagues for teaching purposes. Please do not distribute without permission.

John Norbury – NASA Langley
Francis Cucinotta - University of Nevada, Las Vegas
Tony Brooks – Washington State University (retired)
Dudley Goodhead - Medical Research Council, Oxford (retired)

Low dose exposure situations

Environmental clean-up – Hanford (>$110 Billion to date)

Nuclear Accidents – Fukushima (160,000 evacuated, 20 mGy/yr)

Rad worker exposures

Flight Crews and Astronauts (limits to the Mars mission?)

Potential Terrorist Attacks (dirty bombs, IND)

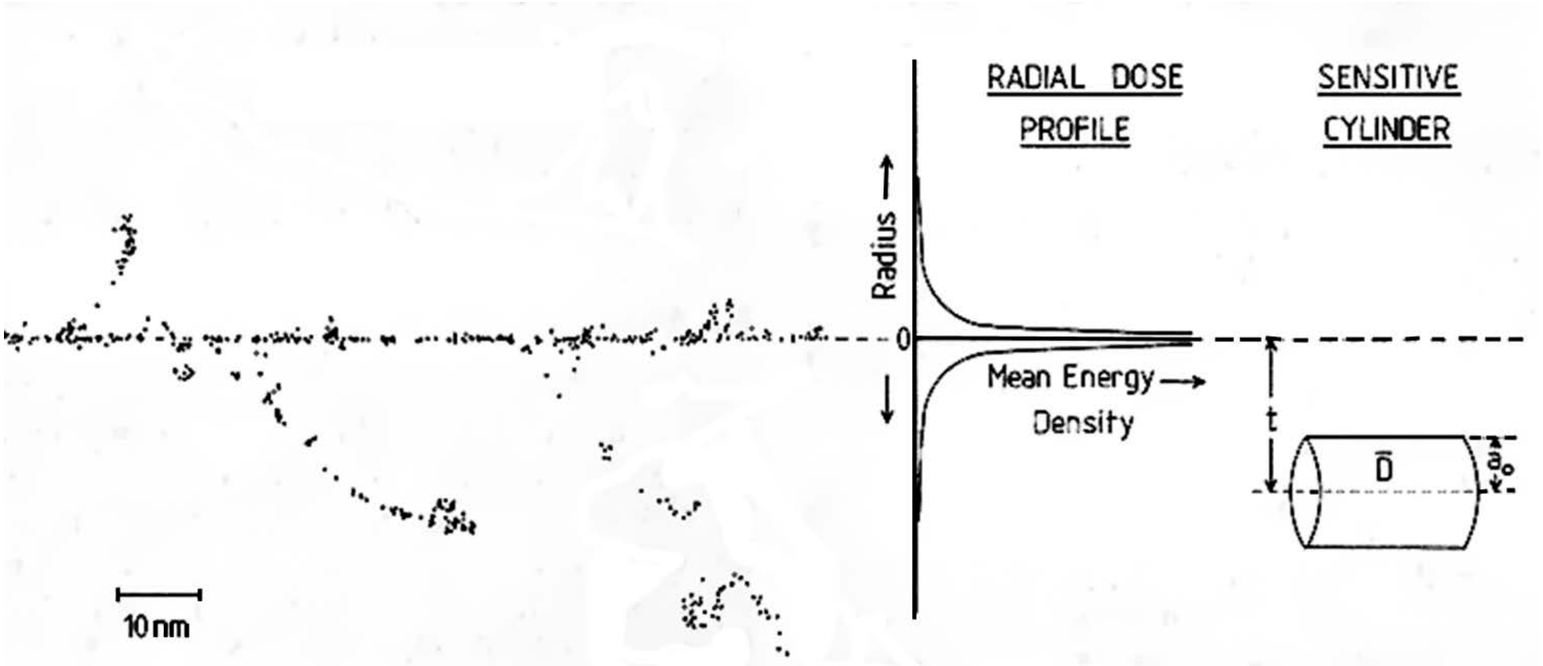
Security issues (airport backscatter machines)

High natural background exposures – Radon, geographical locations in Karala (India) Yanjing (China)

Medical Diagnostics – >90 million CT scans annually 5-100 mSv each (acute exposure v protracted exposure LDRt)

Radial Dose Distribution of a Track

An Average the spectrum of ionization patterns as function of distance from a Track to a molecule



Ionization patterns → Radial dose from Ion deposited in Small cylinder

From D.T. Goodhead