The Atmospheric Ionizing Radiation (AIR) Project – Preliminary Results for Neutron Spectra and Ionization Rate

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Radiation Protection for Air Crews

- High-energy mixed radiation from cosmic rays
  - Roughly half of effective dose from neutrons
  - Large uncertainties in neutron spectrum and H

- Continual exposure of large group
  - 167,000 air crew members in U.S.
  - Civil aircrew working hours aloft ~ 500-1000 h / year
  - Air crews are one of the *most exposed* groups of radiation workers

- Radiation protection limits going down

- New high-altitude civil aircraft designs (?)
Dose Rates from Galactic Cosmic Rays in the Atmosphere Depend on

- **Altitude** - Shielding by air
  - 1030 g/cm² at sea level, 55 g/cm² at 20 km (66,000 ft)
  - Dose equivalent rate, H, at 20 km ~500 × H at sea level

- **Latitude** - Shielding by geomagnetic field
  - Bends slower particles back into space
  - Effect on H increases with altitude
  - H at poles >6 × H at equator at 20 km

- **Time in Solar Cycle** - magnetic field of solar wind
  - 11-year sunspot cycle: Radiation max at sunspot min
  - Effect on H increases with geomagnetic latitude & altitude
  - Solar modulation >2 in polar regions at 20 km
Effective Dose vs. Altitude
for Galactic Cosmic Ray Components

Data from O'Brien LUIN-98F calculation at 55.4° N, 120° W

Corresponds to Mars

Effective Dose (µSv h⁻¹)

Altitude (km)

0 5 10 15 20 25

Total
neutrons
photons + electrons
protons
muons
pions

(\(w_R = 2\))

(1000 ft)
## Contribution of Various Components to Estimated Dose Equivalent Rate

In Polar Regions During Solar Minimum

<table>
<thead>
<tr>
<th>Quantity</th>
<th>60,000 ft</th>
<th>70,000 ft</th>
<th>80,000 ft</th>
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<td>Dose Rate, D</td>
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<td>neutrons</td>
<td>4.5 - 18.0</td>
<td>5.0 - 19.9</td>
<td>5.1 - 20.2</td>
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<td>Z=1 (protons)</td>
<td>≈1.5</td>
<td>≈1.7</td>
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<td>Dose Equivalent Rate</td>
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Jet Altitude Cosmic Ray Neutron Spectra - Previous Measurements

Neutron Energy (MeV) vs. Count Rate (cm\(^{-2}\)sec\(^{-1}\))

- **Hess '59**
  - 200 g cm\(^{-2}\) (11.75 km), 4.0 GV cutoff

- **Hewitt '78**
  - 190 g cm\(^{-2}\) (12.3 km), 2.4 GV cutoff

- **Korff '79**
  - 70 g cm\(^{-2}\) (18.6 km), polar

- **Nakamura '87 (↔3)**
  - 220 g cm\(^{-2}\) (11.3 km), 10 GV cutoff
Existing Jet-Altitude Cosmic Ray Neutron Spectra

**Measured**
- Hess 1959, 220 g/cm$^2$ (11.4 km)
- Hewett '78, 190 g/cm$^2$ (12.3 km)
- Korff '79, 70 g/cm$^2$ (18.6 km)

**Calculated**
- Armstrong '73, 100 g/cm$^2$ (16.3 km)
- Merker '73, 90 g/cm$^2$ (17 km)
The Atmospheric Ionizing Radiation (AIR) Measurements Project

- Collaboration of ~12 laboratories, 6 countries
  - Started by NASA LaRC and EML
- Suite of 14 radiation measuring instruments
- Dedicated flights of NASA ER-2 aircraft
  - Altitudes: 16 - 21 km (53,000 - 70,000 ft) 110 - 50 g/cm²
  - Latitudes: 18°- 60° N over western U.S., Canada, Pacific
  - Each flight 6.5 to 8 hours
  - Multiple flight series over several years of solar cycle
- First flight series successfully completed June 1997
- Measurements benchmark/validate AIR model code

Funded by NASA High Speed Research Program as part of HSCT Environmental Impact studies and by collaborating laboratories
## AIR INSTRUMENT CHARACTERISTICS

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<th>Γ</th>
<th>e⁺</th>
<th>μ⁺</th>
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</table>

✓ - primary particle / quantity  
+ - responds  
~ - partial response  
😊 - complicates primary measurement
Altitude Profiles for 3 AIR Flights

Time after Takeoff (hours)

Altitude (km)

East
South 1
North 2
Ionization Chamber Reading
All Four 6.5-Hour Flights

Time After Takeoff (minutes)

Counts per Minute

North 2
East
South 1
South 2
Predicted and Measured Ionization Rate

Time after Takeoff (minutes)

Ionization Rate (ions/cm² s)

North 2 Flight

EML ion chamber measurement

AIR Model prediction

Paul Goldhagen

Multisphere Neutron Spectrometer (Bonner Spheres)

Set of spherical moderators of different sizes surrounding slow-neutron detectors

Big moderators slow down higher-energy neutrons than small moderators.
Multisphere Spectrometer

Advantages

- Wide energy range (9 - >11 decades)
- Highly sensitive to neutrons, but not gamma rays
- Isotropic response
- Transportable
- Stable response, tried and true

Disadvantages

- Low resolution
- Useful only for uniform, stable or monitored field

To use, need:

- Response functions
- Unfolding
Response Functions of EML
High-Energy Multisphere Neutron Spectrometer

without containers

MCNP / LAHET

Response (Counts cm$^{-2}$ neutron$^{-1}$)

Neutron Energy (MeV)

proton response

Counts

without containers

EML

Paul Goldhagen

RFcans.jnb

6/8/99
Accomplishments

• 5 science flights successfully completed
   June 1997, solar minimum (radiation maximum)

• Full energy range neutron spectrometer developed
   Response functions - calculations, verification experiment
   MAXED unfolding code

• Good data, preliminary results for:
  • Relative ionization rate vs. latitude and altitude

• Full-range neutron spectra measured in an aircraft
   High-altitude (50-110 g/cm²): wide range of latitudes
   Commercial altitudes: one latitude
Conclusions

• Current AIR Model fits relative ionization rate well for all latitudes and altitudes

• AIR neutron measurements will reduce uncertainties in neutron spectrum and effective dose rate
  □ neutron measurements must include correction for protons

• High-energy neutrons are significant
  □ about half of neutron dose equivalent

• AIR measurements can be used to validate cosmic radiation transport codes for Mars

• CR dose calculations for Mars residents should consider
  □ Surface composition - hadron cascades from iron
  □ Low-Z shielding below as well as above/around habitats

• 2nd series of AIR flights would be worthwhile
Thanks


EML: M. Reginatto, W. Van Steveninck, F. Hajnal, F. Raccah

University of Akron: T. Kniss

NASA Ames (Dryden ) Research Center: ER-2 liaison staff, scientists, engineers, ground crew, pilots

All the AIR investigators, their collaborators & support people

W. Friedberg, K. Copeland, K. O’Brien, V. Mares, S. Roesler and others
High-Altitude Cosmic Ray Neutron Spectra

Effect of Default Spectrum

**EML measurement** (preliminary unfoldings)

56 g/cm² (20 km, 66,000 ft),
solar minimum, near polar plateau
AIR ER-2 flight 97-108, 6/13/97, 54° N, 117° W
(corrected for protons)

Using as default spectrum for unfolding:

- **Armstrong '73, HETC-ANISN**
  - 50 g/cm², solar min, 42° NGM

- **Roesler et al. '98, FLUKA**
  - 200 g/cm², 47° N, 11° E, 5/95

Neutron Flu \( \frac{dN}{dE} \) (cm⁻² sec⁻¹)

Neutron Energy (MeV)
High-Altitude Cosmic Ray Neutron Spectra
Effects of Protons and Energy Limit

EML measured neutron spectrum, (preliminary unfoldings)
56 g/cm$^2$ (20 km, 66 kft), solar minimum, near polar plateau
NSMED unfolding

- Blue line: without correction for protons
- Red line: with correction for protons

Same data (without correction for proton effects)

SANDII unfolding cut off at 1 GeV

Default spectrum:
Armstrong '73, HETC-ANISN,
50 g/cm$^2$, 42$^\circ$ NGM, solar min
$x2.34$ for best fit to data
Introduction

AIR Model

• Dose rate empirical formulations
  - air ionization, charged particle stars, 1 to 10 MeV neutrons

• Dose rate equivalent from ICRU 40

• Data set from solar cycle 20 and scaled to the Deep River neutron monitor with the geomagnetic cutoff
Current AIR Model

- Set of scaling and interpolation subroutines
- Data set from solar cycle 20
- Use of the geomagnetic cutoff
- Scaled to the Deep River neutron monitor
- Solar variation with latitude, longitude, altitude, and pressure
Current AIR Model

• Dose rate empirical formulations
  - Air ionization
  - Charged particle stars
  - 1 to 10 MeV neutrons

• Dose rate equivalent
  - ICRU 40
Ultimate AIR Model Purpose

• Accurate prediction of dose and dose equivalent anywhere in the Earth’s atmosphere
• Enable assessment of health risks to flight crew and passengers for airline industry
• Validation model of space radiation transport codes
Calculated High-Altitude Cosmic Ray Neutron Spectra

- **Armstrong '73, HETC-ANISN**
  - 50 g/cm², solar min, 42° NGM
  - x 2.34 for best-fit EML data at above coordinates

- **O'Brien, LUIN-97 (FAA, CARI)**
  - 56 g/cm² (20 km, 66,000 ft), solar minimum, near polar plateau
  - 6/13/97, 54° N, 117° W

- **Roesler et al. '98, FLUKA**
  - 200 g/cm², 47° N, 11° E, 5/95
  - x 4.0 for best-fit EML data
Response Functions of EML
High-Energy Multisphere Neutron Spectrometer

without containers

MCNP / LAHET

det 13 proton response

det 14 proton response

Neutron Energy (MeV)