

CARI-7: Software for Calculating Cosmic Radiation Flight Doses

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Federal Aviation
Administration



Galactic Cosmic Radiation

<6 mSv, primary source

Terrestrial Gamma-Ray Flashes

and

X-rays from Lightning

<30 mSv, very rare

Ionizing Radiation in Aviation

Solar Proton Events

<10 mSv per event, rare



Radioactive Cargo

<0.13 mSv



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AIRCREW DOSES

Highest average annual effective doses among monitored workers worldwide (1990-1994)
[UNSCEAR, 2000].

Practice	Rank	Effective dose / mSv·y ⁻¹
Above-ground radon from oil and natural gas extraction	1	4.8
Nuclear fuel mining	2	4.5
Nuclear fuel milling	3	3.3
Aircrew	4	3.0
Mining other than nuclear fuel or coal	5	2.7
Radioisotope production	6	1.93
Industrial radiography	7	1.58
Nuclear fuel reprocessing	8	1.5

Radiation

	Non-flying United States Resident	Non-flying Resident of EPA Region 8	Los Angeles-Tokyo (36 Round Trips)	Chicago-London (48 Round Trips)	Seattle-Portland (634 Round Trips)
Cosmic, airborne	----	----	2.81	4.52	0.22
Cosmic, ground level	0.38	0.73	0.34	0.35	0.36
Terrestrial gamma	0.24	0.63	0.23	0.23	0.23
Radon decay products	1.31	2.55	1.12	1.13	1.23
Radionuclides in body tissues	0.40	0.40	0.40	0.40	0.40
Total	2.33	4.31	4.90	6.63	2.44

*Assumes 760 block hours

Annual Effective Dose from Natural Sources/mSv

Non-flyer

Airline Pilot*



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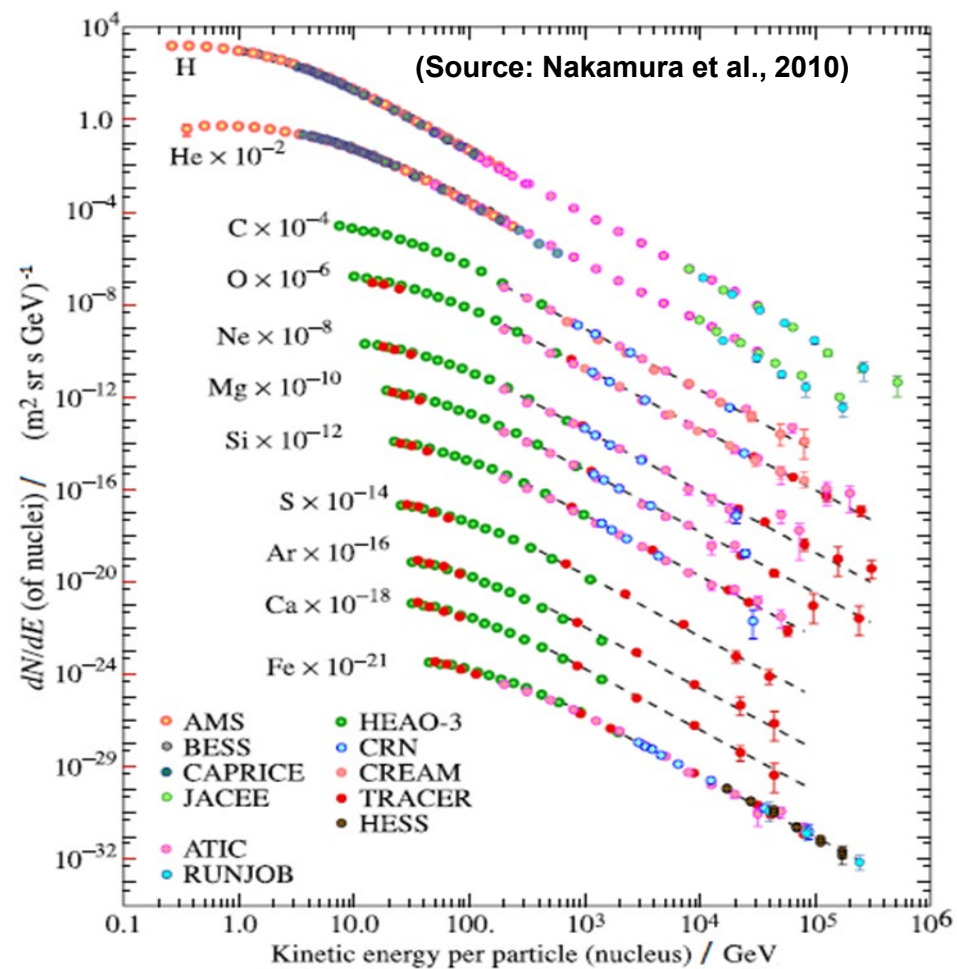
Stochastic and Deterministic Health Effects

Stochastic Effect	Increased lifetime risk*	
	Whole population	Age group 18-64 years
Genetic effects in first two successive generations (children and grandchildren), irradiation before conception.	0.4 in 100,000 per mSv	2.4 in 1,000,000 per mSv
Cancer (non-fatal or fatal)	34 in 100,000 per mSv	23 in 100,000 per mSv
Cancer (fatal only)	8.0 in 100,000 per mSv	6.3 in 100,000 per mSv
*Risks assumes exposure to high-LET radiation (i.e., no DDREF) (ICRP, 2007)		

Deterministic Effect	Threshold Dose
None Significant	<0.1 Gy
Risks to conceptus (mental retardation, malformation, etc.)	0.1-0.5 Gy
Transient mild nausea and headache in adults	0.35 Gy



Galactic Cosmic Radiation: What is it?



Galactic Cosmic Radiation: How does it get here?

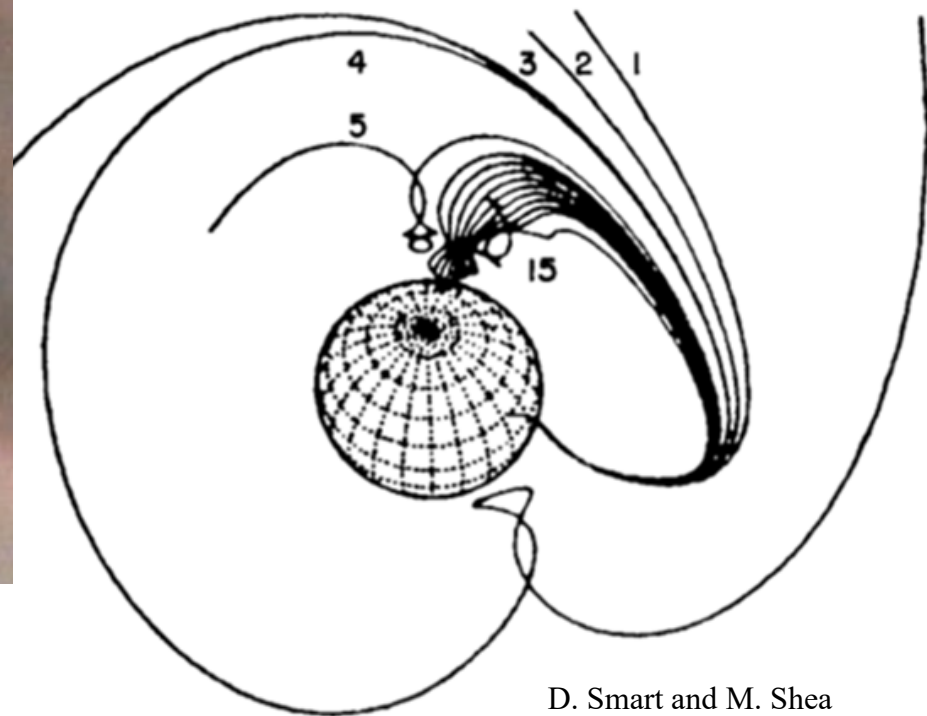
1. The heliosphere



2. Solar wind



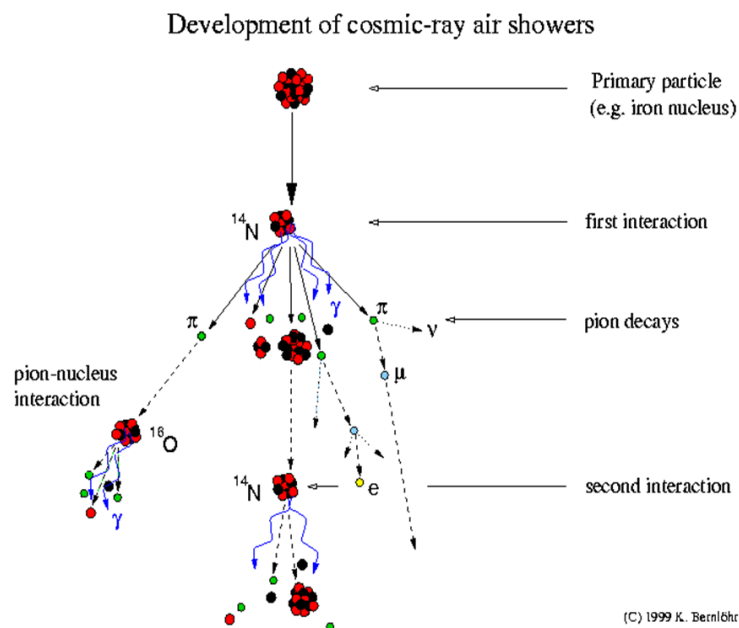
3. Earth's magnetosphere



Earth's Atmosphere

Earth's atmosphere is the final natural shield from cosmic radiation

It is very effective, equivalent to about 10 meters of water.



For CARI-7 the 1976 US Standard Atmosphere was used to create an input deck for MCNPX representing a set of 100 spherically concentric shells, each 1 km thick [Copeland et al, 2008]. The properties of the atmospheric model are:

Maximum altitude above sea level	100 km
Area of its uppermost surface	$5.262 \times 10^{18} \text{ cm}^2$
Total atmospheric depth	1035.08 g/cm^2





Calculating a Flight Dose

INPUTS

1. The GCR spectrum incident on the heliosphere.
2. The solar modulation during the flight, including Forbush effects.
3. The geomagnetic modulation along the flight route, including storm effects.
4. The mass shielding distribution throughout Earth's atmosphere.
5. Aircraft route information, including date and time of departure, altitudes, etc.

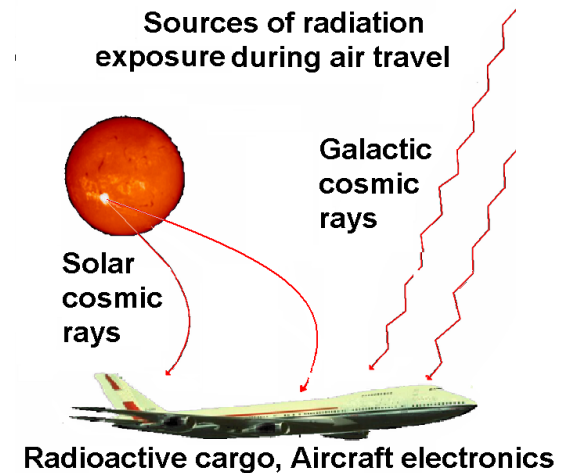
USED TO

1. Calculate the location and altitude of the aircraft along its route.
2. Calculate secondary GCR particles fluxes at aircraft locations
3. Convert secondary GCR particle fluxes to dose rates.
4. Numerical integration of en-route dose rates.



What is CARI?

- The first CARI program was released in the early 1990s. Based on LUIN transport code.
- First called CARRIER, then shortened to CARI.
- Each series of PC computer programs has a base version and some variants, e.g., for NIOSH.
- Used by pilots and airlines worldwide to monitor career radiation doses.
- Used by epidemiologists to estimate past exposures for radiation effects studies.





FAA In-flight Cosmic Radiation Exposure Tools

Galactic Cosmic Radiation:

CARI-7 with Galactic Cosmic Radiation Spectrum

Solar Cosmic Radiation:

CARI-7A with Solar Cosmic Radiation Spectrum

[Radiobiology Services | Federal Aviation Administration](#)

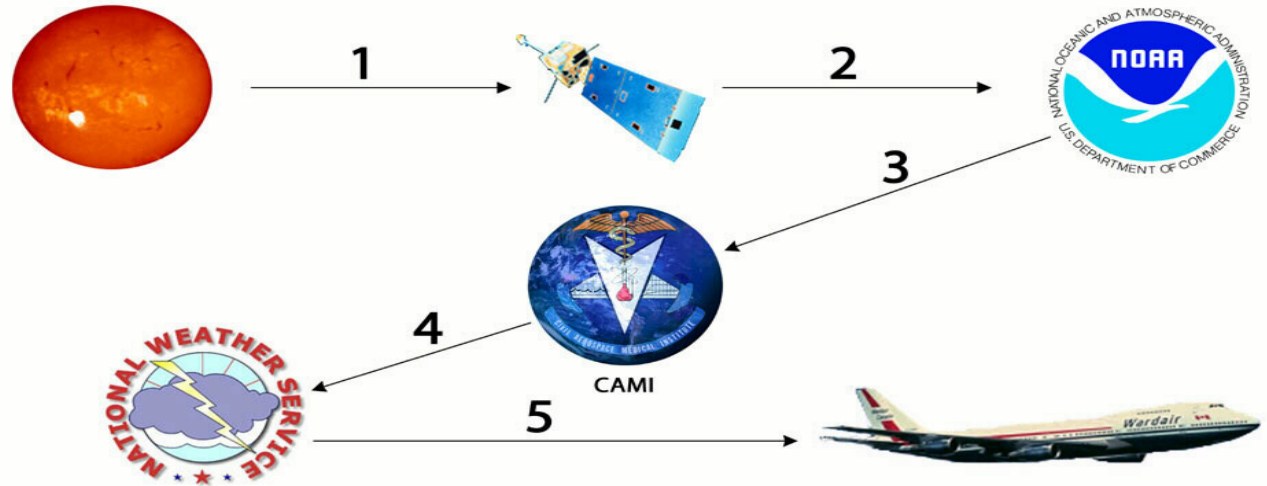


CARI-7 Design

Up through CARI-6, altitude was limited to 60,000-87,000 feet. Uses LUIN [O'Brien 1978].

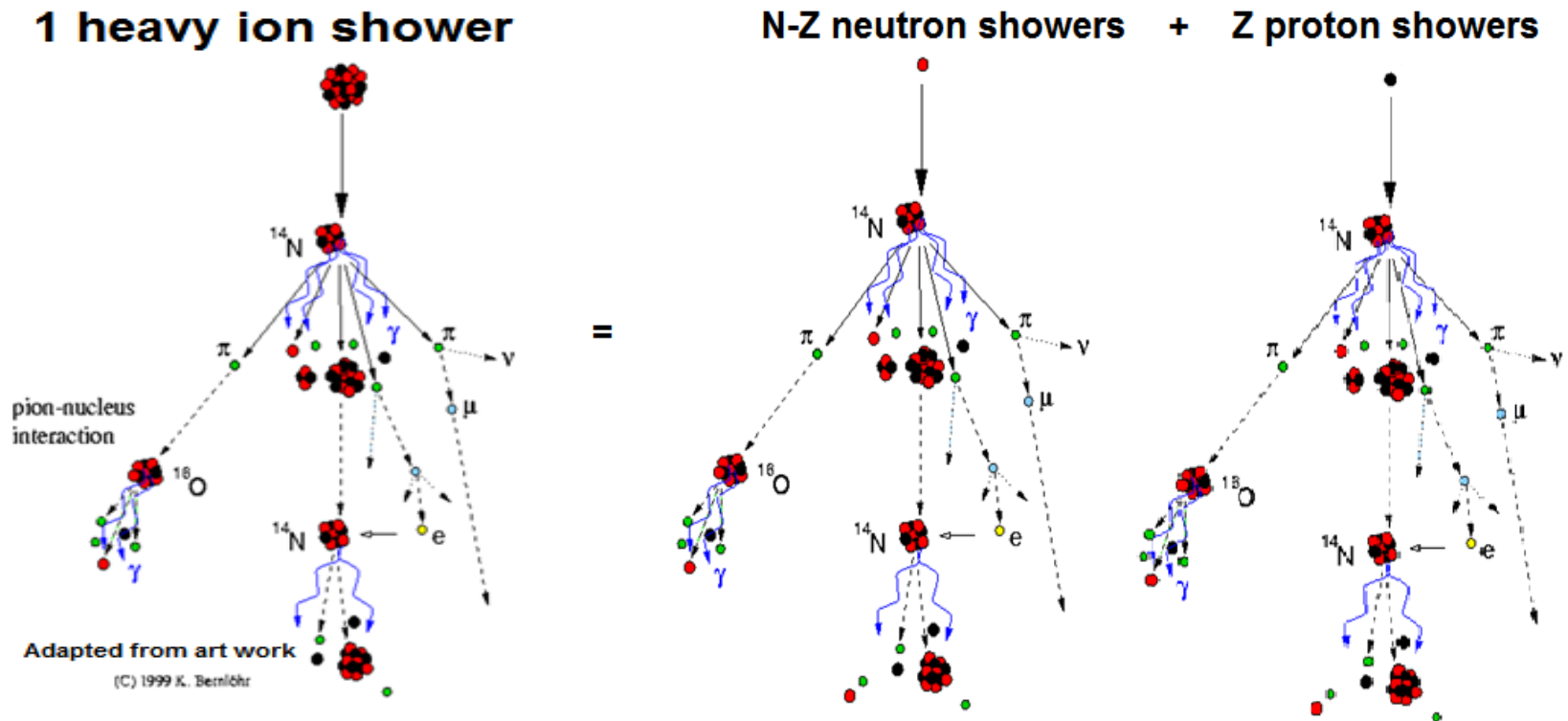
CARI-7 uses MCNPX2.7.0 (=MCNP6v1.0) and is an extension to GCR of the SPE dose calculation concepts used in the Solar Radiation Alert System [Copeland, 2014].

SOLAR RADIATION ALERT SYSTEM



1. An eruption on the Sun raises radiation levels in Earth's vicinity.
2. A GOES satellite measures the radiation and transmits the data to NOAA.
3. A CAMI computer obtains and analyzes the data from NOAA.
4. CAMI issues any needed alert or update to the National Weather Service.
5. The National Weather Service informs the aviation community.

The Superposition Approximation



Advantage: Eliminates the need for heavy ion transport in the atmosphere.

Cost: Inaccurate dosimetry where HZE flux is important.

In CARI-7A using the superposition approximation remains optional (it is no longer allowed in CARI-7).





MCNPX 2.7.0

(Monte Carlo N-Particle eXtended)

Where does it come from?

Los Alamos National Laboratory

Why use it for cosmic ray research?

It can transport all atomic species and dozens of subatomic particles and antiparticles at up to TeV (10^{12}eV) energies.

What is it?

A general-purpose radiation transport code that uses Monte Carlo techniques.

Last Stable version of MCNPX.

Same physics as MCNP6v1.0.





Particle Transport

MCNPX 2.7.0 was used to simulate cosmic ray showers for neutrons and primary GCR ions H-Fe.

All modellable secondaries were transported, including particles that do not contribute significantly to dose (e.g., neutrinos).

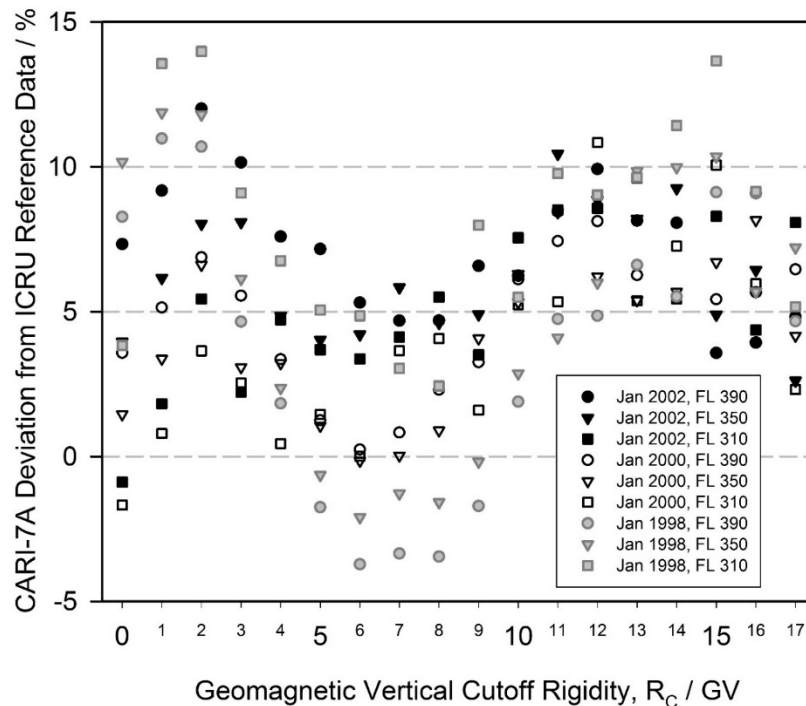
Flux tallies were made throughout the atmosphere approximately every 3 km through 33 km, then more sparsely up to 100 km.

Tallies included n, e, gamma, pi, mu, p, d($^2\text{H}^+$), t($^3\text{H}^+$), alpha, ^3He , and fully ionized Li-Fe.

Tally spectral energy range was 1MeV-1TeV for all particles, with additional lower-energy tallies for neutron and gamma spectra.

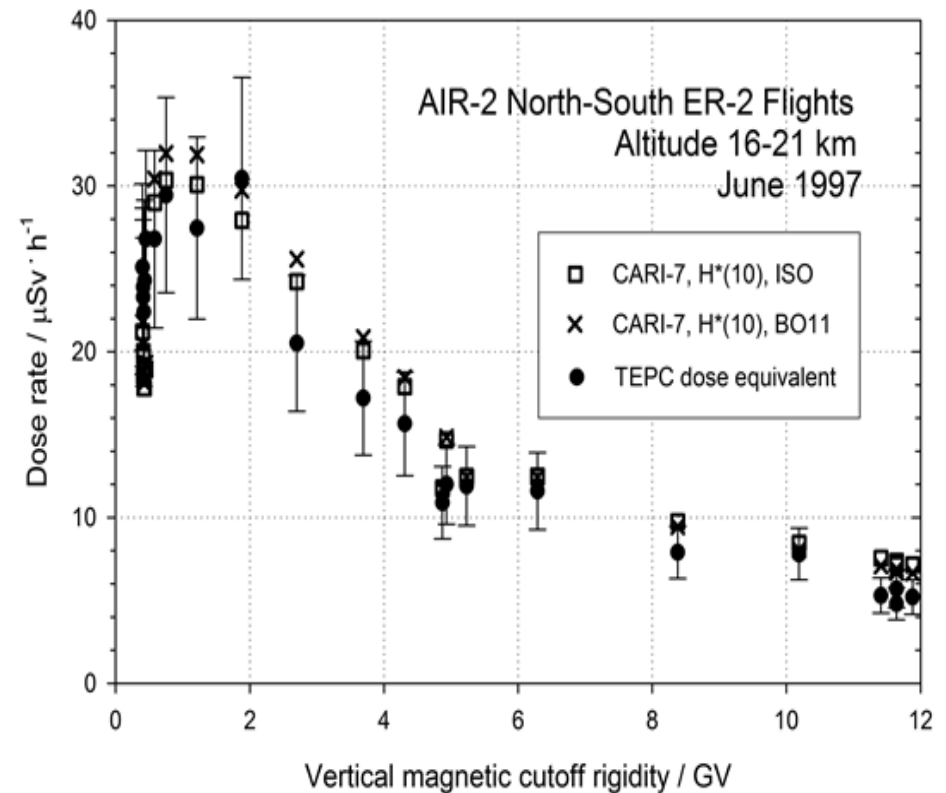


CARI-7 vs Measurements



The largest uncertainty in CARI-7 is from the choice of cosmic radiation spectrum.

CARI-7 compares well with measurements





CARI-7 Weaknesses

- Particles that escape cannot re-enter, even if they should.
- Shower data assume isotropic access to top of the atmosphere, which is an increasingly poor assumption at low geomagnetic latitudes and for early arriving solar energetic particles.
- The shielding approach is too approximate for spacecraft. It does not incorporate the details of internal structures.
- No trapped radiation modeling for spacecraft

CARI-7 Strengths

- Superposition approximation in the atmosphere is avoided.
- Monte Carlo methods are used with modern physics models to build a fast and accurate simulation for atmospheric applications and Low-Earth orbit
- Results are consistently within expected uncertainties of measurements at aviation altitudes.
- Simple upkeep: just a few databases needed for a normal update
- CARI-7 is almost a plug and play replacement of CARI-6 in scripts





Summary

CARI-7A provides accurate calculations of in-flight doses from galactic and solar cosmic rays.

Galactic cosmic radiation is omni-present background radiation in aerospace activities. On rare occasions, transient gamma-ray flashes, solar proton events, cargo related accidents, and terrestrial nuclear accidents can lead to additional exposure.

For current flight practices:

- Crewmember doses are typically a few mSv per year.
- This is well below the annual recommended dose limits of 20 mSv, but equivalent to occupational doses in other high exposure professions such as nuclear fuel processing.
- Rare events such as solar proton events and transient gamma-ray flashes can raise this by 10s of mSv, which is still too low to cause life-threatening deterministic effects.

Considering future flights:

- CARI-7 and other modern calculations indicate effective doses from galactic cosmic radiation are much higher near the top of the atmosphere and at suborbital altitudes.
- Current annual limits will be attainable in a working year (<1000h).



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