Spacecraft Environmental Interactions: Reading the Radiation Design Environments in your project Environmental Requirements Document (ERD)

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What is an ERD?

The **Environmental Requirements Document** is a project document that defines the environments in which the hardware shall function.

A typical ERD defines thermal, dynamic, ground-handling, EMC (electro-magnetic compatibility), and space environments.

This presentation explains the space radiation environments that are found in the ERD

- How the environments are organized
- Descriptions of individual environments that appear in the ERD
- Examples of how those environment specs are used

Organizing the environments

ERD radiation environments are grouped by two types of effects

1. Cumulative damage from mission exposure (particle fluence or dose)
2. Single event effects from particle flux

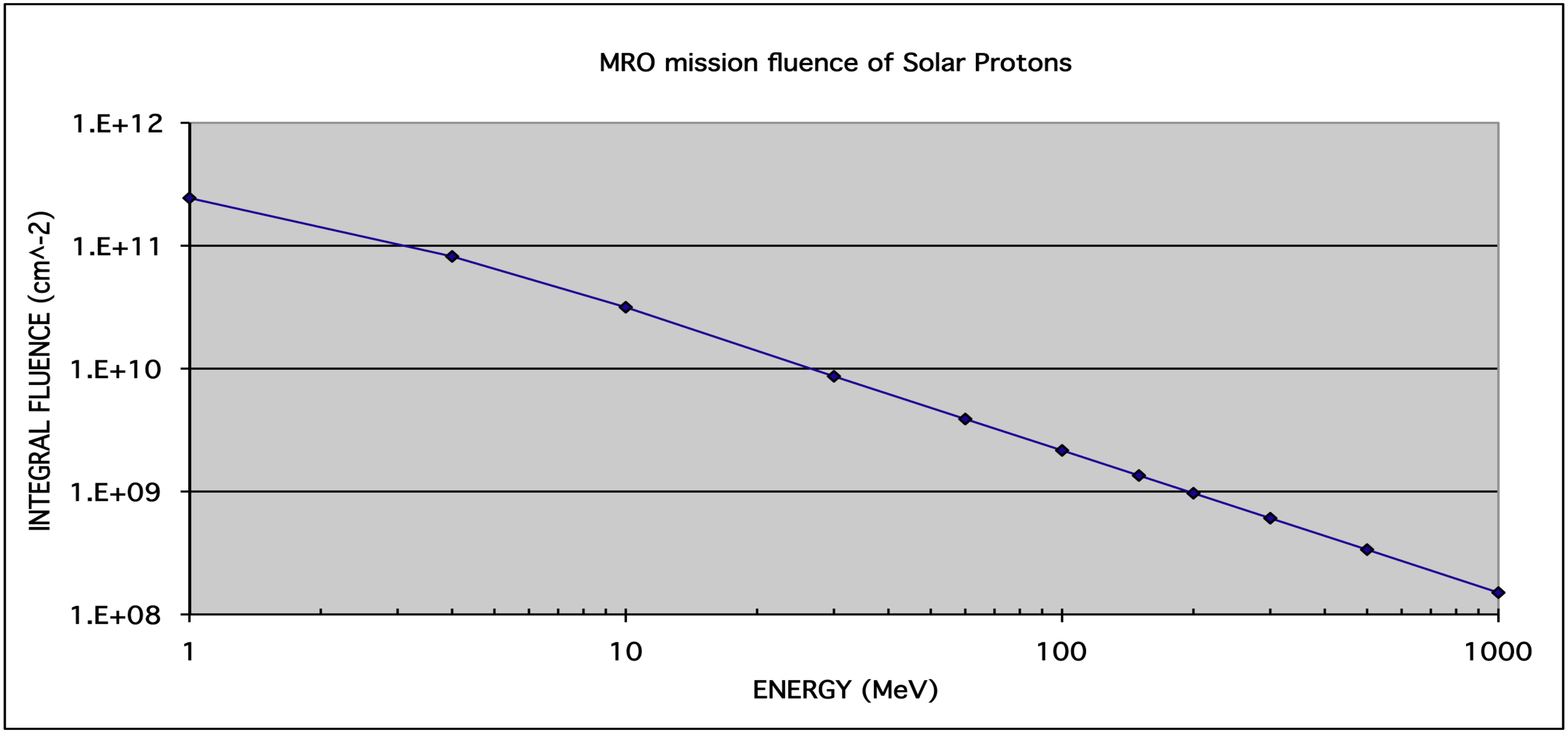
An outline of the ERD's radiation section looks something like this

1. HIGH-ENERGY RADIATION ENVIRONMENT
   - 1.1 Mission Fluence
     - 1.1.1 Fluence A.
     - 1.1.2 Fluence B.
     - 1.1.3 Fluence ...
   - 1.2 Total Ionizing Dose (TID)
   - 1.3 Displacement Damage (or NIEL dose)
   - 1.4 Single Event Effects
     - 1.4.1 Peak Fluxes
     - 1.4.2 Background Fluxes

CUMULATIVE (1.1–1.3)

SEE (1.4)

Now we begin to survey the environments, starting with FLUENCE. To assess cumulative damage, we need to sum the radiation flux over time to get fluence.



It is not feasible to exactly recreate the space environment in a radiation test facility.

We are fortunate that device degradation can approximately be characterized in terms of how much radiation energy is deposited in the device, without regard to the type or energy of the incident radiation.

{The approximation works well for most parts, and the parts specialists know when to suspect that a part may behave in an odd manner.}

However, device degradation does strongly depend on HOW that energy is deposited

There are two main ways of depositing energy

1. Total Ionizing dose (TID)
2. Displacement Damage dose (DDD)

Dose is energy per unit mass. 1 rad = 100 erg/g.

Ionizing dose a.k.a. Total Ionizing Dose, or TID; Units of rad(Si).

Radiation energy creates electron-hole charged pairs in the device.

(Si is for silicon. The amount of dose depends on the material receiving the dose. Most devices are mainly silicon, so that is what we use for dose determination.)

Displacement damage dose

- a.k.a. non-ionizing energy loss (NIEL) dose
- Units of MeV/g(Si)
- or “equivalent 1 MeV neutrons/ cm^2”

Radiation energy displaces atoms in the device, which disrupts the material’s crystal symmetry.

How these processes cause device degradation is an interesting story that will not be covered here.

Digression on the difference between a parts-rad-effects person (JPL sec.514 Radiation Effects Group) and an environments person (JPL sec.513 Mission Environments Group).

The short answer is that
513 determines the radiation at the device,
514 determines what that radiation will do to the device

Digression on the difference … (cont.)

A 514 Rad Effects person

- Establishes piece-parts radiation requirements (based on 513's environment specs for the mission)
- Reviews parts lists and identifies potentially marginal performers; RLATs flight-lot parts
- Works with CogE and 513 circuit reliability person to determine suitability for a particular application, using Worst Case Analysis (WCA) and Single Event Effects Analysis (SEEA)
- Researches effects of radiation on part performance

Digression on the difference … (cont.)

A 513 Mission Environments person

- Establishes mission specifications for the radiation environment external to the spacecraft
- Does radiation transport analyses, i.e. how radiation propagates through hardware configurations, to determine radiation exposure to parts and (if necessary) design radiation shielding
- Develops or updates environment models as new needs arise, as new data becomes available

Now a brief description of how we use fluence specs to get Dose at the location of a part ...

To calculate dose from fluence, take:

- Fluence at the part location
- A good database to transform the Fluence (Particle, energy) to dose
- Sum up the dose contributed by all the particles in the energy spectrum.
- The result is a single value of TID (or a single value of DDD, if you use that database).

In mathematical jargon…

We integrate, over all energies, the product of the energy spectrum and the energy-dependent response function for TID (or DDD), to determine the dose.

Now, you may be wondering...

If you tell me the dose inside your spacecraft bay, can I figure out the dose inside your electronics box in that bay?

NO. WE CAN'T TRANSPORT DOSE THROUGH SHIELDING.

Our spacecraft parts rely on radiation shielding, whose effectiveness depends on the type and energy of the incident radiation.

By integrating to get dose, we have simplified, but we have also lost information about the incident radiation that we need to do transport.

Radiation transport of the fluence through the spacecraft shielding needs to come first. Then we convert to dose.

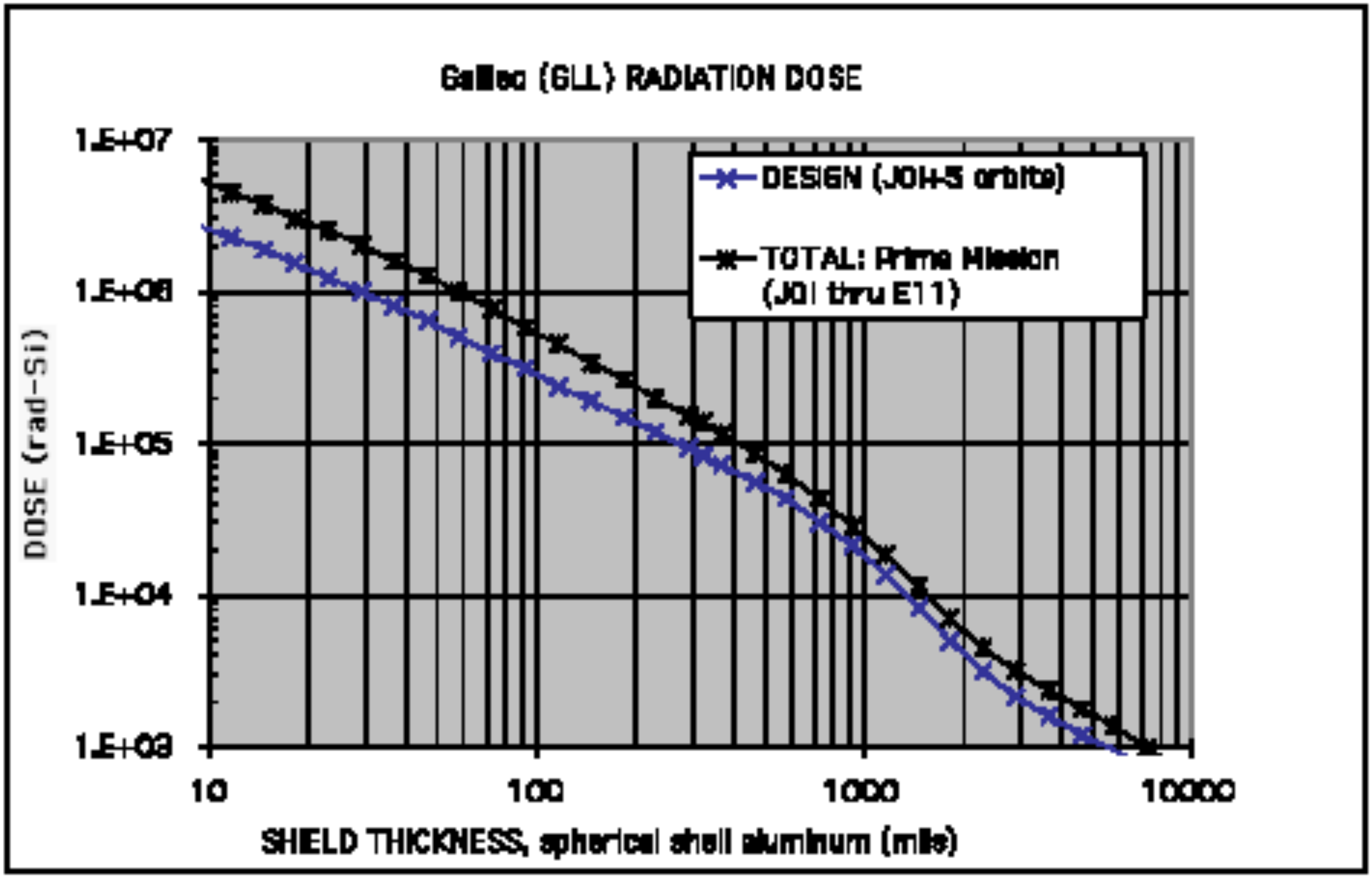
At the start of a project we do not have a mechanical design, which means that we do not know what radiation shielding will be provided by the spacecraft.

So we calculate a dose/depth curve…..

A dose/depth curve gives you the dose at the center of your spacecraft, if your spacecraft is a spherical shell of aluminum.

If you are flying something more complicated than that, then there are still ways to get useful information out of the dose/depth curve.

A sample dose/depth curve



Uses of the Dose/Depth curve

1: It is a way to compare radiation severity on different missions (or different trajectories proposed for a mission).

For example, we can gauge the severity of a mission's radiation environment by looking at the dose behind some plausible shield thickness, such as 100 mils aluminum :

GLL 250 krad-Si (JOI + 5 orbits)

CAS 25 krad-Si (VEEGA to SOI + 2 orbits)

MER 1.3 krad-Si (not including on-board sources)

Uses of the Dose/Depth curve (cont.)

If these spacecraft were 100 mil aluminum shells, with all the parts at the center, then we would apply the Radiation Design Factor (RDF) of 2 (more on this later), and get a part requirement of:

GLL 500 krad-Si (JOI + 5 orbits)

CAS 50 krad-Si (VEEGA to SOI + 2 orbits)

MER 2.6 krad-Si (not including on-board sources)

But these were not the actual part requirements…

Uses of the Dose/Depth curve (cont.)

You may be more familiar with these numbers:

GLL 150 krad-Si

CAS 100 krad-Si

Where did these “Approved Parts” requirements come from?

Uses of the Dose/Depth curve (cont.)

GLL: 150 krad-Si was chosen as a compromise between

- The highest radiation tolerance they could expect to get for most of their parts, and
- The amount of shielding they could carry.

(This answer is based on memory, hearsay, and hunches. I don't know that I can actually document it.)

CAS: 100 krad-Si was about twice the dose behind 60 mils, which was the minimum shear-plate thickness of the bays. Therefore, any part that was good to 100 krad-Si would be adequately shielded at any location within the bays.

Uses of the Dose/Depth curve (cont.)

2: It guides the parts guys in establishing the requirement level of radiation dose tolerance,

- To which they will assess and procure parts,
- To which they will test parts that have insufficient radiation characterization.

Uses of the Dose/Depth curve (cont.)

A TID requirement used to be called out in projects' Parts Plans, but that is no longer necessarily the case. It does sometimes show up in other project requirements documents.

Unfortunately there have been cases where the chosen TID level had no bearing on the actual shielding around the sub-system. They would just, for example, quote the dose-depth curve's dose at 100 mils aluminum, even though the sub-system ended up with 30 mil walls.

What does appear in the generic Institutional Parts Plan is that...

"All flight parts shall operate within post-irradiation specification limits following exposure to the expected **total dose environment including the RDF specified in paragraph 2.2**.

2.2 Mission Requirements and Environments

The parts requirements are driven by the mission life requirements and the thermal and **radiation requirements specified in the Project Environmental Requirements Document (ERD).** All parts requirements shall satisfy the mission environmental requirements as specified in the Project ERD."

So the generic Institutional Parts Plan just says that the parts have to be tougher than the dose environment by a specified amount, called the Radiation Design Factor (RDF).

The wording in the ERD goes something like this:

High-Energy Radiation Environment

This section covers the naturally occurring space radiation environments to which the spacecraft and its assemblies will be exposed. **All assemblies shall be designed to operate within performance specification during and after the exposure to these environments with a designated radiation design factor.** Unless otherwise stated, all tables and graphs within this section represent environments external to the spacecraft/instrument and do not contain a design factor. The radiation design factor (RDF), when applied, is defined as

$$RDF = \frac{\text{Radiation-resisting capability of a part in a given application}}{\text{Radiation environment present at the location of the part}}$$

Notice that there is nothing about being “in spec”.

Notice also that the radiation-resisting capability, or “rad tolerance” of a part can depend on how it is used.

In practice this means that parts are evaluated against an upper-bound dose seen at a certain depth within the spacecraft shielding, such as:

1) inside a bay.

2) inside a box inside a bay.

3) on a board inside a box inside a bay.

4) in a package on a board inside a box...

… as far down as we need to go

to show that a part is protected.

Here is where a section 513 Mission Environments person can come in handy

When a part does not

- Meet the TID radiation requirement, and/or
- Obviously meet the RDF requirement, we refine the estimate of how much shielding is actually available to protect the part

We have radiation transport codes that will take

- A radiation spectrum (particle flux or fluence)
- Detailed information of the spacecraft mechanical structure (everything from prop tanks down to part packages)
- Calculate how much radiation will propagate to a requested location in the spacecraft

If a transport analysis is required, we need some information on the materials and thicknesses of

- Electronics box walls (minimum thicknesses, e.g. hogged-out section thickness)
- Mounting panels
- Adjacent structures that throw a large solid angle shadow on the part

Standard Assembly and Subsystem Level Environmental Verification

The “Standard Assembly and Subsystem Level Environmental Verification” process document (#60133) requires that:

an RDF = 2 be used for the dose requirement, and that

an RDF = 3 must be used in those exceptional cases where a part must be spot-shielded.

Why we need the RDF

- There is uncertainty in the environment models, and variability in the environment that may not be well-characterized in the model

- The accuracy of our method of 3-D adjoint Monte-Carlo radiation transport is typically 10 to 20%

Why the RDF, and 3 in particular

Transport calculations treat the radiation environment as coming equally from all directions. If the shielding is rather unevenly distributed around the part, and the actual radiation environment has some directionality to it that happens to hit a thin segment of shielding, the actual dose could be much higher than the modeled dose.

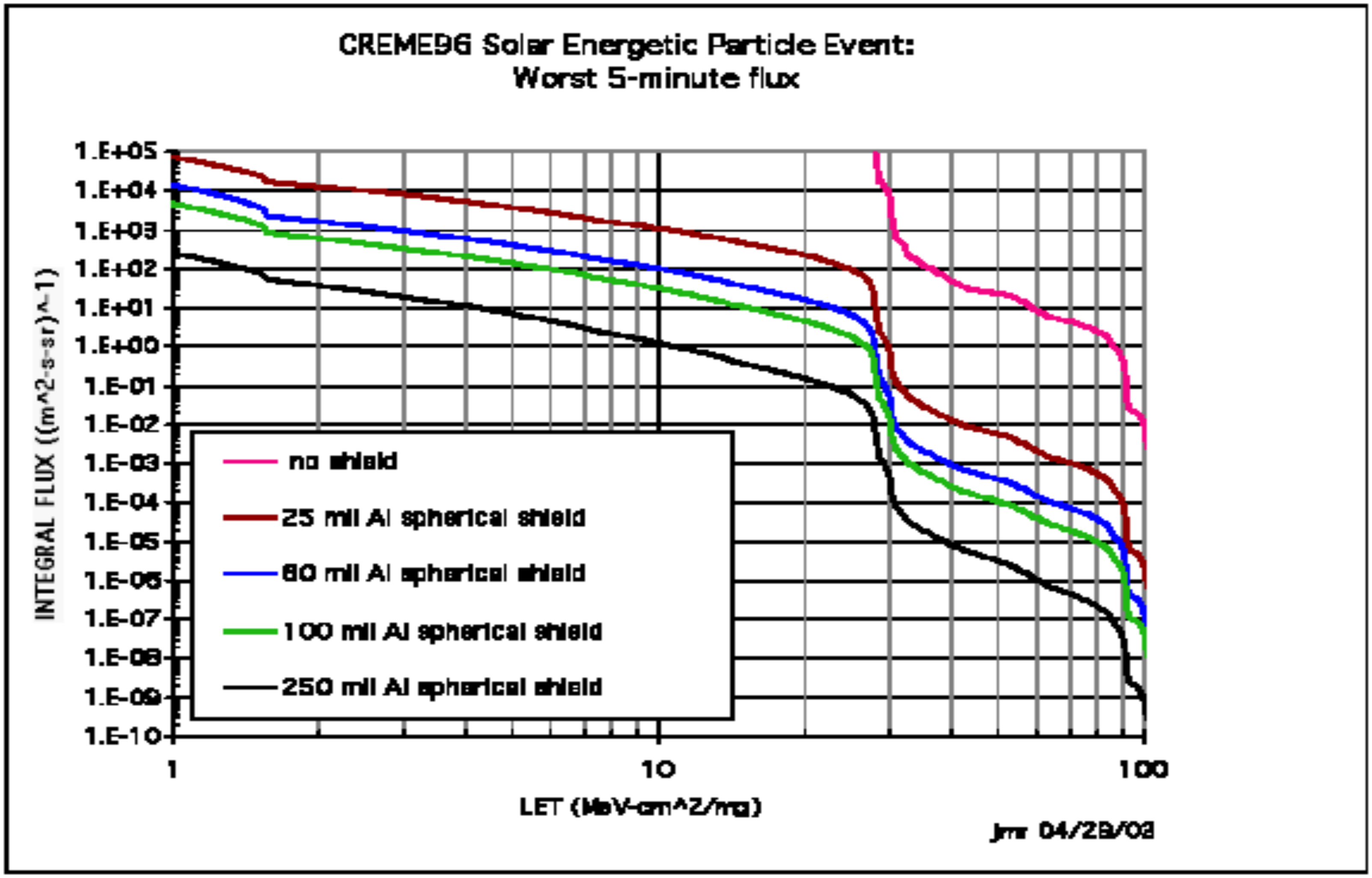
It is typically the environment models' higher-energy particles that have the most uncertainty, which means that thickly shielded locations will have a higher dose uncertainty.

SINGLE EVENT EFFECTS Environments

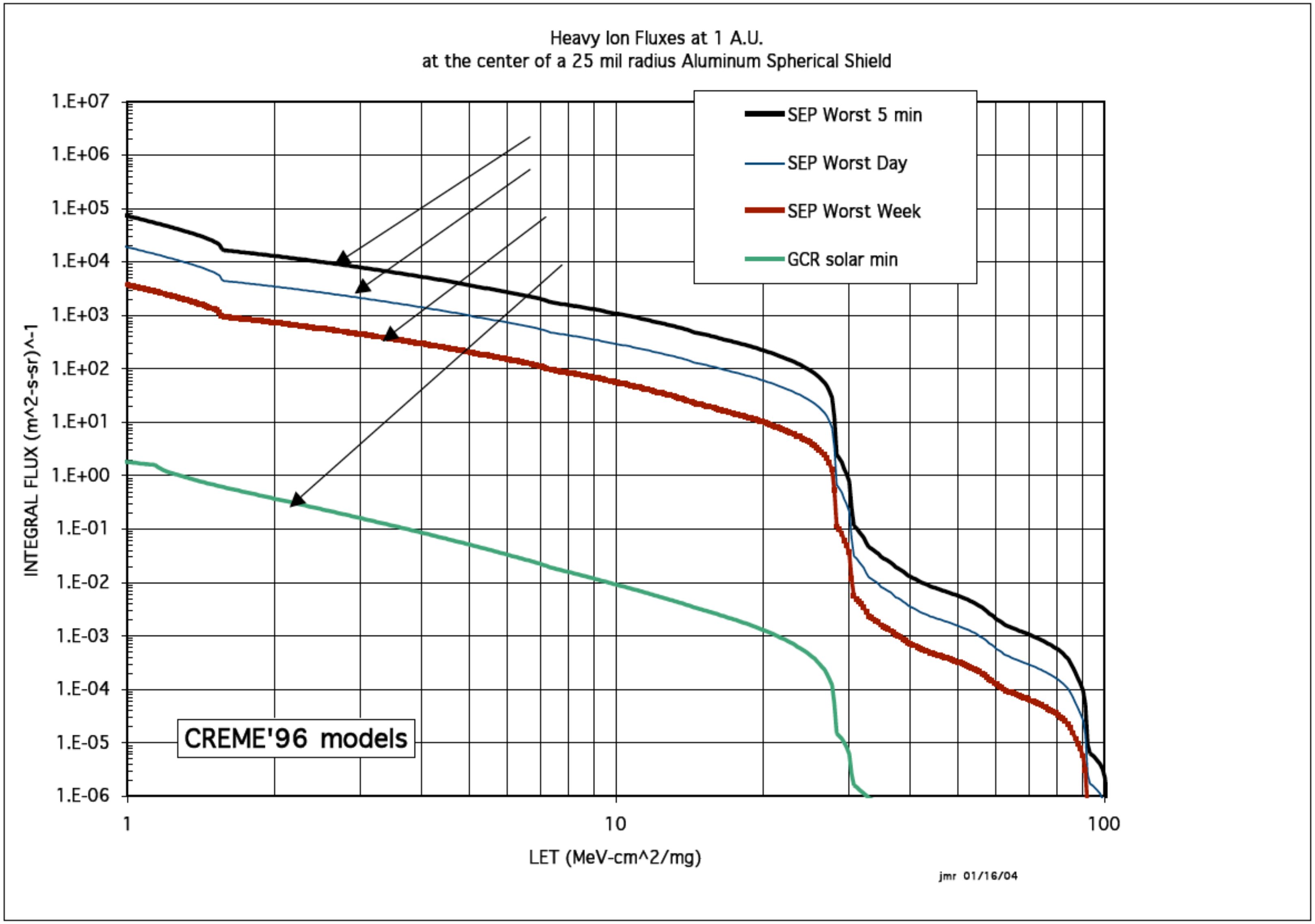
The ERD has

- 1.4.1 Peak Fluxes which are commonly used to assess worst-case SEE rates that could occur during critical events
- 1.4.2 Background Fluxes which are commonly used to assess average rates of SEUs, or probability of getting an SEL or other destructive SEE

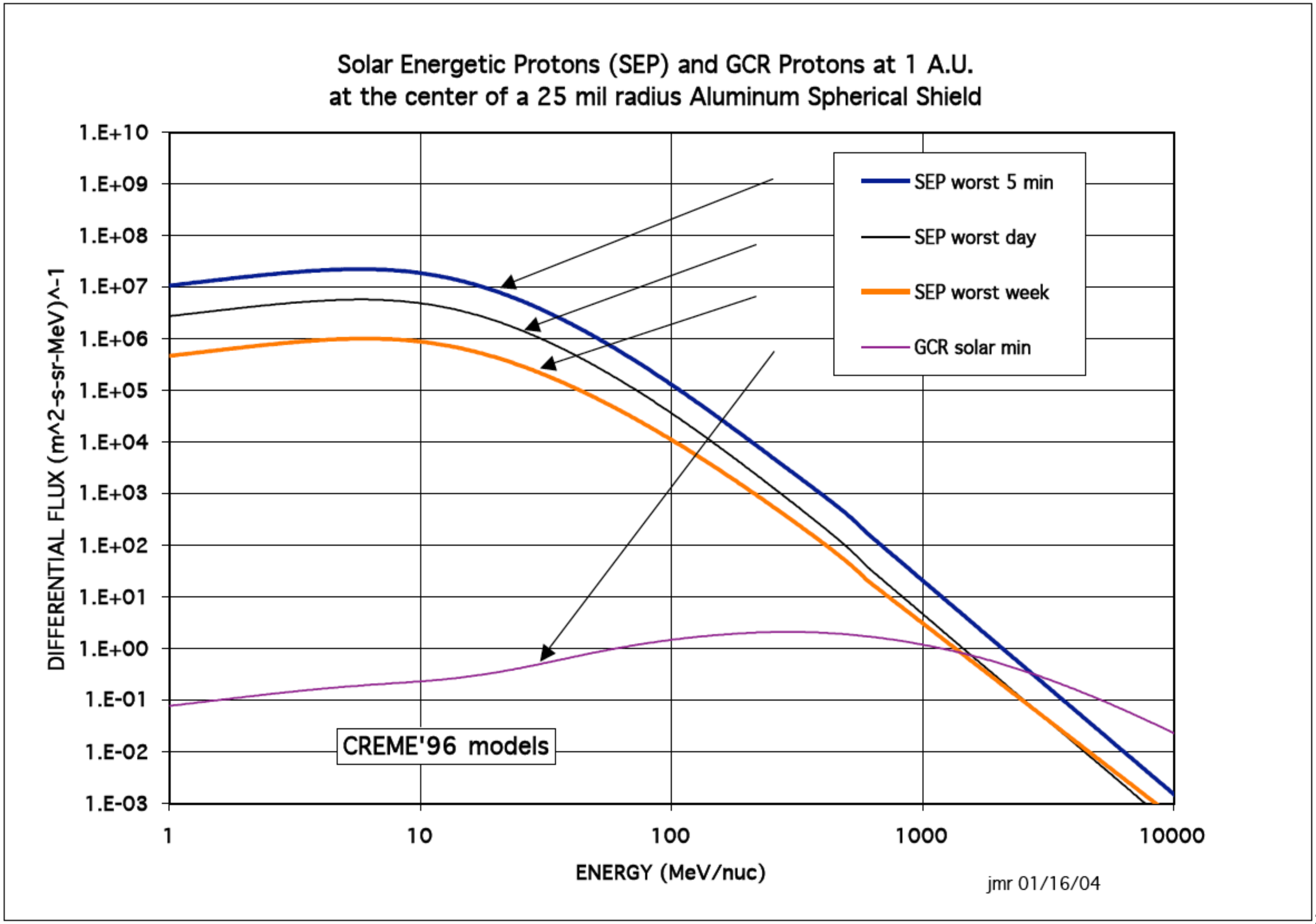
Example of a Peak Flux environment
(effect of shielding a Solar Particle Event)



Example of a Peak Flux environment:



Interplanetary Proton Flux environment



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