Reliability Concerns for Flying SiC Power MOSFETs in Space

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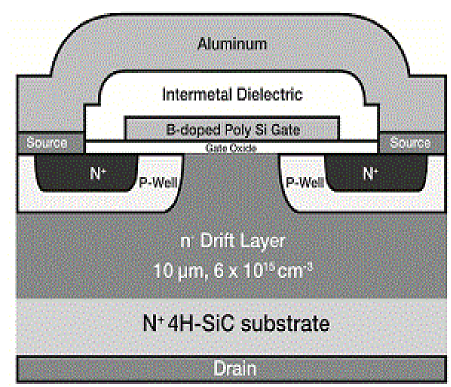
Outline

1. **Why the interest in SiC power?**
2. **Electrical reliability.**
3. **SEB in SiC power MOSFETs.**
4. **Environment.**
5. **Estimating failure rate in space.**



1200 V SiC Power MOSFET

Why Silicon Carbide Power Devices for Space?

SiC vs Silicon Power Devices:

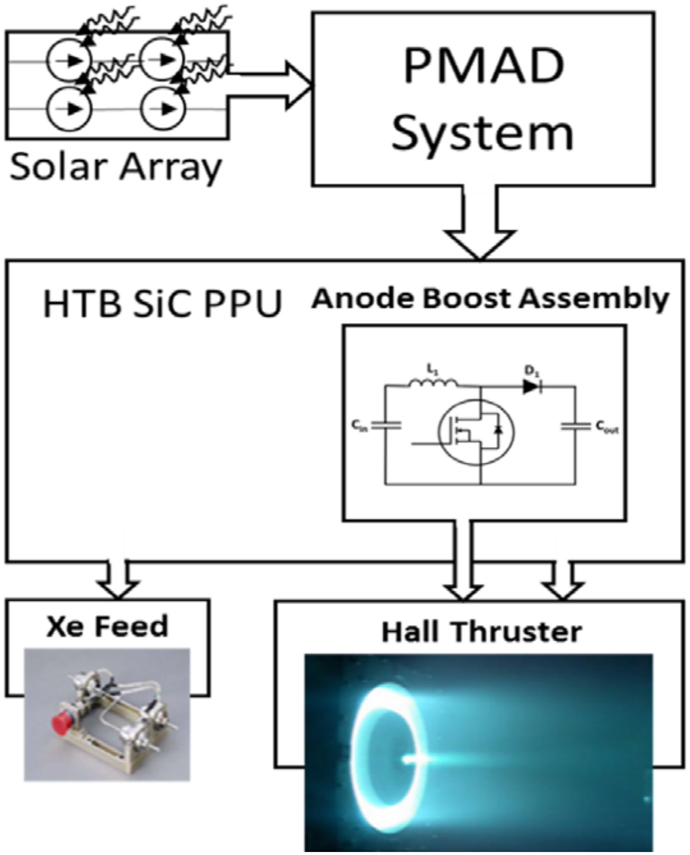
- **Higher Breakdown Voltage (~ 10x vs. Si)**
- **Lower On-State Resistance (~1/100 vs. Si)**
- **Higher Temperature Operation (~3x vs. Si)**
- **High Thermal Conductivity (~10x vs. Si)**
- **Mass, cost, power savings**

After: A. Elasser and T.P. Chow, Proc. IEEE, vol. 90, 2002.

Example: Concept Design of High Power Solar Electric Propulsion (SEP) for Human Exploration

- **Desired power levels ~400 kW**
- **Change from 120 V bus voltage to 300 V**

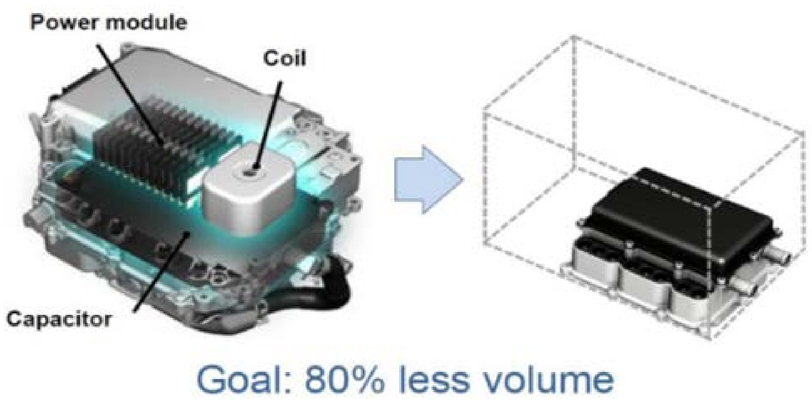
After: D.J. Hoffman, *et al.*, NASA/TM—2011-217281



PMAD: Power management and distribution
HTB PPU: High-temperature boost power processing unit

Toyota and Denso Development for Hybrid Vehicles

- **Power control units (PCUs) contain multiple power semiconductors – usually silicon technology**
- **According to Toyota, ~20% of hybrid electric vehicle (HEV) total electrical power loss is associated with power semiconductors**
- **Goal to improve hybrid vehicle (HV) fuel efficiency by 10% and PCU downsizing of 80%**
- **SiC technology leads to lower weight, higher efficiency**



Silicon technology SiC technology

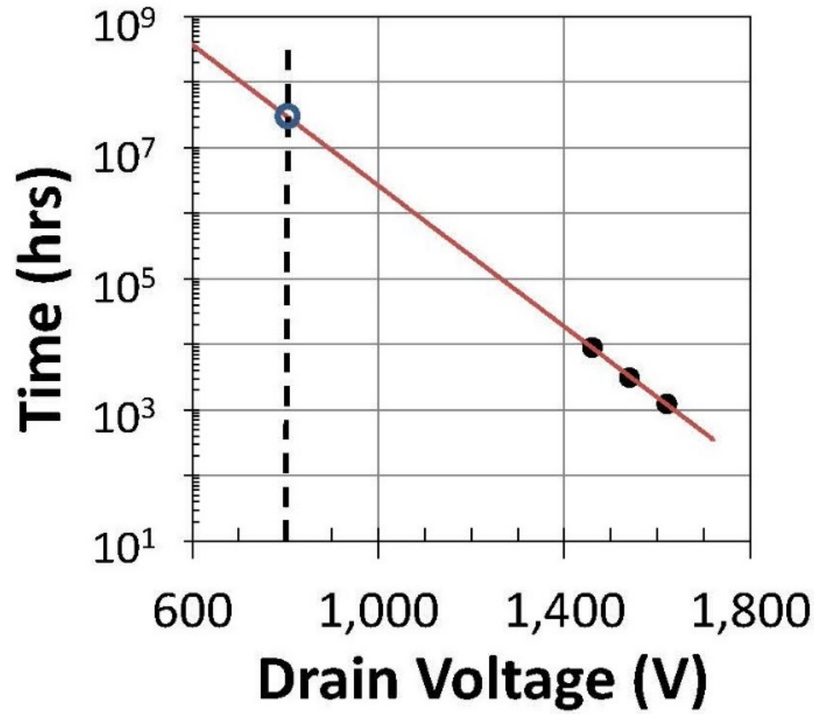
	System with Si IGBT	System with SiC
Weight	7 kg	0.9 kg
Volume	8.775 cc	1.350 cc

https://newsroom.toyota.co.jp/en/detail/2656842 **(Image used with permission)**

http://www.eenewseurope.com/design-center/potential-silicon-carbide-sic-automotive-applications/page/0/3

Accelerated Testing – High-Temperature Reverse Bias

- High-Temperature Reverse Bias (HTRB)
- Wolfspeed 1200 V 20A G2 MOSFETs
- V_{GS} = 0V, V_{DS} = 1460V, 1540V, 1620V
- Mean failure time at a given V_{DS} predicted by extrapolation
- At 800 V_{DS}, extrapolated failure time is ~ 3 x 10^7 hours (~ 3400 years)

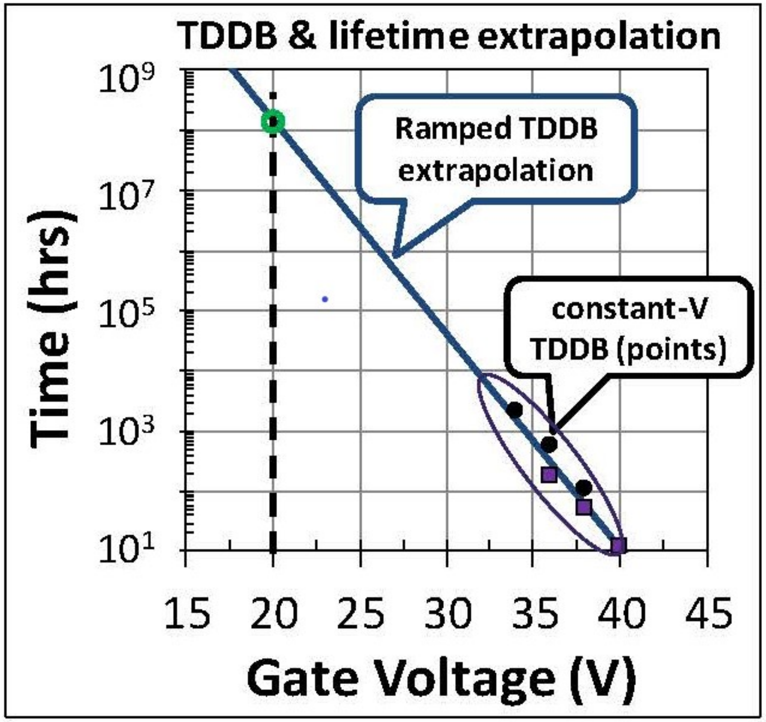


After: D.J. Lichtenwalner, B. Hull, J. Richmond, J. Casady, D. Grider, S. Allen, and J.W. Palmour, Wolfspeed – A CREE Company, presented at NASA Space Technology Mission Directorate Early Stage Innovation Technical Exchange, NASA GSFC, September 2017.

See: D.J. Lichtenwalner, et al., MRS Advances, vol.1, no. 2, pp. 81-89, 2016.

Accelerated Testing – Time-Dependent Dielectric Breakdown

- **Time-Dependent Dielectric Breakdown (TDDB)**
- **Wolfspeed 1200 V 20A G2 MOSFETs**
- **Mean failure time at a given V_{GS} predicted by extrapolation**
- **Extrapolated mean failure time at 20 V_{GS} > 10^8 hours (~ 11,000 years)**

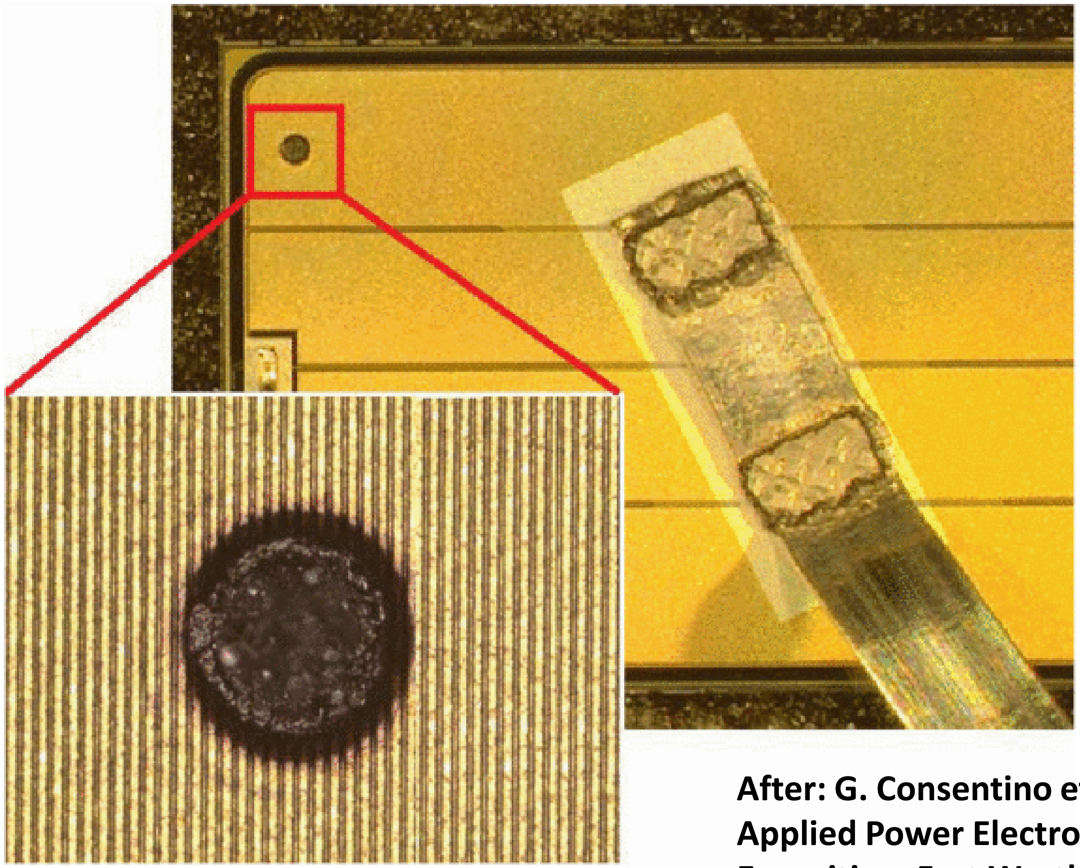


After: D.J. Lichtenwalner, B. Hull, J. Richmond, J. Casady, D. Grider, S. Allen, and J.W. Palmour, Wolfspeed – A CREE Company, presented at NASA Space Technology Mission Directorate Early Stage Innovation Technical Exchange, NASA GSFC, September 2017.

See: D.J. Lichtenwalner, *et al.,* MRS Advances, vol.1, no. 2, pp. 81-89, 2016.

What is the Problem ?

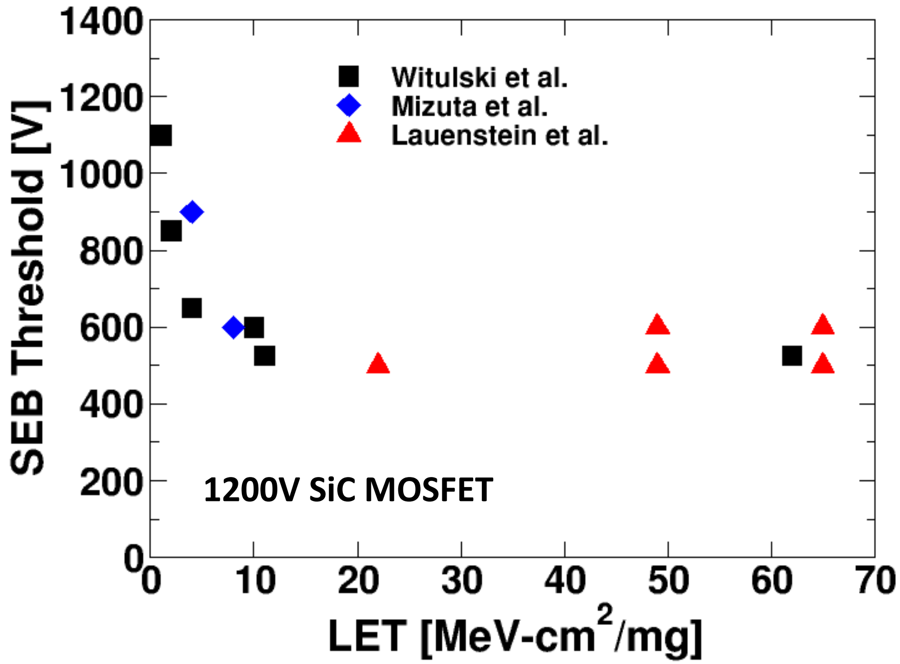
- **SiC power devices – both diodes and MOSFETs – are susceptible to catastrophic failure in the swift, energetic heavy ion environment encountered in space or neutron environments**



After: G. Consentino et. al, 2014 IEEE Applied Power Electronics Conference and Exposition, Fort Worth, TX

Measurement of SEB in SiC Power MOSFET

- **Tests performed on SiC power devices rated 650 V to 3300 V by NASA, ESA, JAXA, and others**
- **Single-event burnout (SEB) occurs at typically ½ rated V_{DS}**
- **Ion-induced degradation observed in gate, drain leakage currents prior to SEB**



LET: linear energy transfer

Witulski, *et al.,* RADECS 2017 and IEEE Trans. Nucl. Sci. (tbp).
Mizuta, *et al.,* IEEE Trans. Nucl. Sci., vol. 61, 2014.
Lauenstein, *et al.,* NASA Report GSFC-E-DAA-TN25023 (2015).

Lethal Ion Criteria

- **Most particles in space are of no consequence to MOSFET catastrophic failure.**
- **To be lethal, a particle (or one of its recoils), must:**
  1. **Have sufficient energy deposition**
  2. **Strike at the proper solid angle**
  3. **Strike within the sensitive area**
  4. **Strike when the biases are in a critical state**

After: J.L. Titus *et. al*, IEEE Trans. Nucl. Sci., vol. 46, 1999.

Estimate of the Failure Rate for 1200 V SiC Power MOSFETs in Space

- **Devices show SEB failure at ≈ 500 V for LET > 10 MeV-cm^2/mg**
- **Assume SEB cross-section saturated for LET > 10 MeV-cm^2/mg**
- **Define SEB failure as operation at a reverse voltage > 500 V for any LET > 10**

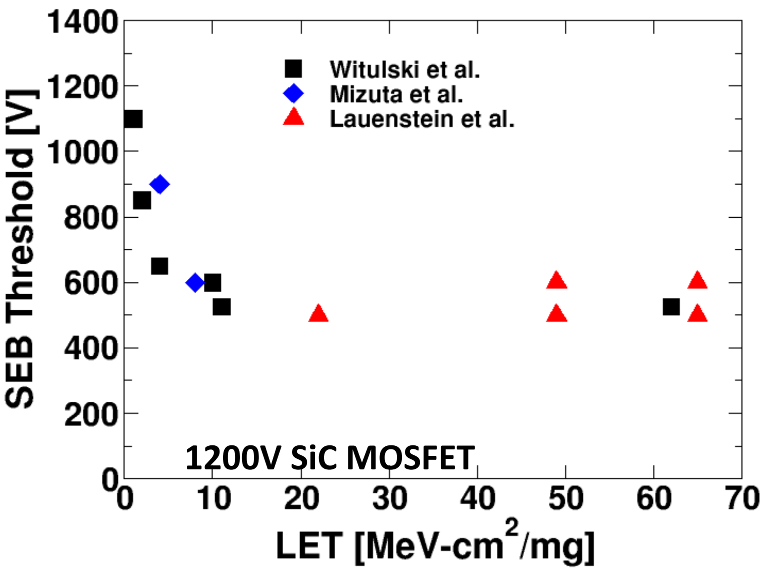
$$\text{Failure Rate (FR)} = \text{SEB cross-section } (\sigma) \int \text{Flux(LET) dLET}$$

$\int$ **Flux(LET) dLET = integral over LET spectrum for LETs greater than 10 MeV-cm^2/mg using CREME96 or Xapsos *et al.***

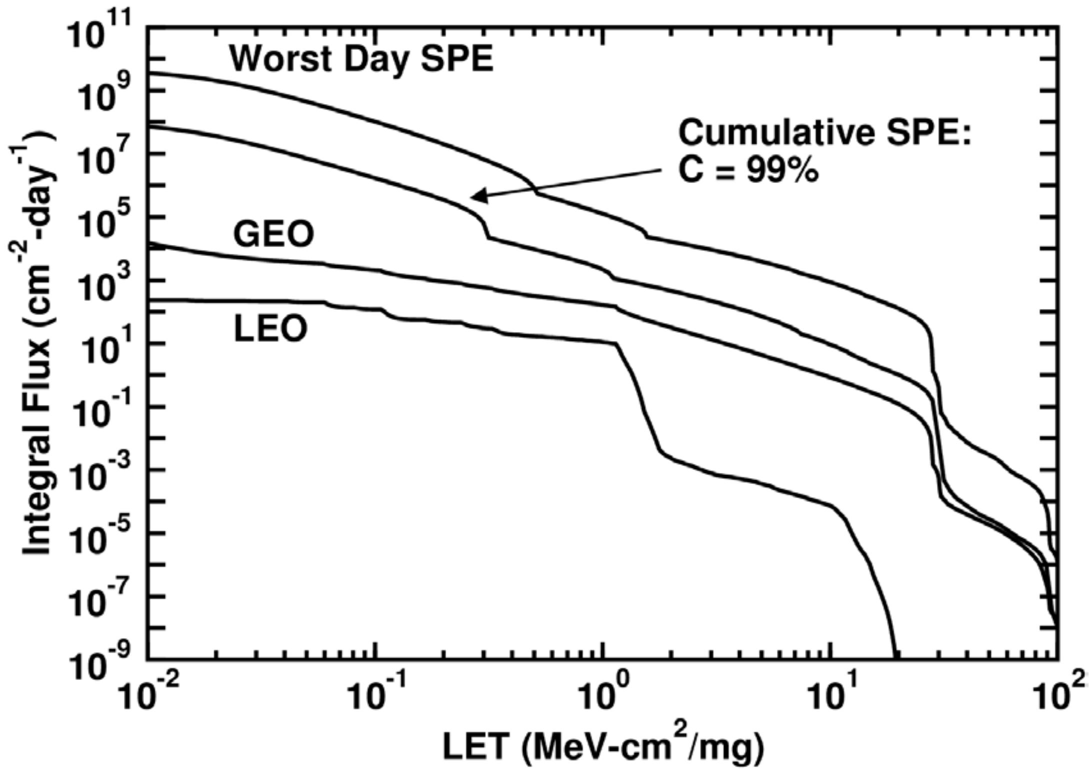
After: E. Dashdondog *et al*., Microelectronics Reliability, vol. 84, 2016.

similar to ……….

J.L. Titus *et al.,* IEEE Trans. Nucl. Sci., vol. 46,1999.
J-M. Lauenstein *et al.,* IEEE Trans. Nucl. Sci., vol. 58, 2011.



Integral LET Spectra



GEO: Geostationary orbit
LEO: Low-Earth orbit

Worst day solar particle event (SPE) from CREME96. GEO and LEO are solar minimum spectra from CREME96. Cumulative solar particle event spectra at the 99% confidence level after Xapsos *et al.* Results for 100 mils aluminum shielding.

See: M.A. Xapsos, C. Stauffer, T. Jordan, J.L. Barth, and R.A. Mewaldt, IEEE Trans. Nucl. Sci., vol. 64, 2007.

Worst Case Estimate of the Failure Rate (FR) for 1200 V SiC Power MOSFETs in Space

$$FR = \sigma \int Flux(LET)\, dLET$$

σ = base MOSFET SEB cross-section on chip area, 1200V chip is ≈ 2 mm x 3 mm assume 50% sensitive area and 50% duty cycle

$$\sigma = 1.5 \times 10^{-2}\ cm^2$$

Integral evaluated for all LET> 10 MeV-cm^2/mg from the 99% confidence level curve from Xapsos *et al.* – appropriate a conservative design estimate of the single-event rate due to solar particles

$$\int Flux(LET)\, dLET = 10\ cm^{-2}\ day^{-1}$$

$$FR = 6.25 \times 10^{-3}/hour \quad \text{and} \quad FIT = 6.25 \times 10^{6}$$

MTTF (Mean Time To Failure) = 160 hours

Integral LET > 10 MeV-cm^2/mg, FIT, MTTF for Different Mission and Satellite Scenarios

	Integral (no./cm^2-day)	FIT (1 per billion hours)	MTTF (hours)
SPEW	1000	6.25E+08	1.6
SPE	10	6.25E+06	160
GEO	0.9	5.6E+05	1786
LEO	1E-04	62.5	1.6E+07

SPEW = worst day solar particle event from CREME96

SPE = cumulative particle event at 99% confidence level from Xapsos *et al.*

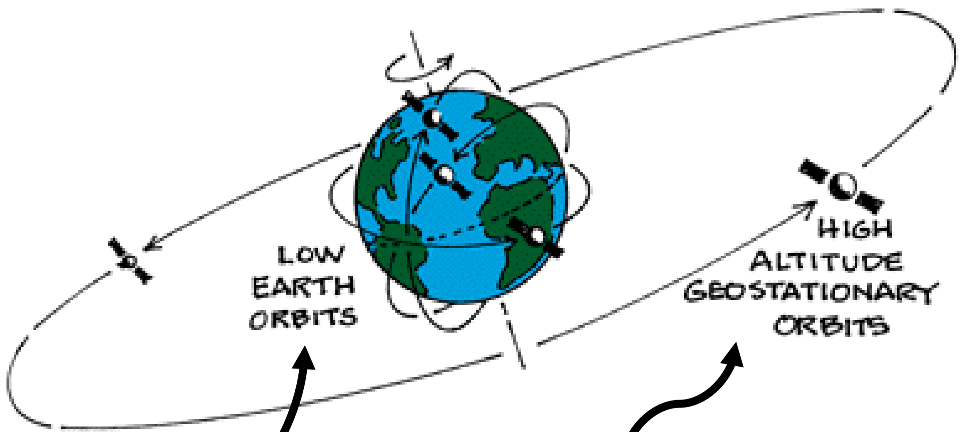
GEO = geostationary orbit during solar min from CREME96

LEO = low Earth orbit during solar min from CREME96

For all, 100 mils of aluminum shielding assumed.

FIT: Failure in time

MTTF on Orbit – 1200 V SiC MOSFET Operated at V_{DS} > 500 V



MTTF ~ 1800 hours (75 days) – GEO from CREME96

MTTF ~ 160 hours – SPE C = 99% from Xapsos *et al.*

MTTF ~ 1.6 hours – SPE worst day from CREME96

MTTF > 1000 years – LEO from CREME96

Image from: National Oceanic and Atmospheric Administration

Summary

- **SiC power MOSFETs have several performance advantages over Si power MOSFETs and silicon IGBTs**
- **Current commercial devices are very reliable**
- **Demonstrated heavy-ion susceptibility**
- **Failure rate estimates indicate a radiation reliability issue for space electronics**
- **Any application of commercially available 1200 V SiC MOSFETs in space would require significant voltage de-rating**
- **Performance advantages may justify use if de-rating and leakage degradation is acceptable**
- **Careful heavy ion testing of any commercially available SiC MOSFET component proposed for spaceborne electronic systems is recommended**

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