NORTHROP GRUMMAN

Climatology that Supports Deep Charging Assessments

Space Weather Week
April 28-May 1, 2009

J. Michael Bodeau

Technical Fellow
Northrop Grumman Corporation

Industry Needs Long Duration Environments to Support Deep-Charging Assessments

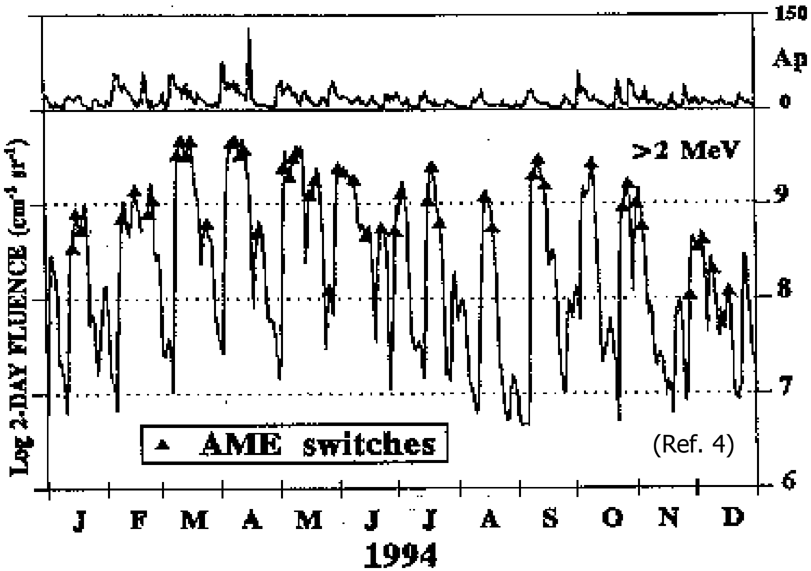
NORTHROP GRUMMAN

- Spec Requested by Users: "Industry Users Group, Model Requirements Update: The Oracle has Spoken," *Working Group Meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering,* Oct 2004 (Ref. 1)
  - ✓ Design Issue #1: Endurability/Wear-out due to mission total dose
    - Long-term average
    - Long-term worst-case
    - Flux energy spectra
  - ✓ Design Issue #2: Outages of rate-sensitive equipment
    - Examples: processors, CCDs (charge coupled devices)
    - Protons, electrons, heavy ions
    - Worst case 5 min, 1 hr, 1 day, 1 week
  - ✓ Design Issue #3: Deep charging
    - Falls between rate-sensitive (flux) and long-duration (fluence)
    - Worst-case day, week, month, 3 months, 6 months electron flux spectra
    - Access to historical flux data for anomaly resolution

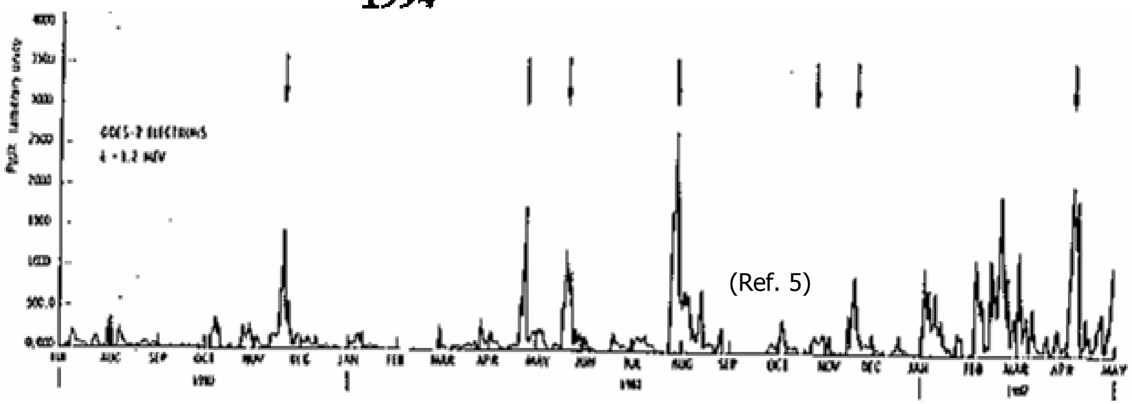
- AE9/AP9 Development Spec only shows time averages to 1 week duration and less (Ref. 2)
- New environment model will have capability to generate longer term averages that meet industry needs (Ref. 3)

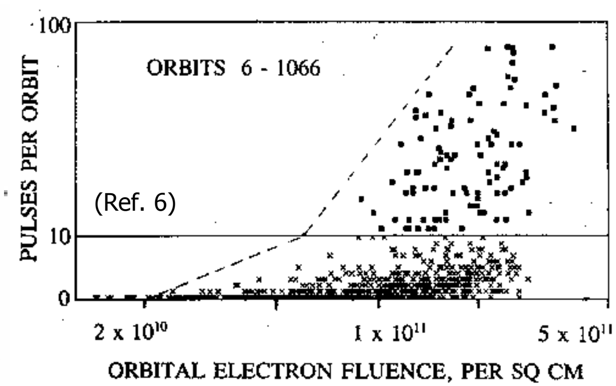
Traditional Focus on Short Term Peak Flux Is Based on Correlation with Anomalies

NORTHROP GRUMMAN



- Many spacecraft anomalies correlate with peaks in flux of energetic penetrating electrons
- 10-hr average, 24-hr average and 48-hr average fluxes have been used in these correlation studies
- NASA guidelines recommend limiting peak flux to a "safe" threshold, and provide a worst-case (several hour averaged) flux for GEO

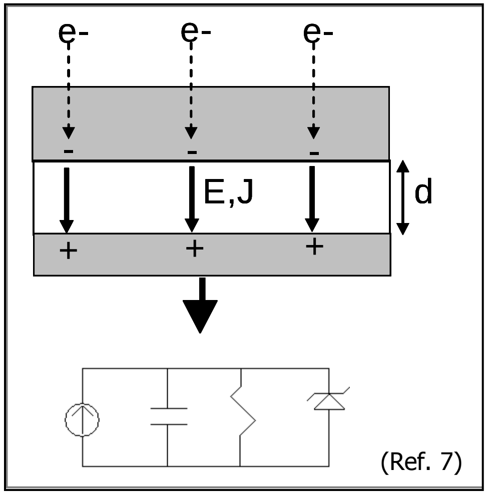




Correlation Is Not Causation & Does Not Support Design

Deep Charging Is Similar to R-C Circuit…

NORTHROP GRUMMAN



$$V(t) = V_c(t=0)\cdot \exp\left(-t/_{RC}\right) + IR\cdot\left[1-\exp\left(-t/_{RC}\right)\right]$$

$$\text{where } R = {\rho d}/_{A},\ C = {\varepsilon_r \varepsilon_o A}/_{d},\ RC = \rho\varepsilon_r\varepsilon_o = \tau$$

$$E(t) = E_o\cdot\exp\left(-t/_{\tau}\right) + \rho J\cdot\left[1-\exp\left(-t/_{\tau}\right)\right]$$

$$q(t) = {Q(t)}/_{A} = q_0\cdot\exp\left(-t/_{\tau}\right) + J\tau\cdot\left[1-\exp\left(-t/_{\tau}\right)\right]$$

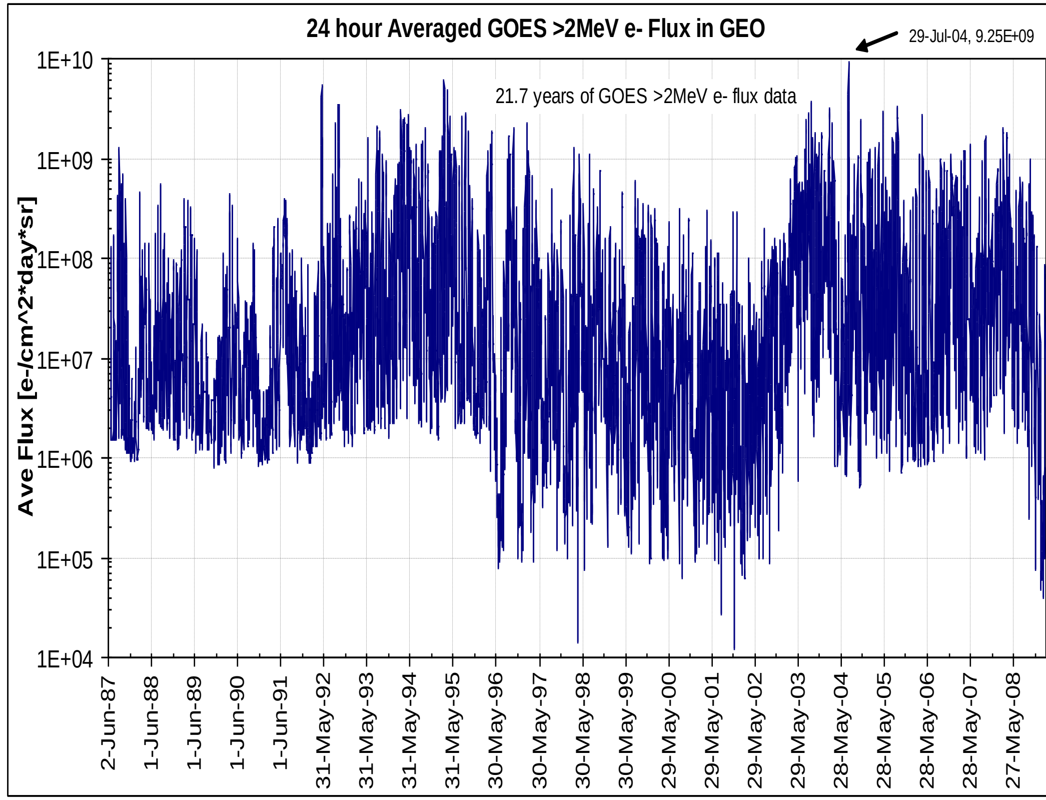
$$\text{EARLY TIME SOLUTION: for } t << \tau = \rho\varepsilon_r\varepsilon_o$$

$$\text{q(t)} = \text{Q(t)/A} \approx \text{Jt} \rightarrow \text{Charge density} = \text{fluence up to time t}$$

$$E(t) \approx Jt/\varepsilon_r\varepsilon_o = \text{fluence divided by dielectric constant}$$

$$\text{STEADY STATE SOLUTION: for } t >> \tau = \rho\varepsilon_r\varepsilon_o$$

$$E(t) \approx \rho J,\ \text{Q(t)} \approx \text{J}\tau$$

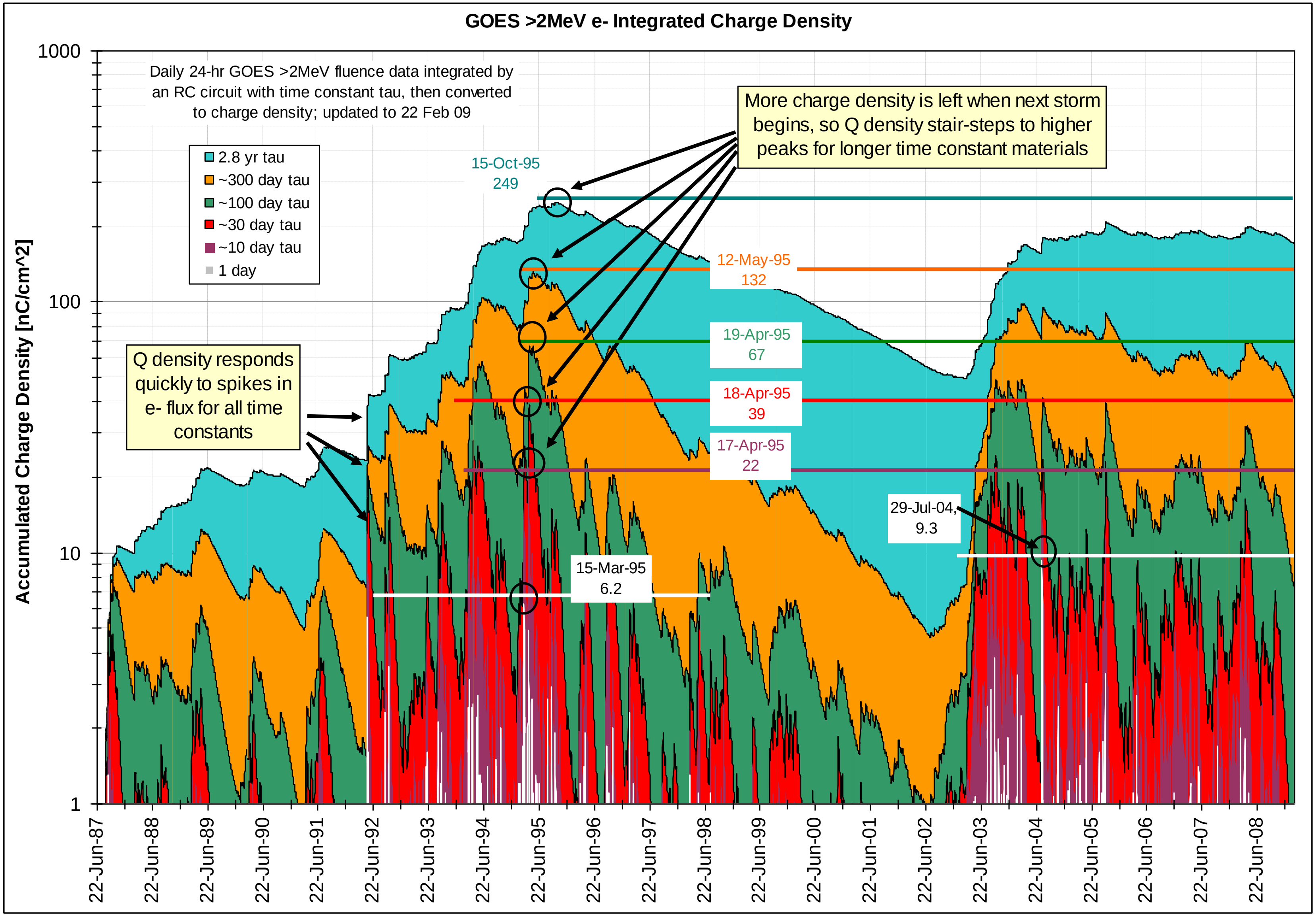


GOES 24 hour averaged >2 MeV flux data courtesy of NOAA-Space Weather Prediction Center (Ref. 8)

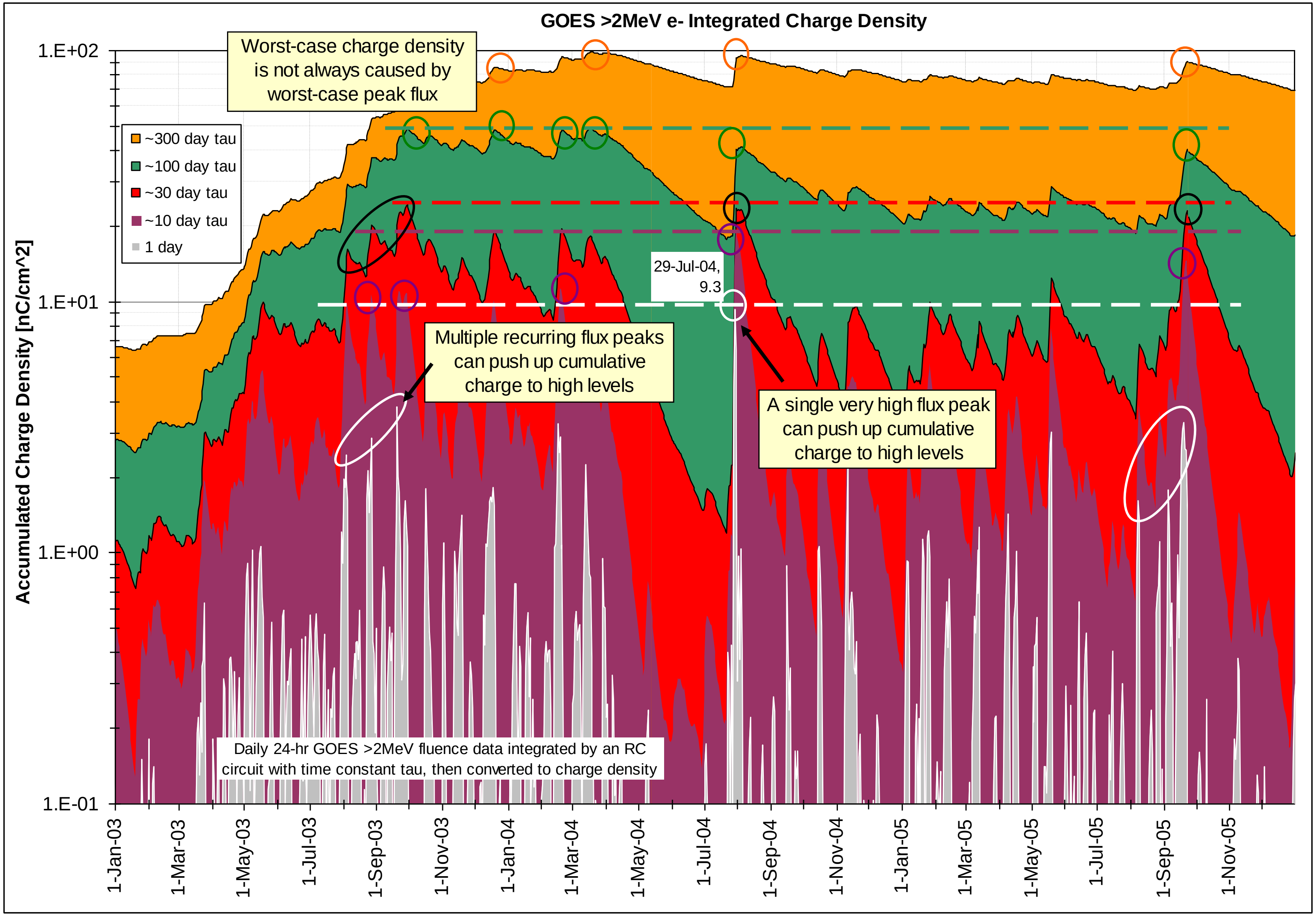
…But the Current Source Varies Orders of Magnitude on Time Scales of Days to 11-yr Solar Cycle

ESD Risk Is Defined by Charge Accumulated Over Long-Time Scales

NORTHROP GRUMMAN

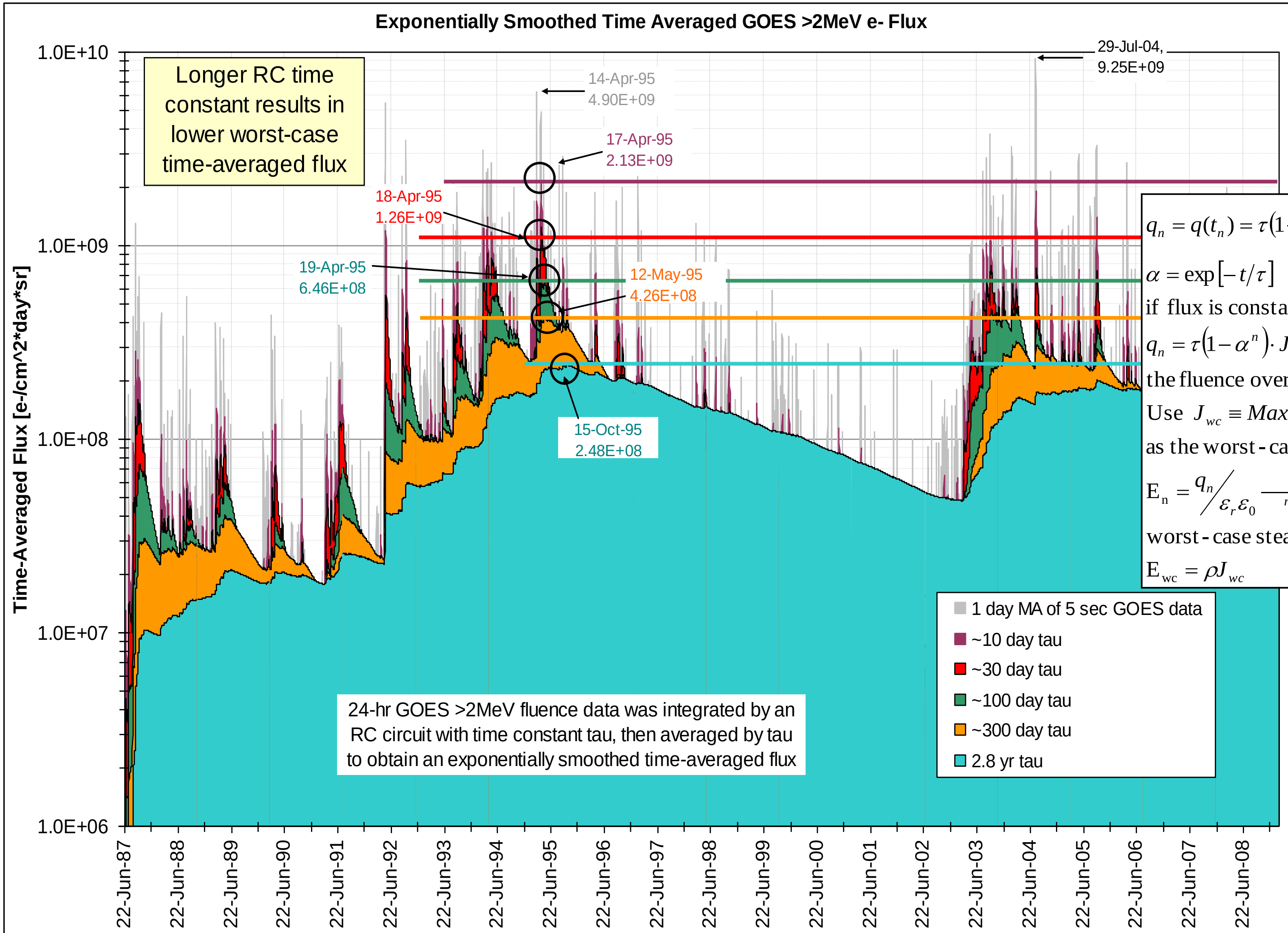


Worst Case Depends upon Material Constants and Frequency of Storms, Not Just Peak Flux



Exponentially Smoothed Flux Provides Worst Case(s) for Deep Charging Assessments

NORTHROP GRUMMAN



$$q_n = q(t_n) = \tau(1-\alpha)\cdot\sum_{m=1}^{n}\alpha^{n-m}J_m$$

$\alpha = \exp[-t/\tau]$

if flux is constant at J_c, then

$$q_n = \tau(1-\alpha^n)\cdot J_c \xrightarrow[n\to\infty]{} \tau J_c$$

the fluence over $t = \tau$

Use $J_{wc} \equiv Max[q_n]/\tau$

as the worst-case time averaged flux

$$E_n = {q_n}/{\varepsilon_r\varepsilon_0} \xrightarrow[n\to\infty]{} \rho J_c$$

worst-case steady state field

$E_{wc} = \rho J_{wc}$

Tests Show Electrical Time Constants of Years-Supports Need for Long-Term Averages

NORTHROP GRUMMAN

- New (Ref. 9) and old (Ref. 10) test data show electrical decay time constants > 1 yr for some materials

Approx time constant	Rho [Ω-cm]	Tau (εr=1) [days]	W-C Cum. Charge Density [nC/cm^2]	W-C Tau Averaged Flux [e-/cm^2-sr-day]
~3	3 E+18	3.07	13.4	4.34 E+09
~10	1 E+19	10.25	22.0	2.13 E+09
~30	3 E+19	30.74	38.8	1.26 E+09
~100	1 E+20	102.5	66.6	6.46 E+08
~300	3 E+20	307.4	132	4.26 E+08
2.8 yrs	1 E+21	1025	249	2.42 E+08
5.6 yrs	2 E+21	2050	342	1.66 E+08

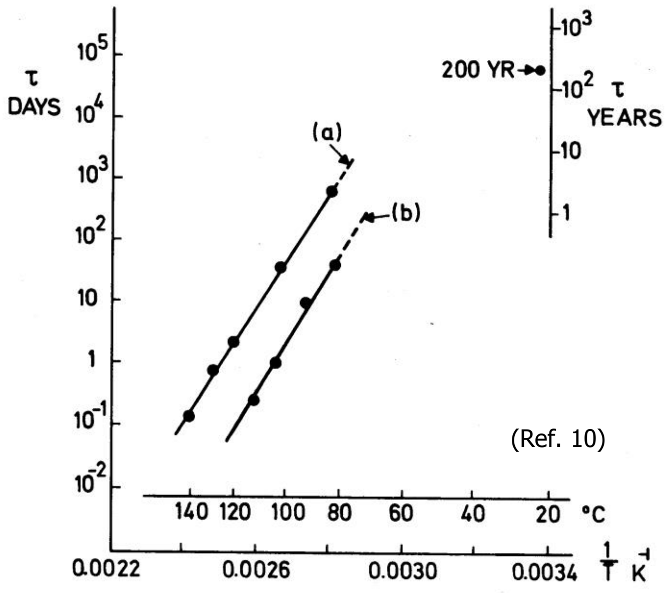


Fig. 2.28. Effective time constant of charge decay as function of temperature for 25 µm Teflon FEP electrets (*a*) negatively and (*b*) positively charged and preaged to voltage of about 250 V [2.155]

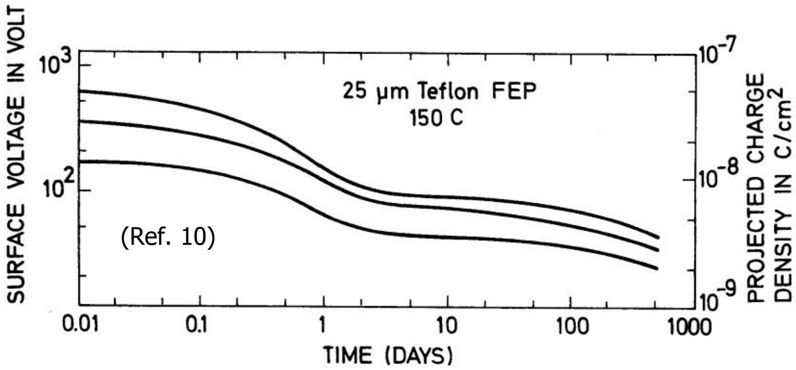


Fig. 2.27. Decay of surface potential of negatively-charged 25 µm Teflon FEP at 150 °C. Samples are aluminized on one side and charged by injection of 20 keV electrons [2.62]

Need W-C Flux Exponentially Smoothed Over Time Scales Matching Material Electrical Decay Time Constants

Good Radiation Models Enable More Credible ESD Risk Assessments

NORTHROP GRUMMAN

- From AE9/AP9 we expect to find *(and thank you for it)*:
  1. "Clean" environment data sets over a wide range of energies spanning at least one solar cycle and preferably two
  2. Data sets integrated and exponentially smoothed over time periods of 1 week, 1 month, 3 month, 6 months, 1 year, 2 years, 3 years
  3. Worst-case accumulated charge density and exponentially smoothed flux for the above averaging time periods (or the means to compute them from the data sets)

- Satellite manufacturers will need to:
  1. Transport external environment into the spacecraft to define internal charging risk (NASA Handbook 4002, discusses ways to do this)
  2. Establish time constant of materials & pick appropriate W-C environment
     - NASA materials data base (another NASA/LWS supported effort - *thank you*)
     - Other historical test data
     - New tests using advanced non-contacting probe test methods

- NASA Handbook 4002 will need to be updated to reflect new definition of worst-case environment, and available material time constants

- Some pieces of the puzzle are still missing
  - Adjustments for temperature (activation energy) and aging in space (change with time in vacuum and dose) are TBD at this time

References:

NORTHROP GRUMMAN

1. "Industry Users Group, Model Requirements Update: The Oracle has Spoken," *Working Group Meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering,* Oct 2004, College Park, MD, available at http://lwsscience.gsfc.nasa.gov/RB_meeting1004.htm
2. "AE9/AP9: New Radiation Specification Models-Update," Ginet and O'Brien, 9 Sep 2008 available at http://lws-set.gsfc.nasa.gov/RadSpecsForum.htm
3. Personal Communication with P. O'Brien.
4. AME switch anomaly plot is from: "Conclusive Evidence for Internal Dielectric Charging Anomalies on Geosynchronous Communications Spacecraft," Wrenn, *Journal of Spacecraft and Rockets*, Vol. 32, No. 3, May-June 1995, pp.514-520
5. Star Tracker anomaly plot is from: "Thick Dielectric Charging on High Altitude Spacecraft," Vampola, *J. Electrostatics*, 20 (1987) 21-30. This paper is essentially identical to a previous publication: "Thick Dielectric Charging on High Altitude Spacecraft", Vampola, Report *SD-TR-86-46*, July 25, 1986 (DTIC access number AD-A171 078, approved for public release, unlimited distribution).
6. CRRES pulse per orbit data is from: "Spacecraft Anomalies on the CRRES Satellite Correlated With the Environment and Insulator Samples," Violet and Fredrickson, *IEEE Transactions on Nuclear Science*, Vol. 40, No. 6, December 1993, pp.1512-1520.
7. The 1-D circuit model for deep charging is widely used. For instance, see Appendix E of "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects," *NASA-HDBK-4002*, Feb 17, 1999; also Figure 2 of "Internal Charging and Secondary Effects," Romero and Levy, *The Behavior of Systems in the Space Environment*, Ed. R. N. DeWitt et al., 1993 Kluwer Academic Publishers, p565ff.
8. GOES 24-hr averaged >2 MeV flux data courtesy of NOAA-Space Weather Prediction Center: http://www.swpc.noaa.gov/ftpmenu/indices/old_indices.html
9. Recent test results that also show very long time constants can be found in "Charge Storage Measurements of Resistivity for Dielectric Samples from the CRRES Internal Discharge Monitor," Green, Frederickson and Dennison, *9th Spacecraft Charging Technology Conference*, Tsukuba, Japan, April 2005 and the references it contains
10. The example plots showing extremely long (>1year) electrical decay time constants are from "Physical Principles of Electrets," Sessler, Chapter 2 of *Electrets: Topics in Applied Physics*, 2nd edition, Volume 33, Springer Verlag, 1987

NORTHROP GRUMMAN