Experience and Capabilities of Boeing Radiation Effects Laboratory (BREL-Seattle) to Support RSS Programs

Prepared for Reusable Space Systems Group,
December, 1998

Brief Summary of Who and What is BREL

Boeing Radiation Effects Lab

- **BREL, Boeing Radiation Effects Laboratory**
  - **First established 35 years ago**
  - **Dynamitron and linear accelerator its first radiation effects simulators**
  - **Radiation facilities expanded with FX-75 Flash X-ray, Co-60, etc**
  - **Decades-long use of ATE test equipment (recent IMS tester) located adjacent to Co-60 and accelerators**
  - **For SEU: Cf-252 chamber, and 14 MeV neutron generator, Hi Level portable ETS and development of interface cards for automated testing**
- **In-house equipment augmented by use of specialized test facilities**
  - **Heavy ion accelerators**
    - **88" Cyclotron at Lawrence Berkeley Lab (LB)-have dedicated beam line, vacuum chamber, dosimetry system; "Aerospace cocktail"**
  - **High energy proton beams**
    - **UC Davis (60 MeV), Mass Gen'l (150 MeV), TRIUMF (500 MeV)**
- **Primary role throughout 1970s-90s was to support Heritage Boeing space programs for which Boeing had key role**
  - **Radiation effects parts selection/evaluation, survivability assessment**

Brief Summary of Who and What is BREL Cont'd

Boeing Radiation Effects Lab

- **To augment BREL capabilities to fulfill space radiation effects needs of Boeing programs, BREL personnel have been**
  - **Heavily involved in the nuclear/space radiation effects community**
  - **Obtained numerous R&D contracts from government Labs and agencies, aerospace and electronics companies (Aerojet, Hughes, TRW, Lockheed M&S, Spectrolab, etc.)**
  - **Compiled test data into vast database of parts characterization results on the radiation response to TID, dose rate, displacement damage and SEE**
- **During the 1990s focus mainly on effects of the natural space environment**
  - **Major support for large programs such as Space Station, Sea Launch, IUS**
  - **Developed ancillary expertise such as capability to fully define the natural space radiation environment (done for NASA on Space Station)**
  - **Developed expertise/methodology to apply parts data to mission environments to calculate parts response to TID, dose rate, displacement damage and SEE effects**

Major Radiation Effects Subgroups Within BREL

Boeing Radiation Effects Lab

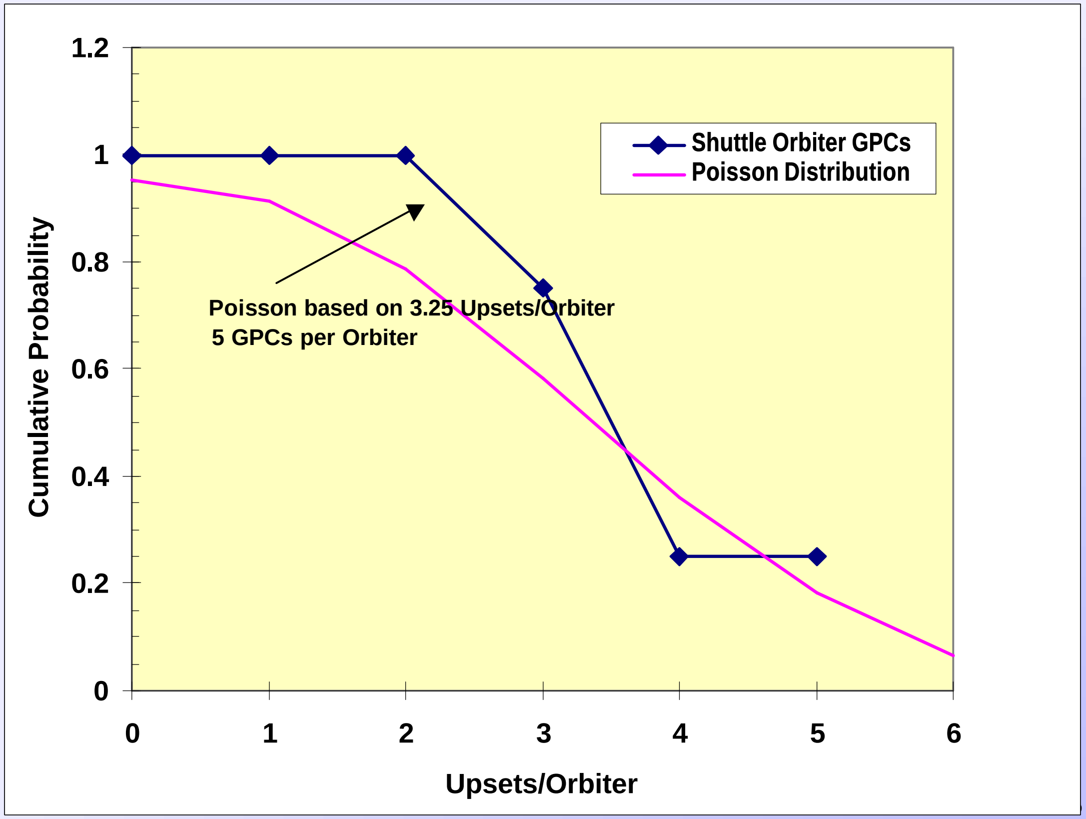
- **Overall Leadership**
  - **W. Will, Mgr E. Normand, Chief Scientist J. Wert, Lead Test Eng.**
- **TID and Dose Rate Testing and Analysis**
  - **J. Wert, R. Edwards, G. Perry, R. Kennerud (Engineers) , C. Vick and J. Beymer, (Techs)**
- **SEE Testing and Analysis**
  - **Dr. E. Normand, J. Wert, Dr. D. Oberg, Dr. P. Majewski, L. Stevens (Engineers), C. Vick (Tech)**
- **Compilation and Maintenance of Radiation Response Databases**
  - **Dr. P. Majewski, R. Kennerud, G. Perry (Engineers)**
- **Calculation of Space Radiation Environment**
  - **Dr. P. Majewski, Dr. D. Oberg, Dr. P. Measel, Dr. T. Criswell, Dr. E. Normand**
- **Radiation Application Analyses**
  - **D. Egelkrout, Dr. E. Normand, Dr. P. Majewski, Dr. D. Oberg, R. Edwards, Dr. T. Criswell**

BREL Has Good Working Relationships w/ NASA Center Personnel

- **Radiation experts at all the major NASA centers**
  - **GSFC** — **K. LaBel, J. Barth, Stass**
  - **Langley Research Center** — **J. Wilson, J. Shin**
  - **MSFC** — **J. Watts, T. Parnell, J. Howard, B. Kaufman**
  - **JSC** — **P. O'Neill, W. Culpepper, G. Badhwar**
  - **JPL** — **C. Barnes, J. Coss, G. Swift**
  - **Ames** — **S. Scimemi (SOFIA)**
  - **KSC** — **K. Milon (SEUs in GPCs)**

Upsets in Shuttle Orbiter GPC Computers on Ground

- **Ground upsets in Shuttle Orbiter GPCs on the ground (during simulations) are randomly distributed among the GPCs, therefore they are SEUs**



BREL Personnel Have Long Established Relationships in Rad Effects Community

Boeing Radiation Effects Lab

- **All major institutions within the radiation effects community**
  - **Space Parts Working Group W. Will, Secretary, last 8 years**
  - **IEEE NSREC W. Will, E. Normand, D. Oberg, J. Wert have been session chairs, reviewers, Short Course lecturers, etc.**
  - **DTRA (formerly DSWA) Lou Cohn: One BREL contract, one SSED contract BREL assisted with, many proposals submitted**
  - **NRL One BREL contract, continuing interactions w/ personnel: J. Ritter, A. Campbell, C. Marshall, S. Buchner**
  - **DOE Labs Sandia annually contracts use of radiation sources**
  - **Los Alamos - BREL leader in use of WNR beam**
  - **AF Labs Continuing interactions w/ personnel: G. Mullen, R. Frederickson, R. Pugh, C. Brothers**

BREL Experience in Space Radiation Qualification of Electronics

Boeing Radiation Effects Lab

Radiation Effect	Test Facilities	Programs Supported	Methods to Utilize Test Results
TID (Total Ionizing Dose)	Co-60 (3- High rates and 2-Low Rate) Oven (Annealing) ATE (Testers)	Space Station (ISS) Advanced Projects MILSTAR, DSP Contractors: Hughes, Aerojet, UTMC	Extensive file/retrieval system of test reports extending over decades Relational database of IC responses w/web retrieval front end with both device results and physics analysis Concerted effort to stay current w/ vast data in open literature
SEE (Single Event Effects)	Cf-252 Chamber Dedicated vacuum chamber at LBL Special eqpt for NSCL testing in air (MSU) Proton tests at UC Davis, Harvard, etc	Space Station (ISS) Advanced Projects SSED, IUS Contractors: UTMC, COMDEV, Hughes	ISS file system of radiation test reports/procedures Created/maintain web-based Access database of all ISS test results Via industry contacts, concerted effort to stay current w/ vast data in open literature
Displace-ment Damage	Dynamitron (1 MeV protons) 14 MeV neutrons UW Van de Graaf (10 MeV protons) Sandia SPR reactor (1 MeV eq neutrons)	Space Station IUS Advanced Projects IR&D	Lead ISS effort to assess effects in optocouplers Extensive file/retrieval system of test reports and relational database of IC responses w/web retrieval Via industry contacts, concerted effort to stay current w/ data in open literature

Case Study: SEU/SEL in Intel 87C51 Microcontroller on ISS

Boeing Radiation Effects Lab

- **BREL identified ISS-PG-3 parts susceptible to SEU, 12/ 91**
- **Authorized to carry out initial heavy ion SEU testing of devices including 87C51**
- **First tests, 2/92, at U of Washington Van de Graaff, (in conjunction w/ SEU testing for 777), showed SEU and "lockup" in 87C51**
- **Space Station program apprised, concerned, more tests warranted**
- **2nd test, 3/92,**
  - **Circuit included watchdog timer to avoid errors**
  - **AMD version of microcontroller tested with Intel devices**
  - **SEE results the same as first test, watchdog timer not the answer**
- **Other ISS SEU group, IBM Fed. Sys. (McDac sub) questioned results**
  - **BREL determined need to use higher energy/LET ions to test for SEL**
  - **3rd test, 6/92 at 88" Cyclotron at LBL, higher LET ions**
  - **Microcontroller latched up; good agreement w/ IBM results on 80386**

Case Study: SEU/SEL in Intel 87C51 Microcontroller - Cont'd

- **BREL put ISS in contact w/ SSED group at Boeing developing design for ASIC-based "rad hard" version of the microcontroller**
  - **ISS PG-3 group (Huntsville) determined best approach was SSED**
  - **PG-3 funded SSED to complete design of replacement microcontroller chip**
  - **Part of process was for BREL to test ASIC version w/ heavy ions**
- **BREL also carried out proton SEU/SEL tests (Harvard,TRIUMF) SEU, no SEL**
  - **Report issued documenting all tests and conclusions**
  - **Space Station program accepts test report, SSED approach to make "rad-hard" version of microcontroller**
- **Final heavy ion tests on SSED designed rad-hard version, 80C51FC Processor, (made by UTMC) verified <u>very</u> low SEU, no SEL**

Case Study: Space Qualification of Power MOSFETs

Boeing Radiation Effects Lab

- **Two different radiation effects involved**
  - **Single event effects (SEE, energy from charged particle destroys the part)**
  - **TID (total ionizing dose causes part's electrical parameters out of spec)**
- **Two different SEE effects**
  - **Single event burnout (SEB): destructive pulses in the main epi layer due to an avalanche feedback mechanism**
  - **Single event gate rupture (SEGR), charged particle tunneling through thin gate causes it to rupture**
  - **Higher the voltage rating of the MOSFET, the more likely it is susceptible to SEB and/or SEGR**
- **SEB first reported on by A. Waskiewicz et al (Rockwell) in 1986**
- **Fist method of nondestructively testing for SEB developed by Oberg and Wert (Boeing) in 1987**
- **BREL first to show high energy neutrons also can induce SEB; test of current parts w/ protons gave agreement w/APEX satellite data**

Case Study: Space Qualification of Power MOSFETs-Cont'd-2

Boeing Radiation Effects Lab

- **Boeing, Rockwell and JPL develop guidelines for qualifying power MOSFETs for use on Space Station in 1992 (incorporated in ISS docs)**
  - **Test MOSFETs with heavy ions normal to device, LET of 26 MeV-cm^2/mg and having range of 35µm in silicon**
  - **As increase voltage across the drain, V_{ds}, of MOSFET, look for**
    - **Burnout pulse (test circuit protects against permanent damage)**
    - **Increase in gate leakage current (precursor of gate rupture)**
  - **Determine minimum passing voltage, V_{ds} at which no SEB or SEGR is seen**
  - **Allowable V_{ds} that may be used in application is minimum passing voltage multiplied by 75% derating factor (accounts for part-to-part variations)**
  - **For MOSFET applications in which the 75% derating is not high enough, can increase to 80-85% by carrying out SEB/SEGR lot acceptance testing using 10 samples**
- **Many power MOSFETs tested for SEB/SEGR on ISS, D. Oberg of BREL compiled all of this data**

Case Study: Space Qualification of Power MOSFETs-Cont'd-3

Boeing Radiation Effects Lab

- **On Teledesic program (BREL involved since 1995) total dose levels much higher (~100 Krad) compare to ISS (5 Krad)**
- **On Teledesic, power system design being developed by Rocketdyne using large quantity of power MOSFETs**
  - **Need to meet both TID and SEB/SEGR criteria**
- **Use of special rad-hard MOSFETs (~$1K each) prohibitively expensive**
- **BREL working with Rocketdyne and small microelectronics vendor**
  - **Develop, test and verify commercial MOSFET designs**
  - **Meet both TID and SEB/SEGR criteria for Teledesic orbit**

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack

Boeing Radiation Effects Lab

- **BREL supporting EXPRESS Rack (independent program in Huntsville related to ISS) for more than 4 years**
  - **Review of parts lists**
  - **Brief assessment of the susceptibility of parts to SEU and SEL**
  - **Small effort, ~ 100 hours/year, but valuable to the program**
- **Previous to 1998, BREL assisted on two testing efforts**
  - **Testing of Aitech developed computer using Motorola 68020 µcontroller**
    - **Latchup circumvention circuit was designed since they could not obtain SEL-immune version of µcontroller from SG-Thompson**
    - **BREL performed heavy ion testing of circuit at LBL 88" Cyclotron, but circuit had some problems**
    - **BREL performed simpler latchup test of modified circuit using our Cf-252 system; test showed new circumvention circuit worked properly**
  - **Single event burnout testing and evaluation of test data of power MOSFETs for Hughes-Scotland (sub of MacDac subcontractor)**

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-2

Boeing Radiation Effects Lab

- **Early 1998, BREL asked to evaluate 2 types of COTS boards:**
  - **Advanced Aitech computer board with MPEG-2 Encoder**
  - **Commercially available hard drives**
- **Heavy ion SEE testing of such boards presented a huge challenge**
  - **Using LBL not feasible; each board with 3-8 devices needing testing; would have to delid each device on board, still have board 100% functional**
  - **All devices are PEMs (plastic encapsulated microelectronics); have to be delidded by use of nitric acid**
  - **Individual PEMs can be easily delidded (success rate ~80%, bond wires may be accidentally destroyed), but entire COTS board is not feasible**
  - **Similarly, no way to replace all of the parts that are soldered onto the board, with sockets into which delidded parts could be placed**
- **As alternative, BREL suggested doing testing with ions of high enough energy so they could penetrate the package lid and reach the die**
- **Since the BEVALAC accelerator closed at LBL in early 1990s, no US accelerator facility available for this work, only 2 in Europe**

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-3

Boeing Radiation Effects Lab

- E. Normand learned that National Superconducting Cyclotron Laboratory (NSCL) at Michigan State was looking for outside customers
- BREL contacted NSCL for use in testing of the COTS boards; ion beams available appeared to have enough energy to penetrate PEMs
- BREL needed to understand operation of NSCL to adapt for our test
  - Other SEU groups also became aware of the NSCL; NASA-GSFC organized a multi-party test program (8 separate groups) on April 1-2, 1998
  - BREL only industrial participant, mainly NASA and National Labs
  - We tested two devices, in both an ordinary and a delidded PEM package, as a trial of our approach, and found that it worked successfully
    - Measured cross sections consistent from two packages
    - Could calculate backwards, knowing thickness of plastic cover, to find degraded energy (and LET) of the degraded ion when it strikes the die
  - Test very valuable in providing an understanding of what services could be easily provided by NSCL, and which we would have to provide ourselves

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-4

- **Special equipment designed to make testing at NSCL feasible**
  - **X-y stage (moving up-down and left-right)**
  - **Cards had up to 8 separate parts to be exposed to beam; we had to remotely move the card so that the desired part was within the 1'' diameter beam**
  - **Other unconventional features were also incorporated**
    - **Laser alignment systems**
    - **Our own real time dosimetry system**
- **Procedures developed for testing all of the boards lead by J. Wert and D. Oberg of BREL, in conjunction w/Aitech and EXPRESS Rack engineers**
- **Testing carried out at the end of June 1998**
- **7 different boards (34 devices) were exposed to heavy ions to measure the susceptibility to single event induced functional interrupt and latchup**

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont’d-5

- **4 Aitech boards were used to test 13 different devices for SEE (SEL and SEFI) susceptibility**
  - **Of 13 parts, two parts have high enough rates to be of potential concern**
    - **Video encoder**
    - **Analog Devices DSP**
  - **Heavy ion induced functional interrupts in the video encoder manifested themselves in a variety of malfunctions during recording**
  - **DSP was prone to one single event latchup event as well as to functional interrupts**
  - **Relatively high SEL and SEFI rates calculated for the DSP based on outside SEE data for related Analog Devices DSPs, thus to be regarded as conservative**

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-6

Boeing Radiation Effects Lab

Part #	Part Type	Vendor	Results	Est'd SEE Rate Space Station, Effect/day
Yellowknife Board				
PPC106A RX66CD	PCI Bridge/ Memory Controller	Moto-rola	SEUs, LET > 14; Avg X-Sctn~2E-5	1.4E-06
MPC750A RX266xx	Microprocessor	Moto-rola	SEUs, LET > 16;Avg X-Sctn ~1E-5	5.0E-07
C2300 Board				
CA91C042-40	VME Interface Chip	Tundra	SEL at LET=30; Avg X-Sctn ~2E-4	2.0E-06
AM29F016-120EC	Flash EEPROM	AMD	No Effect	No Effect
Symbios Logic Controller Board				
SYM53C885	PCI SCSI-2/ Ethernet Controller	Symbios Logic	SEFI at LET 23, 32; No effect LET< 18; Asymp X-Sctn ~1E-3	4.0E-05
DP83840A VCE	Ethernet Phys. Layer	Nat'l	No effect for LET < ~15,	
DP83223V	10/100 Twist	Nat'l	No effect for LET < 8-10	

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-7

BOEING PHANTOM WORKS

***B**oeing **R**adiation **E**ffects **L**ab*

Part #	Part Type	Vendor	Results	Est'd SEE Rate Space Station, Effect/day
MVision10	Video Encoder	VISIO N-Tech	SEFI at ~1E4 p/cm^2; assumed worst case SEFI s 10 times this, 1E-3 cm^2, lowest LET for SEFI ~4.3	SEFI~2E-3 event/day
SAA7111A	Digitizer	Philips	SEFI seen at LET 15-17 w s ~1E-5; Asympt s taken as 1E-4 at ~LET=13;	SEFI~1E-5 event/day
ADSP-2185	DSP	Analog Devices	SEL: Measured- ~LET=18.5; s ~2E-5 cm^2 but SEL data on similar ADSPs (others) is LET_{th} =12 and s ~1E-2; SEFI: Measured- ~LET~3; s ~2E-5 but also used SEU data on similar ADSPs (others) s ~1E-3	SEL: ~1E-3 LU/day upper bound rate based on SEL in other DSP; SEFI: ~1E-2† SEFI/day based on our/other SEU in related DSPs

Case Study: SEU/SEL in COTS Boards for EXPRESS Rack-Cont'd-8

Part #	Part Type	Vendor	Results	Est'd SEE Rate Space Station, Effect/day
V360EPC-50LP	PCI Interface	V3	SEL at ~LET=15; s ~1E-5 cm^2, used~3E-4; SEFI seen at ~LET~16; s taken as ~5E-3	SEL: ~2E-5 LU/day SEFI: ~3E-4 event/day
D42280GU -30	FIFO	NEC	SEU effect mainly transients, but ~15% lead to SEFI; transients down to LET~3; s ~3E-3 cm^2	Single event transient rate ~1.4E-2 event/day; SEFI ~2E-3 is conservative
AD1877	ADC	Analog Devices	Induced SEFI (LET ~20) was hissing noise in video; s for this effect ~1E-5 cm^2, used s as 1E-4 cm^2	SEFI rate for hissing noise ~3E-6 event/day

BREL Experience in Displacement Damage Studies

Boeing Radiation Effects Lab

- **Variety of devices tested**
  - **Electronics (many different types as required by weapons specs)**
  - **Solar cells (Si, GaAs, CdTe, CIS) (many different types)**
  - **Optocouplers (many different types, mainly InGaAs)**
  - **GaAs MMICs**
  - **$LiNbO_3$ optical waveguide**
- **Three different local sources available**
  - **Dynamitron (1 MeV protons, 16 µm range in Si)**
  - **14 MeV neutrons (no range limit)**
  - **U of Washington Van de Graaff (18 MeV protons, 1.9 mm range)**
- **Long experience in using external sources**
  - **Sandia SPR reactor (1 MeV equiv. Neutrons)**
  - **High energy protons (UC Davis - 60 MeV, Mass Gen'l -150 MeV)**
- **Availability of NIEL cross sections for Si, GaAs, InP to correlate measured effects to spectra for specific orbits/missions**

Other Boeing Groups with BREL Long-Term Cooperative Relationships Supporting Radiation Qualification Issues

Boeing Radiation Effects Lab

Group	Function	BREL Relationship
SSED (Solid State Elec-tronics Develop-ment)	Provides state-of-art ASIC design services with mature capabilities. Has specialized capabilities for advanced digital VLSI and other ASIC designs. Experienced in designing ASICs to meet high radiation (rad-hard commercial process hardening by design), temperature, and reliability environments.	Planning and performing radiation testing, developing rad-hard strategies, etc.
Shock Physics Group	Expertise in experimental and theoretical techniques for the study of dynamic response of materials and structures to mechanical & thermal shock loading. Shock Physics Lab has facilities for hypervelocity impact and explosion testing. Program experienced in impact and explosion cratering, hazard analysis of space debris impact, etc.	Utilizes BREL radiation sources for specific testing; coordinates micrometeroid, debris and cratering impacts with radiation environment.
Materials and Processes Techno-logy (MAPT)	Responsible for developing technical expertise for evaluation & analysis of electronic packaging for all components/systems on Boeing defense & space programs. Prepares & coordinates documentation & specifications for engineering requirements related to procurement, use, etc. of program components.	Coordinates radiation testing activities in accord with specs in hardness survivability and assurance plans.