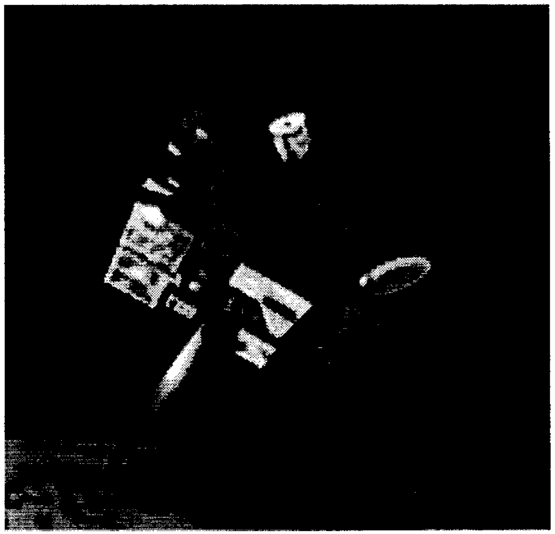
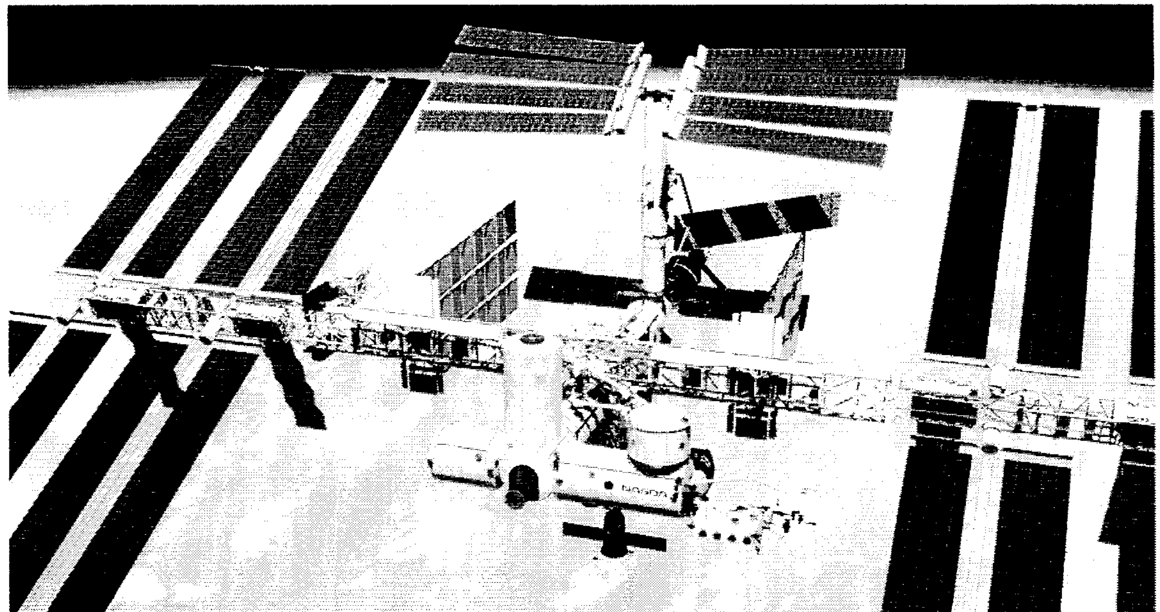
Ultra-Reliability and Long-Life

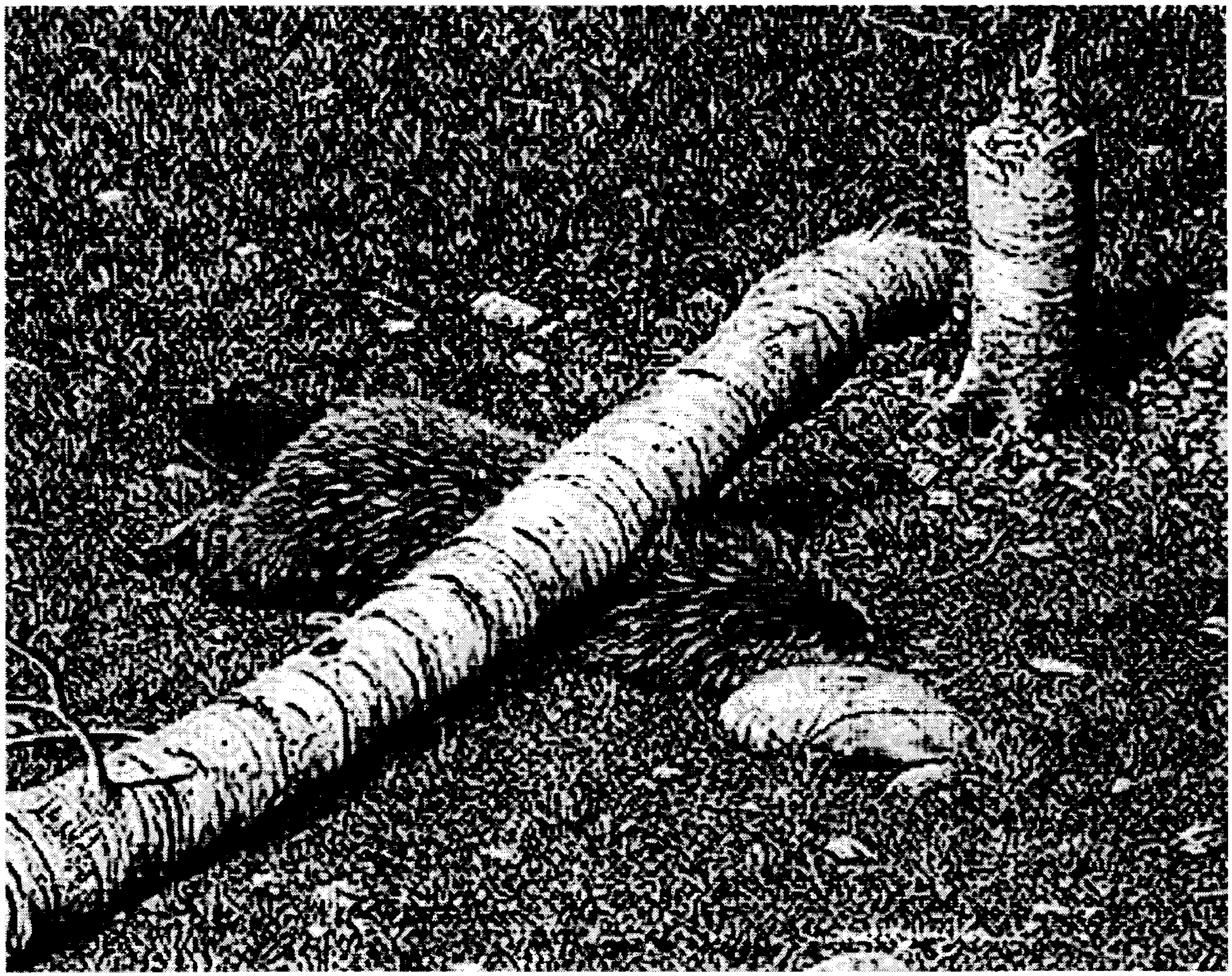
Why Ultra-Reliability/Long-Life?





- Space Systems must work right, the first time and ***every*** time.
- As system cost and complexity increase, traditional methods of attaining reliability, such as redundancy, are no longer sufficient.
  - Failure rates will have to be reduced by orders of magnitude.
  - Maintainability will have to be enhanced.
  - Long Life required to recoup huge investments (I.e., Space Station, Hubble)
- Future success will depend on achieving knowledge and technology necessary to design, build, operate complex, ultra-reliable systems.

Frankly, We Have a Long Way to Go When Even Simple Systems Can Fail*



*Note: No beavers were harmed in making this chart!

Agenda

- Define what we mean by "Ultra-Reliability" versus "Long-Life"
- Identify the primary causes of spacecraft failure
- Explore the environmental causes of failure
- Review the JPL experience in Long-Life missions
- Discuss methods for achieving Ultra-Reliability and Long-Life

Definitions

- Ultra-Reliability: A very high probability of mission success given the mission parameters such as environment, application, and duration:

  "10 times better than what we have"

  "No probability of failure"

  "No need to test"

  "As sure as death"

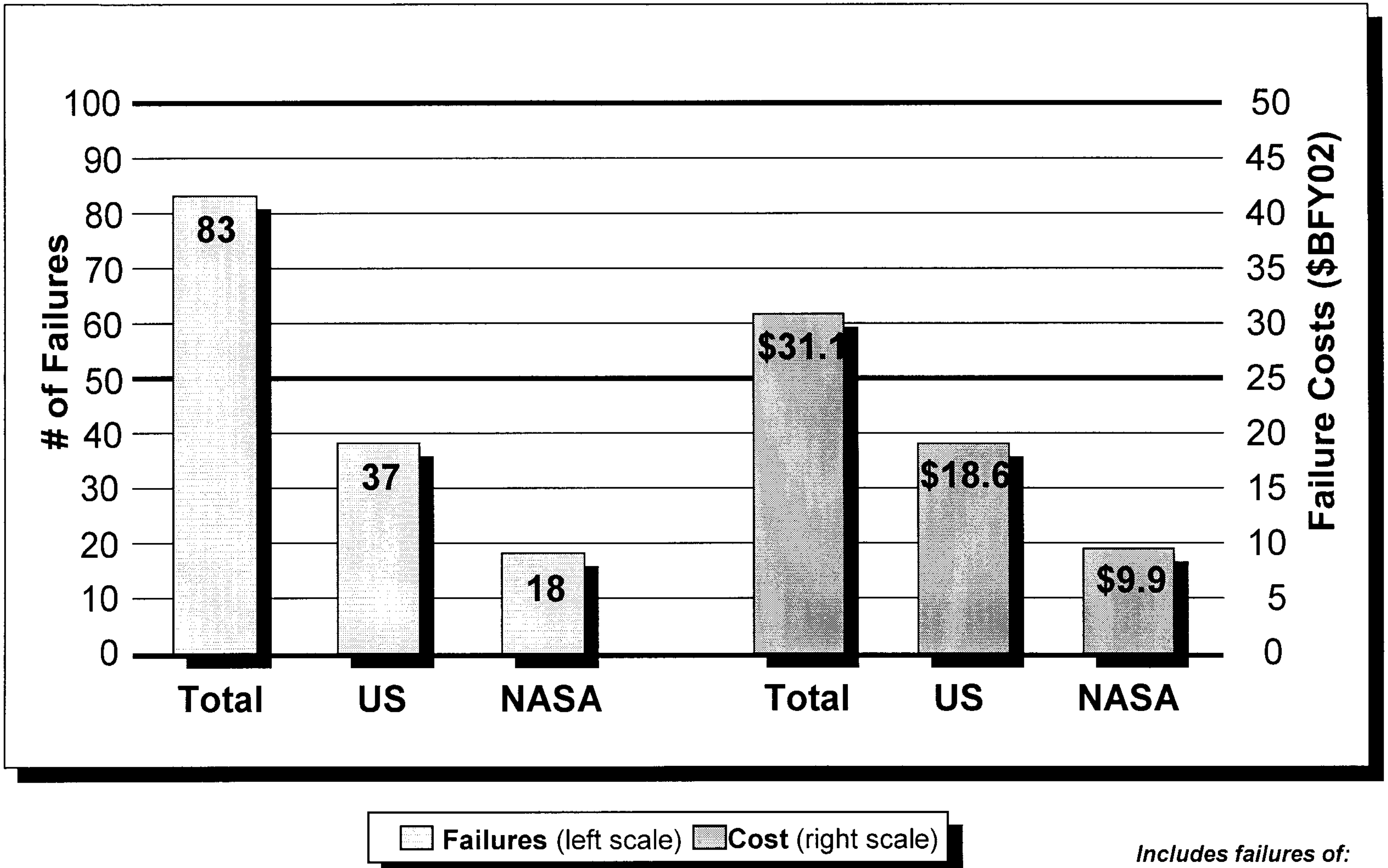
- Long-Life Mission: A mission that is designed to function reliably for 10 or more years in the space environment. "Long(-enough)-Life" may also be applied to a mission that is able to operate well beyond its design life-time. In a ultra-harsh environment such as on the surface of Venus, 10 days would qualify!

  "Voyager"

  "Pioneer"

  "IMP 8"

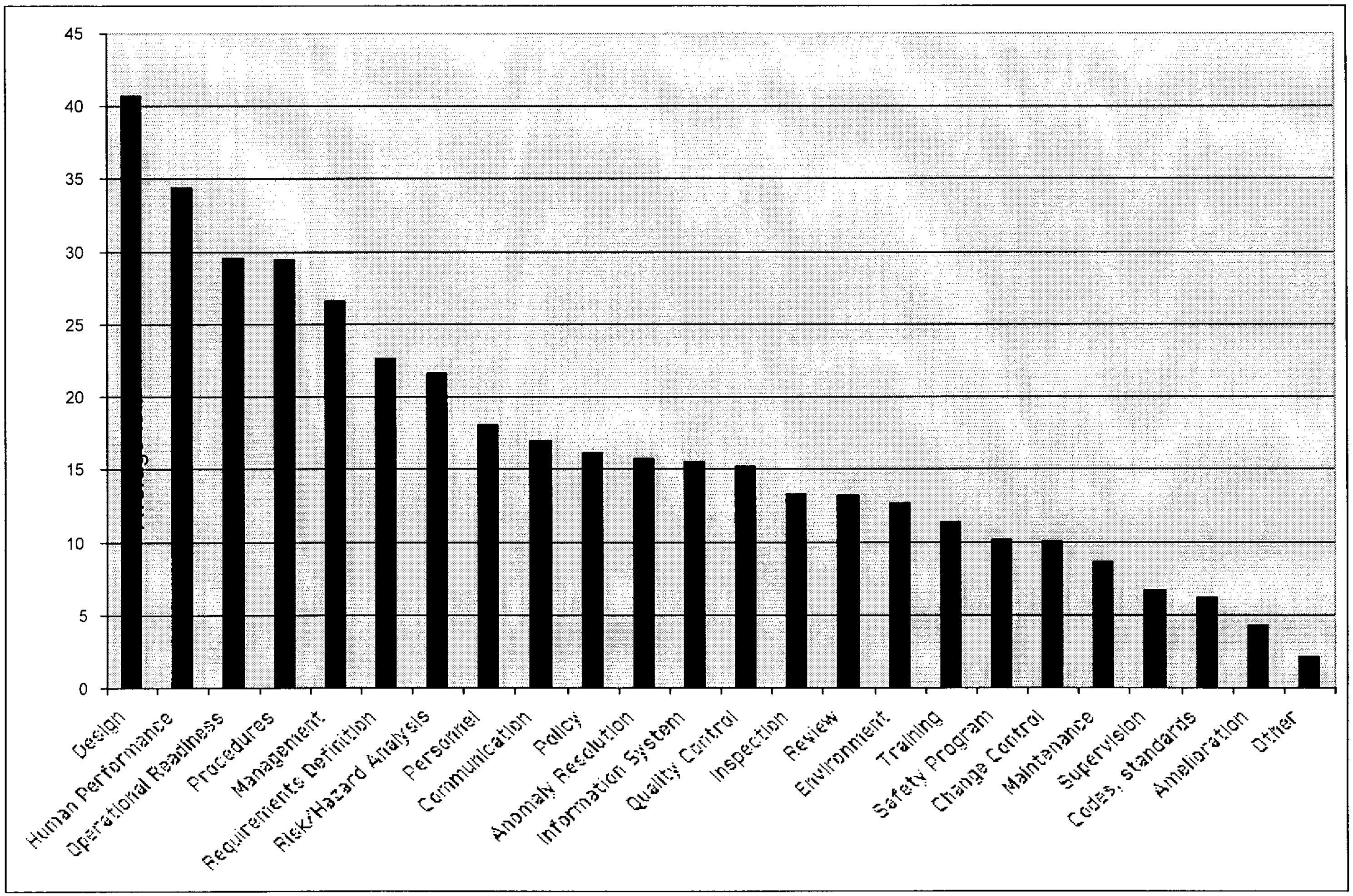
Space Mission Failures: 1986 – 2001



Includes failures of:
Shuttle & Launch Vehicles
LEO & Planetary Spacecraft
Other experimental vehicles

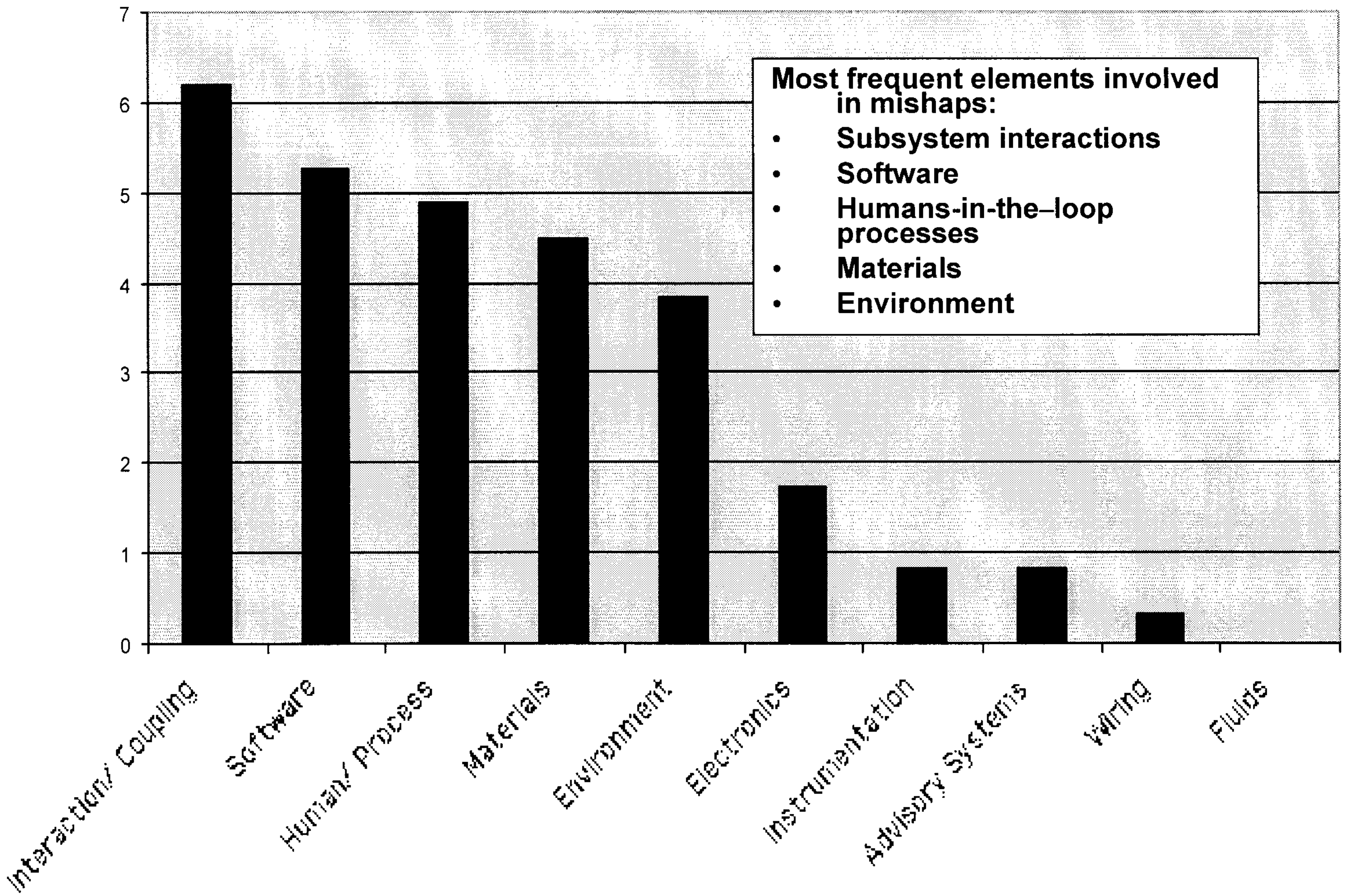
Source: SAIC Mission Failure Cost Study
Note: 50% of NASA failure cost due to Challenger

Space Mission Reliability Demographics



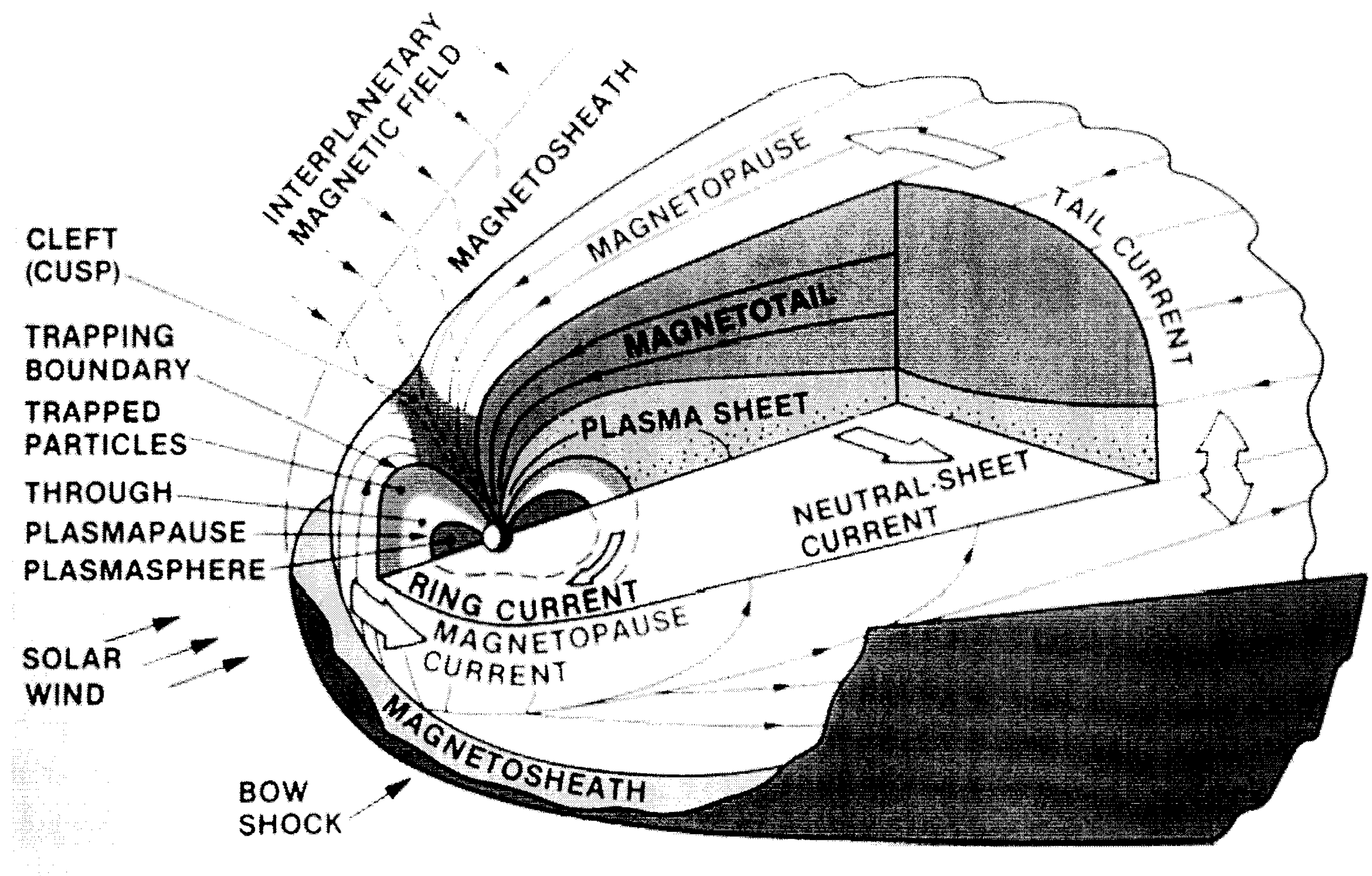
BASED ON SAIC/AEROSPACE STUDY

Space Mission Reliability Demographics



BASED ON SAIC/AEROSPACE STUDY

SPACE ENVIRONMENT EFFECTS



Impact of the Environment on Space Systems

Distribution by Anomaly Diagnosis

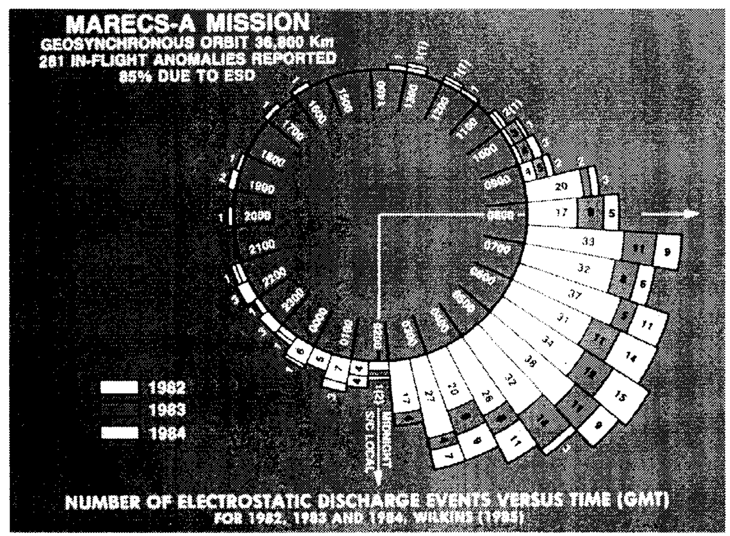
Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	**162**
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	**85**
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	**16**
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	**36**

‡Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The Impact of the Space Environment on Space Systems", presented at Charging Conference, Nov 1998.

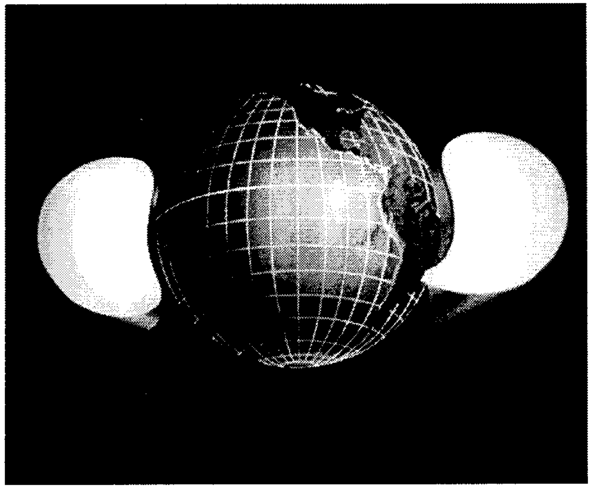
Missions Lost/Terminated Due to Space Environment

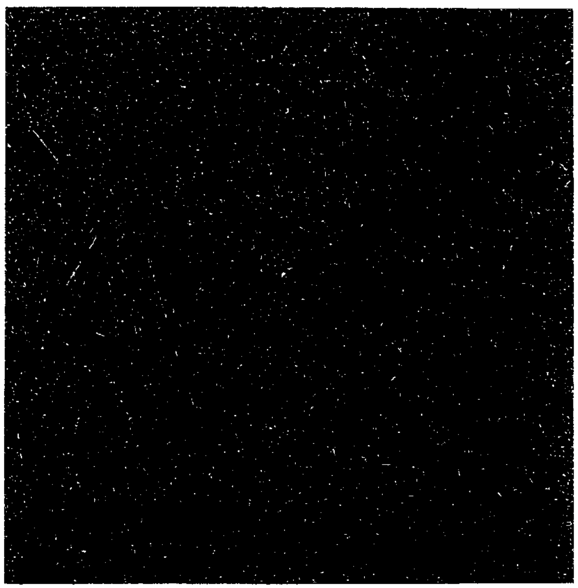
Vehicle	Date	Diagnosis
DSCS II (9431)	Feb 73	Surface ESD
GOES 4	Nov 82	Surface ESD
DSP Flight 7	Jan 85	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Mar 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

*Mission had been completed prior to termination



RADIATION EFFECTS





RADIATION EFFECTS ON MATERIALS

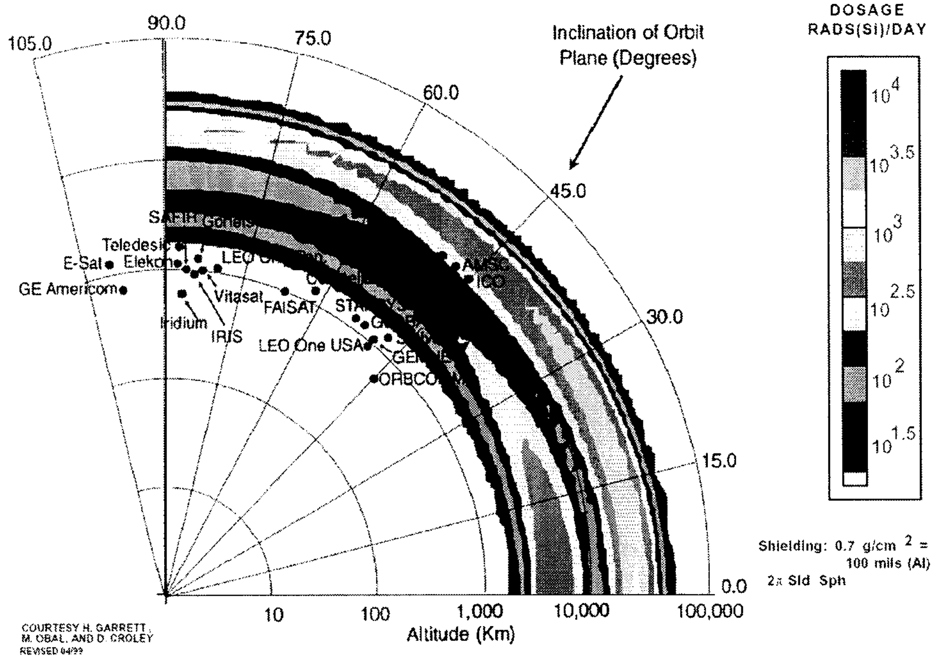
MATERIAL	LIMIT. DOSE (Rads)	MISSION RATING	REF.	STATUS
Metals	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
Ceramics	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
Carbon/Carbon	10 E 12	1	C	No problem; Damage threshold in excess of 10 E 12 rads
White Paints	10 E 10?	2	D	Use Hughes H-1 paint; very stable (electrons and protons)
Black Paints	10 E 11	2	D	Most acceptable; use QS-1 for additional margin
Composites	10 E 10?	2	A,D	Choice; Cyanate matrix based on RTX366 (250F cure)
Cabling	5 E 6	3	D	RayChem SPEC-44, 55 cables, plus required shielding
Fiber Optics	?	2?	?	Probably OK; data classified
Adhesives	10 E 10	2	A,D	Shielded in use; current adhesives (like EA9394) OK
Seals/Gaskets	5 E 7	3	A,D	Shielded in use; need to verify dose/tolerance
Lubricants	10 E 9	2	A,D	Shielded in use; all OK; Dichronite, dry lubes excellent
Blankets	5 E 9	2	A,D	Kapton should be OK; CP-1 film for additional margin
ESD Coatings	10 E 12	1	?	OK; Indium tin oxide, flight heritage-Voyager/Galileo
Propellants	10 E 8	3	A,D	Shielded in use; testing needed to verify acceptability
AR Coatings	10 E 12	1	D	Silica, tantala; verified in hi-rad environments; OK
Glass	10 E 6	4	A,B,D	Shielding required; testing/flight history required
Silica	1.4 E 7	2	A,B,D	Excellent, rad-hard; flight history Voyager/Galileo

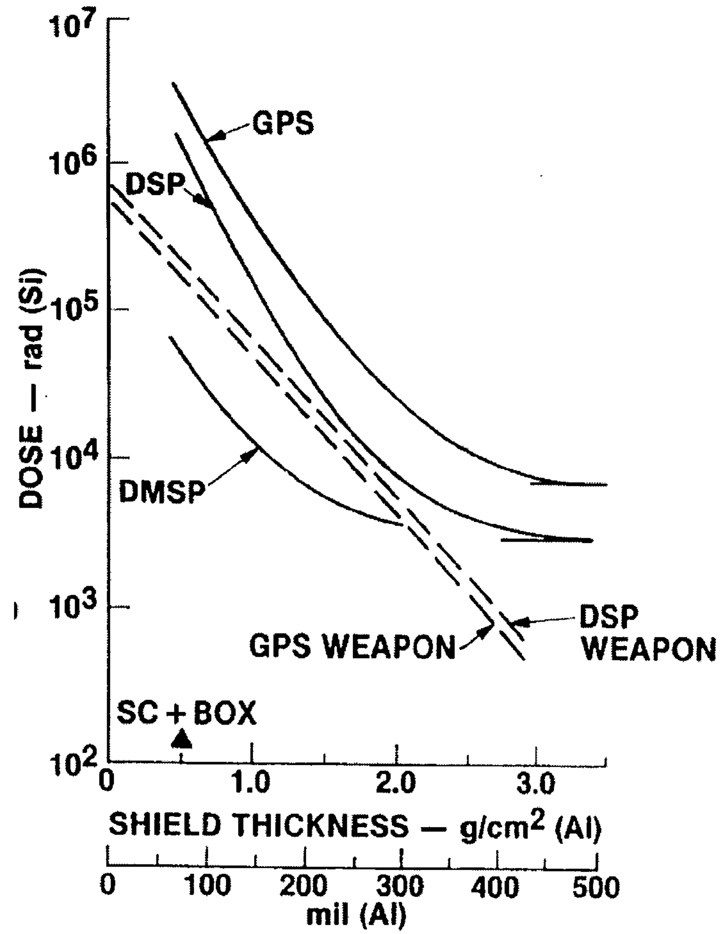
Mission Rating:
1 = Current materials acceptable
2 = Acceptable; requires dose calculations
3 = Acceptable; with dose calculations & test data
4 = Questionable; conclusive proof required
5 = Unacceptable

General References:

A = "Designers Guide to Radiation Effects on Materials for Use on Jupiter Fly-Bys and Orbiter" F.L.Bouquet, IEEE Transactions, Vol. NS-26, August 1979
B = "A Review of Reliability and Quality Assurance Issues for Space Optics Systems" V.R.Farmer, Jet Propulsion Laboratory
C = "Radiation Effects on Non-Electronic Materials Handbook", B.P.Dolgin, Jet Propulsion Laboratory
D = JPL / Manufacturer's test data

TOTAL IONIZING DOSE EFFECTS

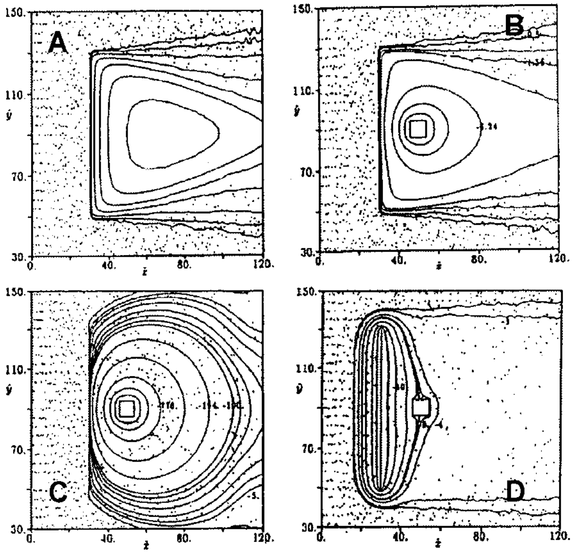




RADIATION HARDENING APPROACH

- Define the shielded radiation environment
- Parts parameter data--characterization screening
- Worst case circuit analysis--conservative design rules
- Shield to provide the part performance requirements
- Employ radiation tolerant circuit designs

CHARGING EFFECTS

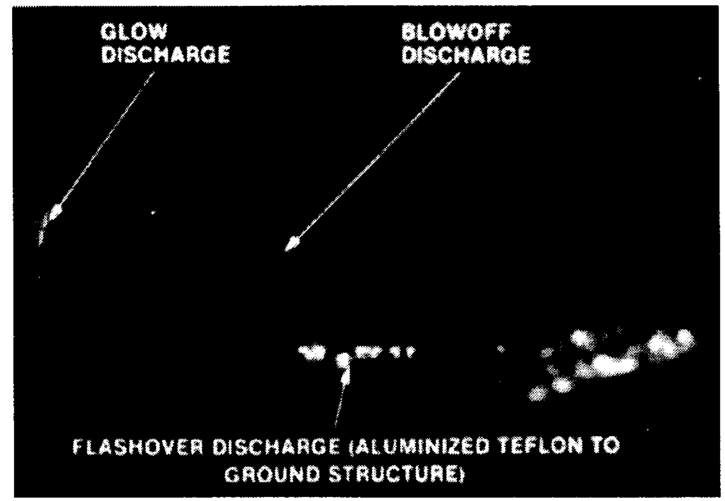


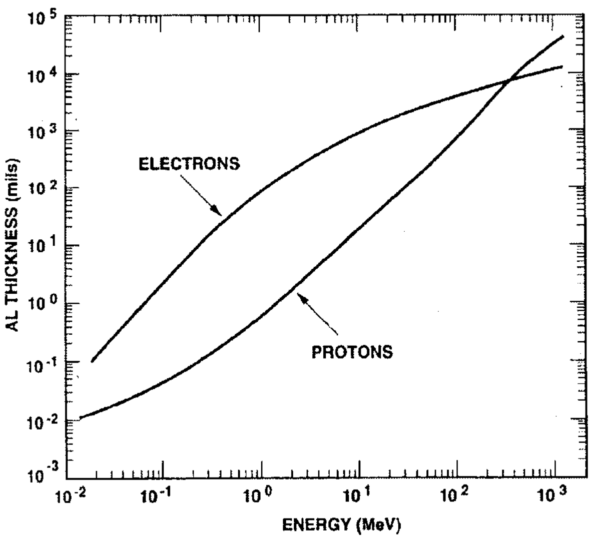
A. AMBIENT CHARGING

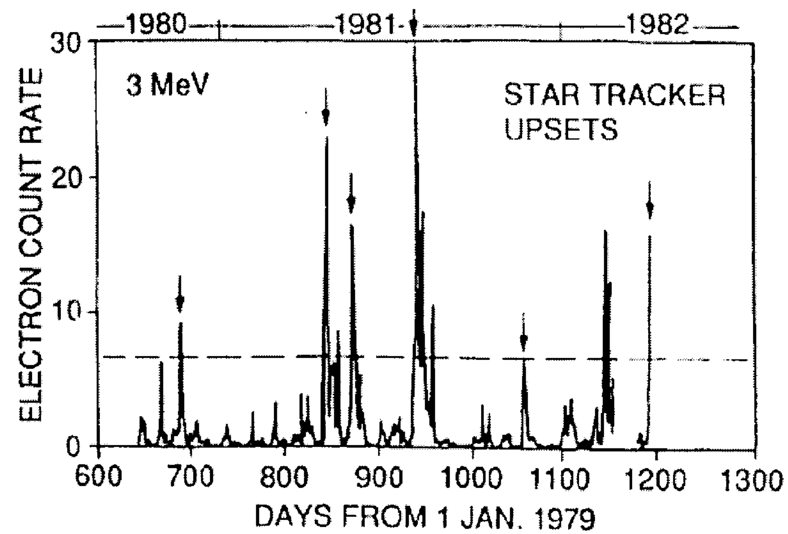
B. MULTIBODY CHARGING

C. AURORAL CHARGING

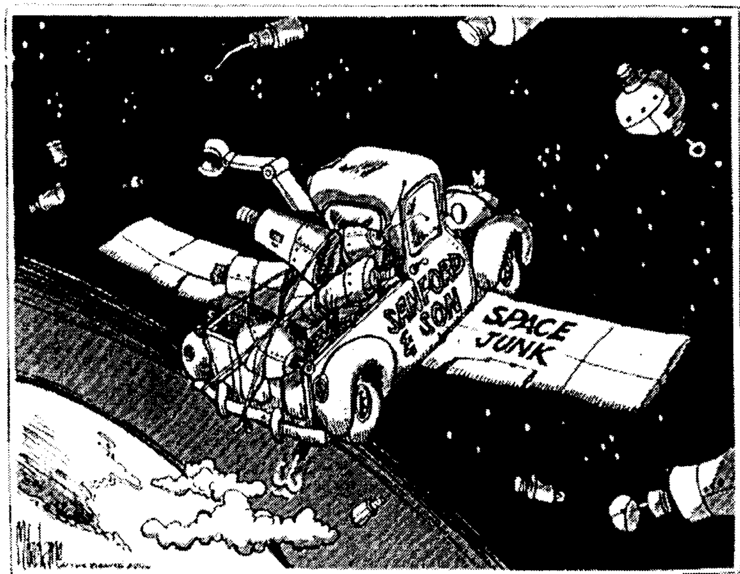
D. BIASED + AURORAL

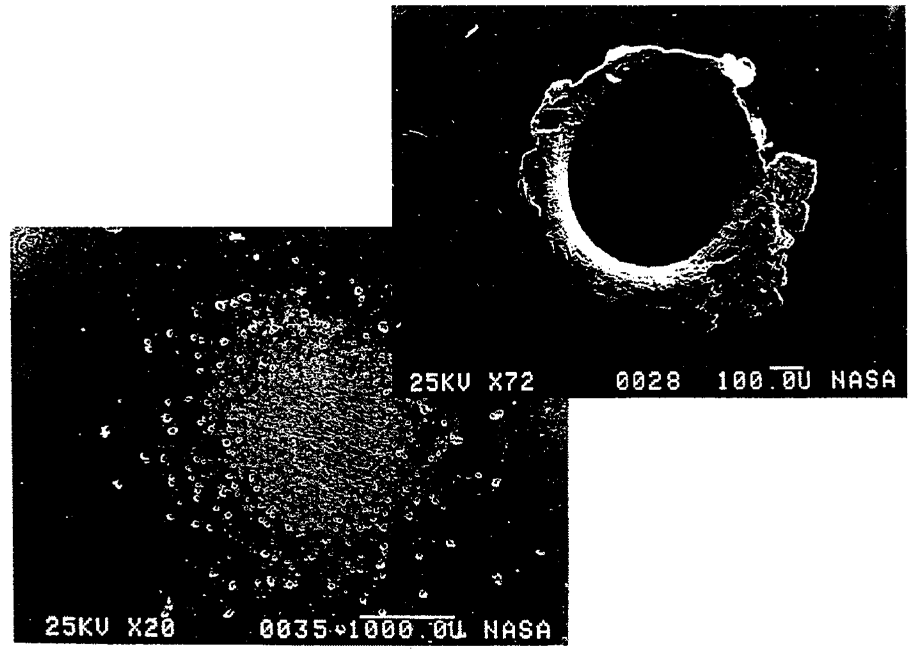


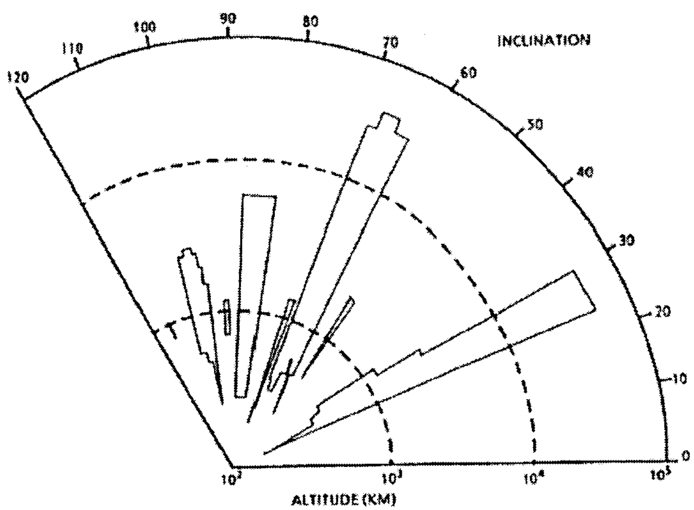


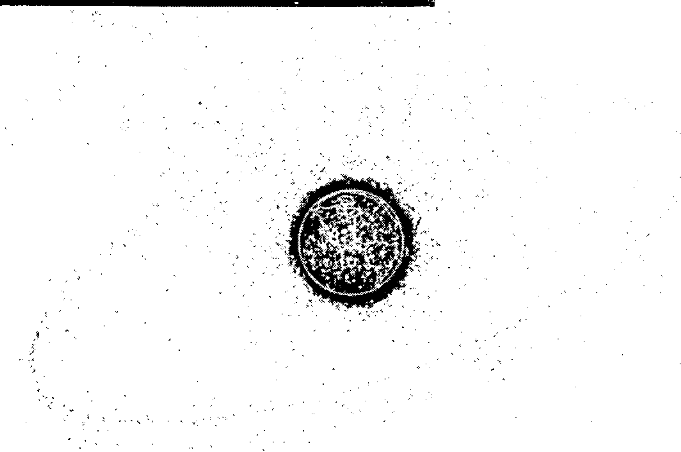


METEOROID/DEBRIS EFFECTS



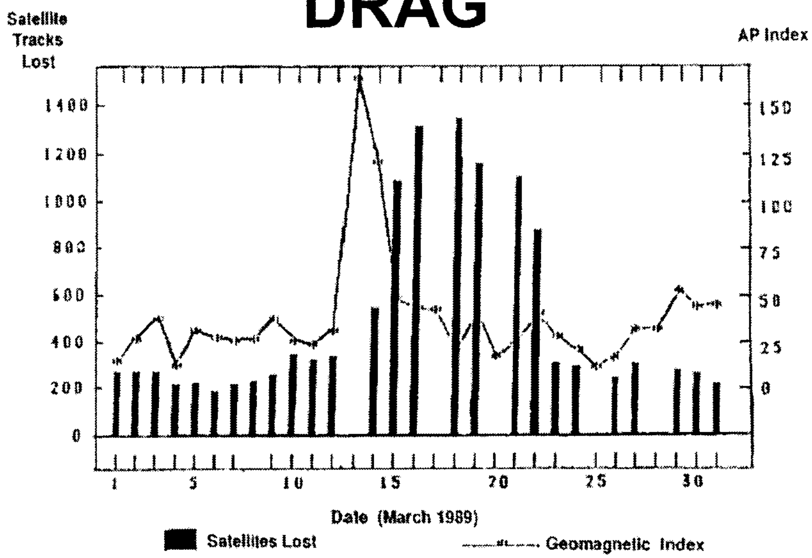




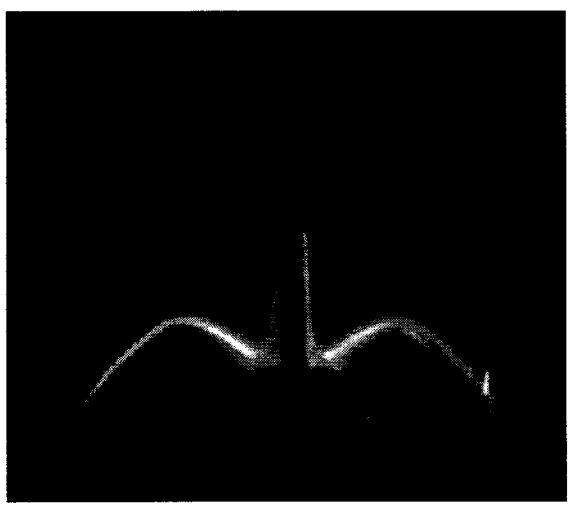


ATMOSPHERIC EFFECTS

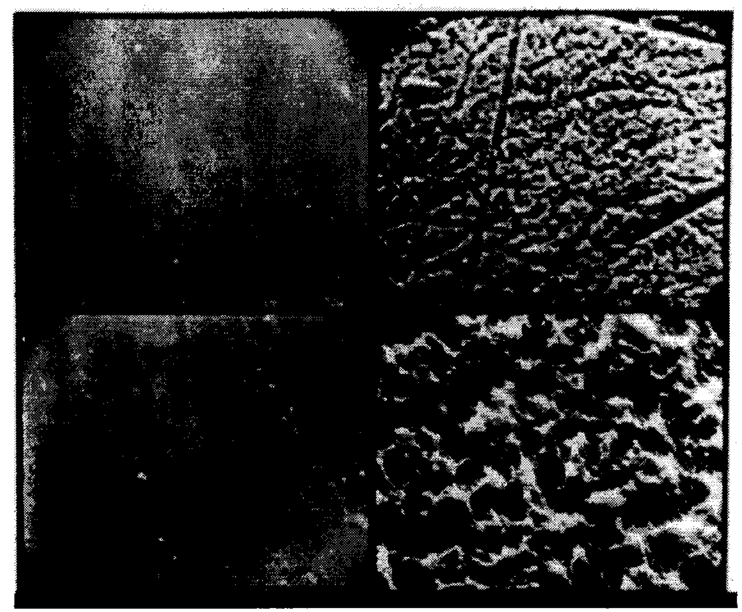
DRAG



GLOW



STS-3/CMP THERMAL BLANKET



OXYGEN EROSION

JPL INTERPLANETARY MISSION EXPERIENCE

VOYAGER

DESIGN:

- Mostly redundant
- Large design margins
- All circuits designed to operation from -20°C to +75°C in radiation environment of 60 krads and de-rated for life (10% to 25%) and minimum EEE parts specification
- Part electrical stress minimized
- Junction temperature < 110°C when box is at qualification temperature of 75°C or < 35°C rise
- Fault protection software (4k memory)

Courtesy T. Gavin, JPL

JPL INTERPLANETARY MISSION EXPERIENCE

VOYAGER

DESIGN ANALYSIS:

- Rigorous pre-launch failure analysis
- Failure Modes Affect Analysis on interfaces and secondary functions
- PRA to support design trades for cross strapping
- WCA, power supply and power bus stability analysis

TEST PROGRAM

- Qualification S/C –PTM
- Dynamics, acoustic–STV-EMC At spacecraft level
- Dynamics, temperature at box level
- 1500 operating hours – achieved

Courtesy T. Gavin, JPL

VOYAGER EEE PARTS APPROACH

First significant electronic parts radiation hardening effort

- CMOS (RCA 4000 series)
- National Linear Devices

Large number of grade B+ screened parts

No random piece part failures - true for 24-1/2 years

All failures in engineering systems have been accounted for

- Receiver fuse - 1978, single cell memory failures (5-10) from 1978-1985
- Solid state S-band transmitter-1978
- Flight Data System memory-1985
- Multiple mechanical difficulties

All electronic part failures traced to inadequate parts qualifications screening or design applications

- Oxide failures in CMOS
- Polyimide capacitor
- S-band power amplifier transistor

Courtesy T. Gavin, JPL

JPL INTERPLANETARY MISSION EXPERIENCE

GALILEO

CHANGES FROM VOYAGER:

- Class-S parts (semiconductors)
- ER parts - Passives
- 500 hrs. pre-delivery requirement to spacecraft
- 1000 hrs. in system test
- Better electrical piece part screens (margins over operating voltage)
- Block redundant
- Design margins same as Voyager (survived 500 krads 3x design)

RESULTS TO DATE:

- Operational for 13 years
- No EEE failures
- No redundancy utilization
- Some SBA faults
- Antenna deploymeant failure
- 750 krads total dose

Courtesy T. Gavin, JPL

CASSINI

CASSINI CHANGES:

- Class-S semiconductors-except Solid State Recorder
- ER parts - Passives
- Block redundant
- Minimized mechanical devices

RESULTS TO DATE:

- Launched October 15, 1997
- Stay tuned

Courtesy T. Gavin, JPL

JPL INTERPLANETARY MISSION EXPERIENCE

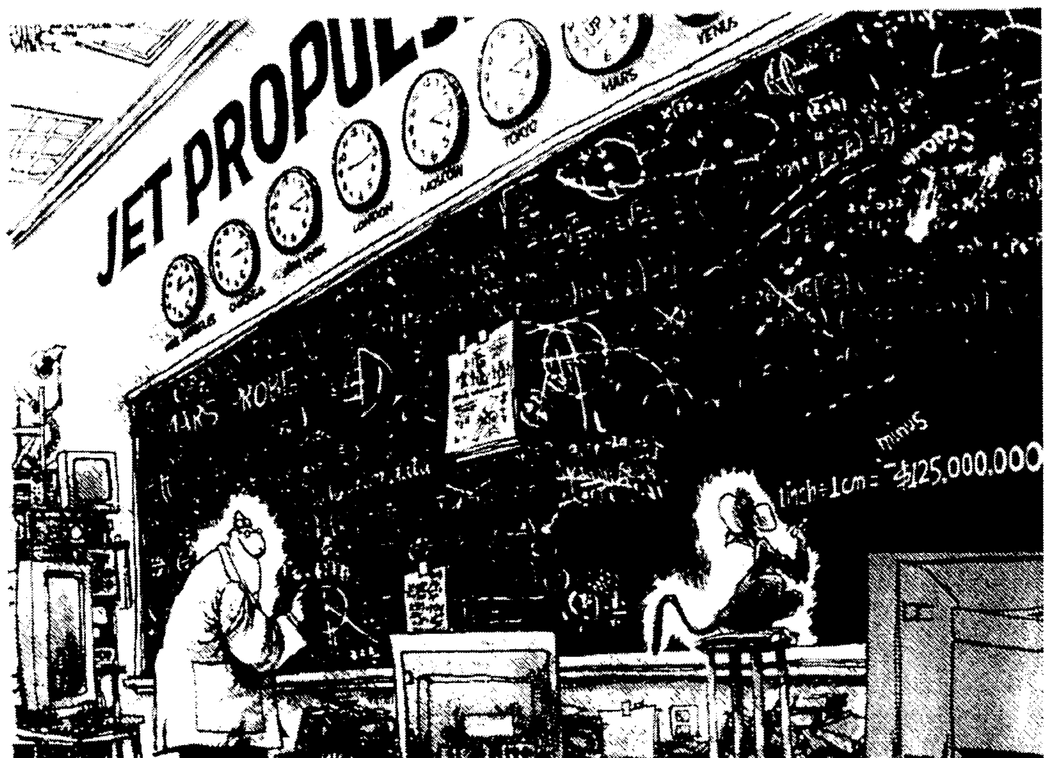
	Mission Life to Date (YRs)	Redundancy/SPF	Margins	New Technology	EEE Parts	Redundancy Utilization
Voyager	25	Functional, cross strapped/block	JPL STD Voyager	S/W F.P + X-Band, CMOS, radiation hard	B+	Yes
Galileo	13	Cross strapped/ block	JPL STD Voyager	Dual spin CCD, Rad 6000 processor	B+	No
Cassini	4+	Cross strapped/ block	JPL STD Voyager	Solid state recorder, HRG, DST, SSPS, ASCIS	B+	No
MGS	7	Block	Std	None	B+	No
Mars '01	1	Block	Std	None	B+	No
Stardust	3	Block	Std	None	B+	No
Genesis	0.75	Block	Std	None	B+	No
DS-1	3 (turned off)	Func/Single string	Std	SDST	B+	Yes-Func
Pathfinder	1	Single string	Std	Airbags, Rad 6000 processor	B+	No

Courtesy T. Gavin, JPL

However, Sometimes We Fail…….

Mars Climate Orbiter

MICHAEL RAMIREZ



"AN OUNCE OF PREVENTION IS WORTH A KILOGRAM OF CURE….."

JPL INTERPLANETARY MISSION EXPERIENCE

JPL SECRETS TO LONG-LIFE

- Wide performance margins
- Strong environmental test program
- All missions had some workmanship failures in test that would have been mission limiting
- Maximize operating hours > 1500 hours prior to launch
- Block redundancy
- Grade B parts minimum (note: DPA saves money)
- Software design flexibility

Courtesy T. Gavin, JPL

Recommended reading:

DESIGN, VERIFICATION/VALIDATION AND OPERATIONS PRINCIPLES FOR FLIGHT SYSTEMS

JPL D-17868
REV A
NOVEMBER 15, 2000

This document addresses the principles followed in the formulation and implementation processes for JPL Flight Projects, including hardware and software design/development, margins, design verification, Safety and Mission Assurance and flight operations control and monitoring. These principles apply to spacecraft, and to major payloads/instruments. They apply to system contractor/partner as well as in-house/ sub-system project implementation modes.

Courtesy T. Gavin, JPL

Recommended reading:

Long Life/High Reliability Design and Test Rules Study Report

JPL D-9899
Rev. 2
JULY, 1999

This study report was prepared by a team effort in response to the Cassini Project's need to identify basic rules for design and test of hardware required to function for very long lifetimes. High reliability design and test rules are included to the extent that they relate to long life. The study team provided extensive support, and consensus was reached after considerable discussion of each rule.

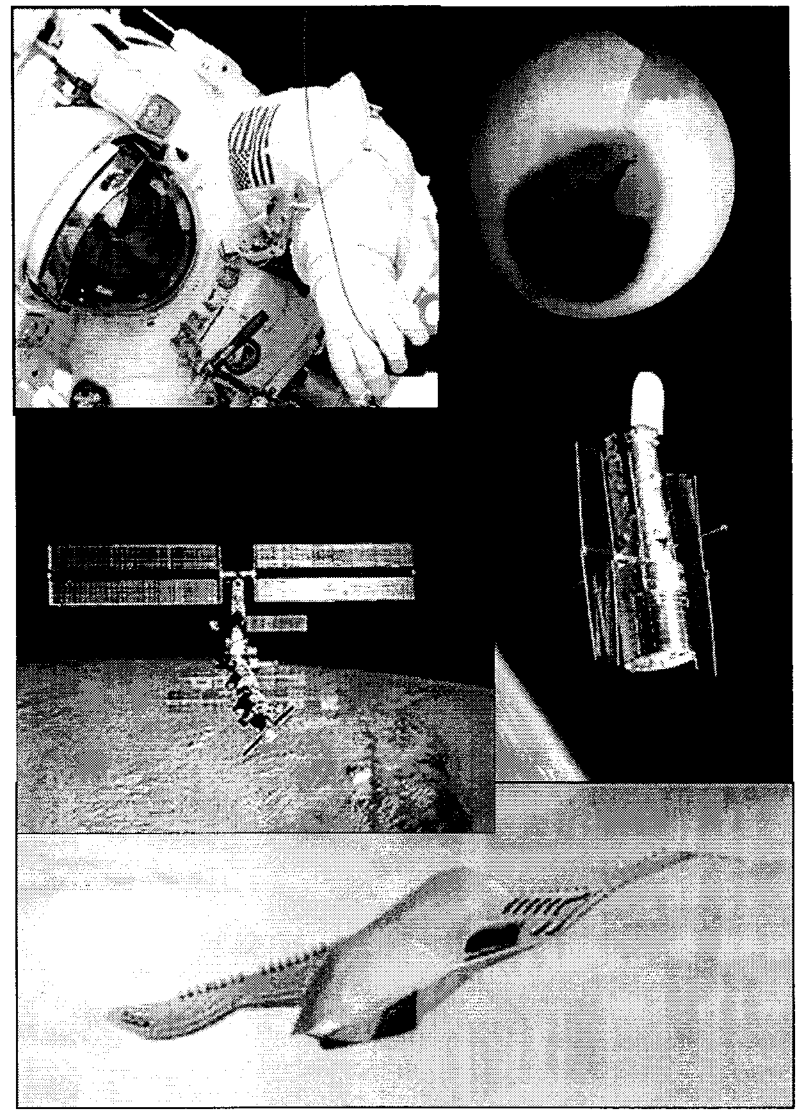
Courtesy T. Gavin, JPL

General "Rules" for Ultra-Reliability and Long-Life….

- **Standardization – Use common equipment where possible (batteries, high data rate transmitters, DC/DC converters, etc.)**
- **Processes – Ultra-Reliability may not be achievable, but ten-fold improvements may be**
- **Better use of available tools – Lessons Learned, GIDEP, Reliability Software Tools**
- **Implementation – Implement reliability early in design concept phase**
- **Education – Educate on proper application of EEE and NASA Standard Preferred Parts as well as the benefits of high reliability parts and the use of the EPIMS Database**
- **Reviews – Engineering peer reviews to prevent design errors**
- **Technologies – Use new technologies that result in lower part counts and connections, fewer moving parts, simple, robust designs, and improve reliability of solar arrays, batteries, gyroscopes & wheels**

Summary

- The status quo just won't cut it.
- As missions and systems become more complex and costly, increased capabilities in reliability are necessary to assure safety and mission success and to recoup sunk costs.
- Ultra-Reliability and Long-Life will enable us to achieve our ambitious goals.



And Finally.....

THINGS THAT GO BUMP IN THE NIGHT........

"AND WHAT, OH WISE ONE, SHOULD WE DO......?"

- CONCENTRATE ON EARLY DETECTION, PREVENTION, AND MITIGATION
- TEST, TEST, TEST, TEST, TEST, TEST,.....................
- "TRUST BUT....INSPECT AND VERIFY--IN PERSON IS BEST!!!"
- UTILIZE YOUR MISSION ASSURANCE, RELIABILITY, SAFETY, AND QUALITY ASSURANCE PERSONNEL"

AND FINALLY:

- GARLIC CLOVES SHOULD BE INCLUDED ON ALL INTERPLANETARY SPACECRAFT (JUST IN CASE)

QUESTIONS TO CONSIDER FOR THE FUTURE

- **Do we know, given the current SBIRS-Low architecture strategy, what role Ultra-Reliability and Long-Life will play?**
- **Is replenishment the solution or will high costs per unit/per launch be the drivers?**
- **How do we plan to incorporate Lessons Learned and "fly as you test" into the architecture design?**

Backup Material

JPL

SIMPLE APPROACH TO ENVIRONMENT MITIGATION

STEP 1
ENVIRONMENTS VS INTERACTIONS

INTERACTIONS

ENVIRONMENTS	CUMMULATIVE RAD EFFECTS	SINGLE EVENT UPSETS	LATCH-UP	SURFACE CHARGING/WAKES	INTERNAL CHARGING	POWER LOSS	VxB	SURFACE DAMAGE	CONTAMINATION	GLOW	PARTICLE IMPACTS	TORQUES	THERMAL
NEUTRAL ATMOSPHERE													
E,B FIELDS				ES			e					E	
ULTRAVIOLET RADIATION				S				S	S				
INFRARED RADIATION								S					S
SOLAR WIND PLASMA				s								s	
IONOSPHERIC PLASMA				S		e	e						
AURORA PLASMA				E									
TRAPPED RADIATION	E	Ep	E		E								
GALACTIC COSMIC RAY		P	p										
SOLAR PROTON EVENTS	Sp	Sp	Sp										
METEOROIDS						s					SEP	S	
DEBRIS											s		

Legend: X = Major Effect; x = Observable Effect; E,e = Europa; P,p = Pluto Express; S,s = Solar Probe

STEP 3
DESIGN OPTIONS VS FACTORS

FACTORS

DESIGN OPTIONS	COST	WEIGHT	POWER	COMPLEXITY	RELIABILITY	AVAILABILITY	USABILITY	SPECIAL ISSUES (RPS)
SHIELDING	3	3	2	3	3		3	3
POSTIONING	2	1	1	3	1	2	3	3
MATERIAL PROPERTIES	3	2		2	2	3	1	3
ELECTRONIC PARTS	2			2	3	2	3	
CIRCUIT/SYSTEM DESIGN	3	2	3	3	3	2		3
GROUNDING	2		2	3	2		2	
TRAJECTORY	1		2	2	2			3
OPERATIONAL PROCEDURES	3		1	2	2		3	3
CONSTRUCTION METHODS	1		2	3	2		1	2

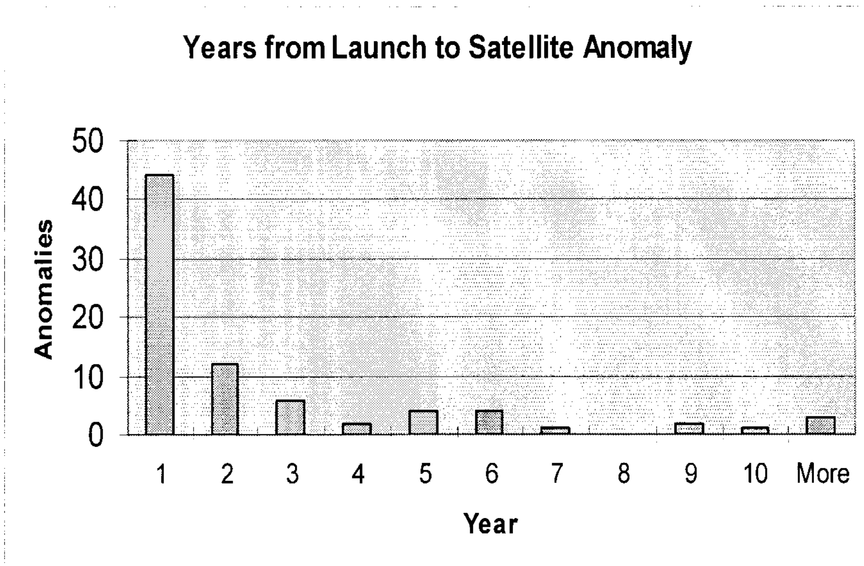
Legend: 3 = Major Effect; 2 = Observable Effect; 1 = Minor Effect

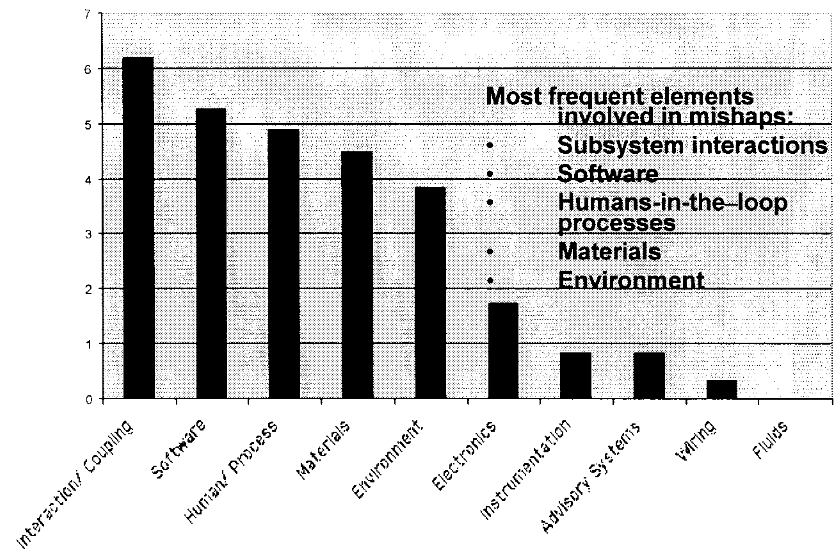
STEP 2
INTERACTIONS VS DESIGN OPTIONS

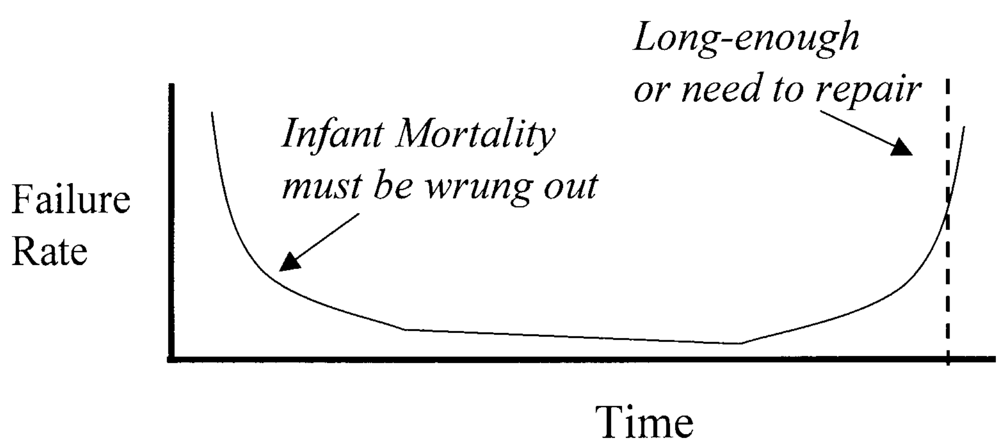
DESIGN OPTIONS

INTERACTIONS	SHIELDING	POSTIONING	MATERIAL PROPERTIES	ELECTRONIC PARTS	CIRCUIT/SYSTEM DESIGN	GROUNDING	TRAJECTORY	OPERATIONAL PROCEDURES	CONSTRUCTION METHODS
CUMMULATIVE RAD EFFECTS	3	3	2	3	3		3	1	
SINGLE EVENT UPSETS	2	1		3	3		2	2	
LATCH-UP	2	1		3	3		2	2	
SURFACE CHARGING/WAKES	3	3	3	1	3	3	3	2	3
INTERNAL CHARGING	3	2	3	2	3	3	3	2	3
POWER LOSS	3	3	3						1
VxB		3				3	2		
SURFACE DAMAGE		3	3						1
CONTAMINATION	3	3	3			2		2	3
GLOW		3					2	3	1
PARTICLE IMPACTS	3	3	2				3		
TORQUES		3	3				2	3	
THERMAL	3	3	3				1	3	

Space Mission Reliability Demographics





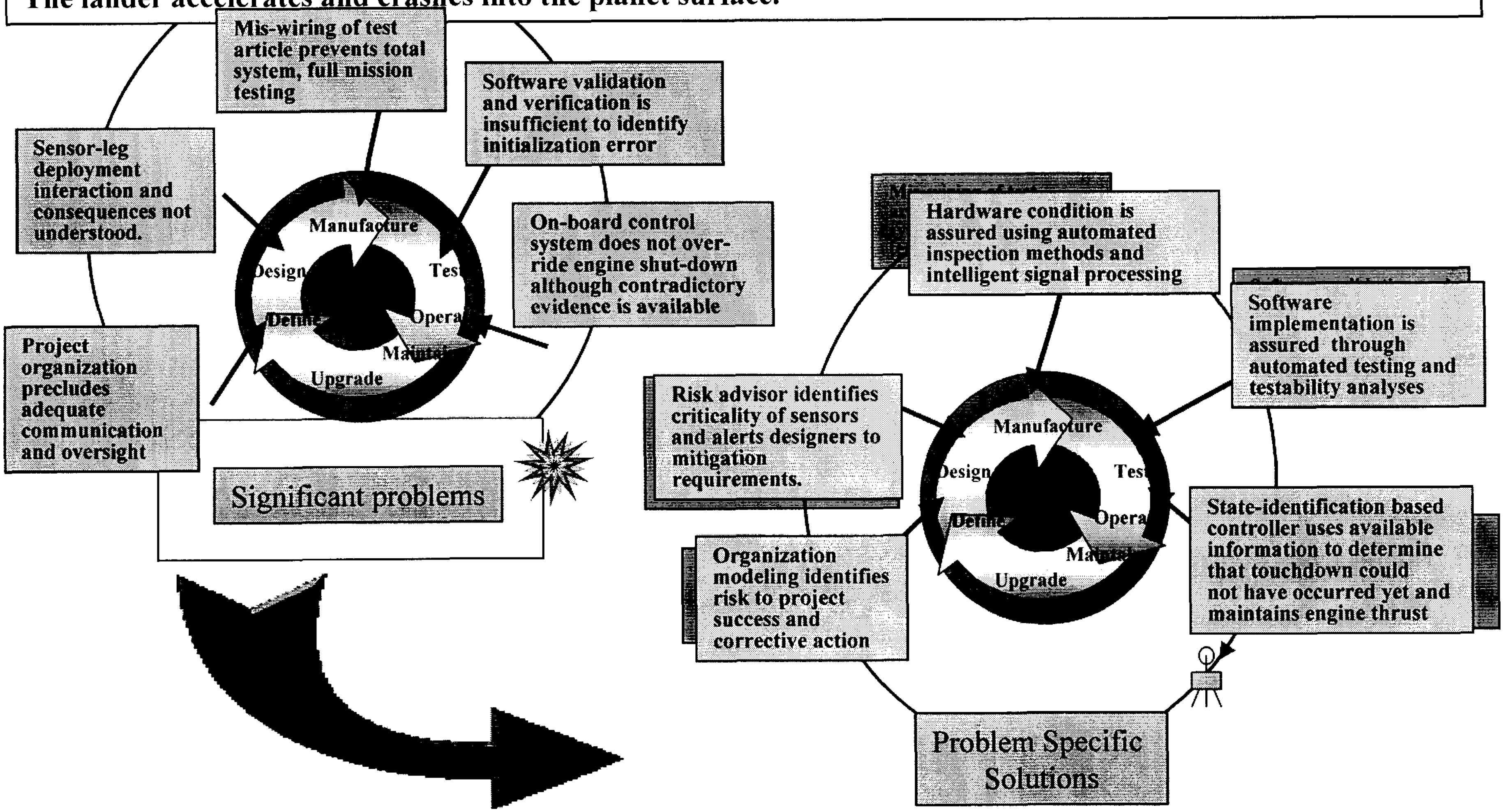


Representative Failures

Mishap	What Happened	Primary Cause
Progress-Mir (6/25/97)	Collision of Progress into Mir during remote manual docking procedure.	Multiple contributing causes: lack of accurate position and velocity information, lack of proper training, extreme crew stress
Lewis Spacecraft (8/26/97)	Loss of spacecraft atittude control due to flat spin that pointed the solar arrays edge-on to the sun	Design error in the Attitude Control System; failure to monitor spacecraft during initial operations
Solar Heliospheric Observatory (6/25/98)	Contact lost during period of calibration and reconfiguration	Loss of attitude due to operational errors, failure to monitor, and bad decisions
Wide-Field Infrared Explorer (3/4/99)	Uncontrolled tumbling and loss of telescope cryogen after planned venting of hydrogen tank	Transient during pyro box power-up caused premature separation of telescope cover
Mars Climate Orbiter (9/23/99)	Destroyed while entering Martian atmosphere on steeper than expected entry trajectory	Failure to use metric units in ground software trajectory models
Mars Polar Lander (12/3/99)	Unable to re-establish contact after entry, descent, landing	Premature shutdown of descent engines due to spurious touchdown indication as legs deployed

Case Study: Mars Polar Lander

Sensors in the lander's legs send false positive signals upon leg deployment. Control software incorrectly retains the initial sensor signals and terminates engine thrust when control is enabled at 40 meters altitude. The lander accelerates and crashes into the planet surface.



Observations

- Ultra-Reliability means the development of materials, components, systems, and networks that are designed to withstand the peak stresses and wear of long-term missions.
- Sufficient failure tolerance, health monitoring, and on-board diagnostics are needed to drastically reduce the probability that any single failure can result in loss of mission objectives.
- Reliability prediction and risk assessment methodologies must be applied to "navigate" through a large number of design options for complex systems on the way to Ultra-Reliability.
- A highly significant reduction in the human error rate is needed to attain Ultra-Reliability for complex systems.
- Ultra-Reliability will require Research and Development for new technology over a long period period of time with sustained effort.

Observations

- Challenges in characterization/simulation/validation
  - Predicting/demonstrating long-life or ultra-reliability
  - Identifying all life-limiting items
  - Unknown/uncertain environments or conditions can cost $$$!
  - Operations in extreme environments
  - Mechanism reliability
  - Earlier, higher fidelity simulations and demonstrations
- Value of standardization
  - Re-use provides heritage, lower costs
  - Modular, repairable designs
  - Well-known, previously characterized interfaces
  - Accumulated reliability/life information
  - Which standards and how long versus obsolescence

Observations

- Long-Life implies we need to capture information completely and must maintain expertise which may have long since become obsolete
- Long-Life implies more fuel or more efficient fuel
- More fuel implies
  - Bigger/better launch vehicles, or,
  - Smaller spacecraft/payload, but,
  - Physics constraints (e.g. aperture, planetary positions)
- Smaller spacecraft/payloads imply
  - Less science, or swarms of spacecraft
  - Less redundancy, but more repairability, or
  - More miniaturization, but less component reliability versus less complex system
  - Environmental test savings
  - More standardization (swarms) implies more modularity and associated savings ('high volume' builds, reduced downstream repair costs)
- Swarms of spacecraft imply
  - More objects to track/monitor/control, or
  - More autonomy, but qualification of autonomy/infrastructure

Observations

- COTS
  - Desirable features: off-the-shelf, more capabilities, standards
  - But, largely unknown long-life/extreme environment performance
  - Unknown process adequacy versus lot-to-lot variations
  - Industry not driven by NASA/DoD
  - Where have all the rad-hard lines gone?
- Autonomous operations
  - Self-test, self-repair offers a lot of promise
  - Reduces mission operations costs
  - Increases software development costs
  - Significant reduction in telemetry (reduced problems for ground intervention, send-mode only operations) good for DSN loading issues
  - Less impact on mission design to ensure continuous link
  - But how to develop/test autonomous software? Enough infrastructure?
  - How to to ensure the intelligent part is fault-free?