FA **_Failure Analysis_**

Engineering Services & Technology Licensing

Presents

Shifting Risk to Satellite and Launch Vehicle Builders

by Dr. Len Losik

Failure Analysis
Engineering Services

- *Reason for Presentation*
  - *Educate satellite, spacecraft and launch vehicle suppliers and customers that have been designing, building, testing and purchasing space vehicles for over 50 years, that there is a faster, cheaper more reliable way*

NASA slogan “faster, better, cheaper”

Failure Analysis

Engineering Services

- *After 50 years of suffering major losses from infant mortality failures, a spike in infant mortality failures since 1999, and with no expected improvement in overall launch vehicle and satellite reliable, private insurance underwriters are looking for relief*
  - *Insurance underwriters want vehicle builders to assume risk from infant mortality failures*
    - *Space vehicle builders are risk, profit and schedule driven*
      - *What's the payback for vehicle builders accepting more risk?*
        - *None*
      - *What's the impact to vehicle builders accepting more risk from infant mortality failures?*

Failure Analysis

Engineering Services

- *Increase risk of decreasing profit after contract has been completed*
  - *Vehicle contract profit margins don't support increase risk of reducing profits*
- *In-orbit incentives work, they motivate technical and programmatic decisions to increase the likelihood of earning extra profit on the contract*

- *To make risk acceptable, satellite customers are willing pay high premium for space insurance*
  - *Current vehicle contracts only requires "best effort"*
    - *What's "Best Effort"*

Failure Analysis

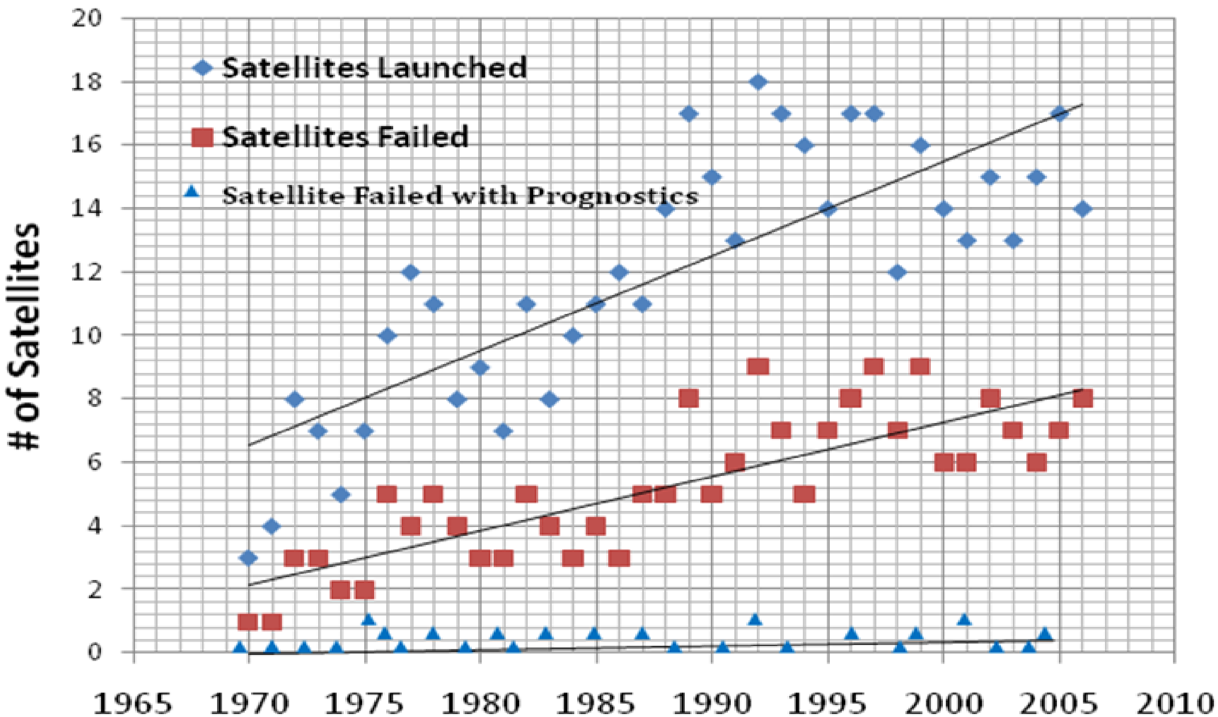
Engineering Services

- *To mitigate risk for satellite owners, the commercial space insurance industry evolved*
  - *High stakes gambling, 1 policy out of 4 pays out claim*
  - *Current insurance premiums for insuring launch, first year of use is around 20%-25% total cost of launch vehicle, satellite and satellite lifetime earning potential*
    - *Resulting in upfront premiums from $15M to $75M*
      - *What can be done to improve vehicle reliability for $15 to $75M?*

Failure Analysis

Engineering Services

- *Little Change in 35 Years in Infant Mortality Failure Rate Using Current Vehicle Diagnostic Analysis and Acceptance Testing*



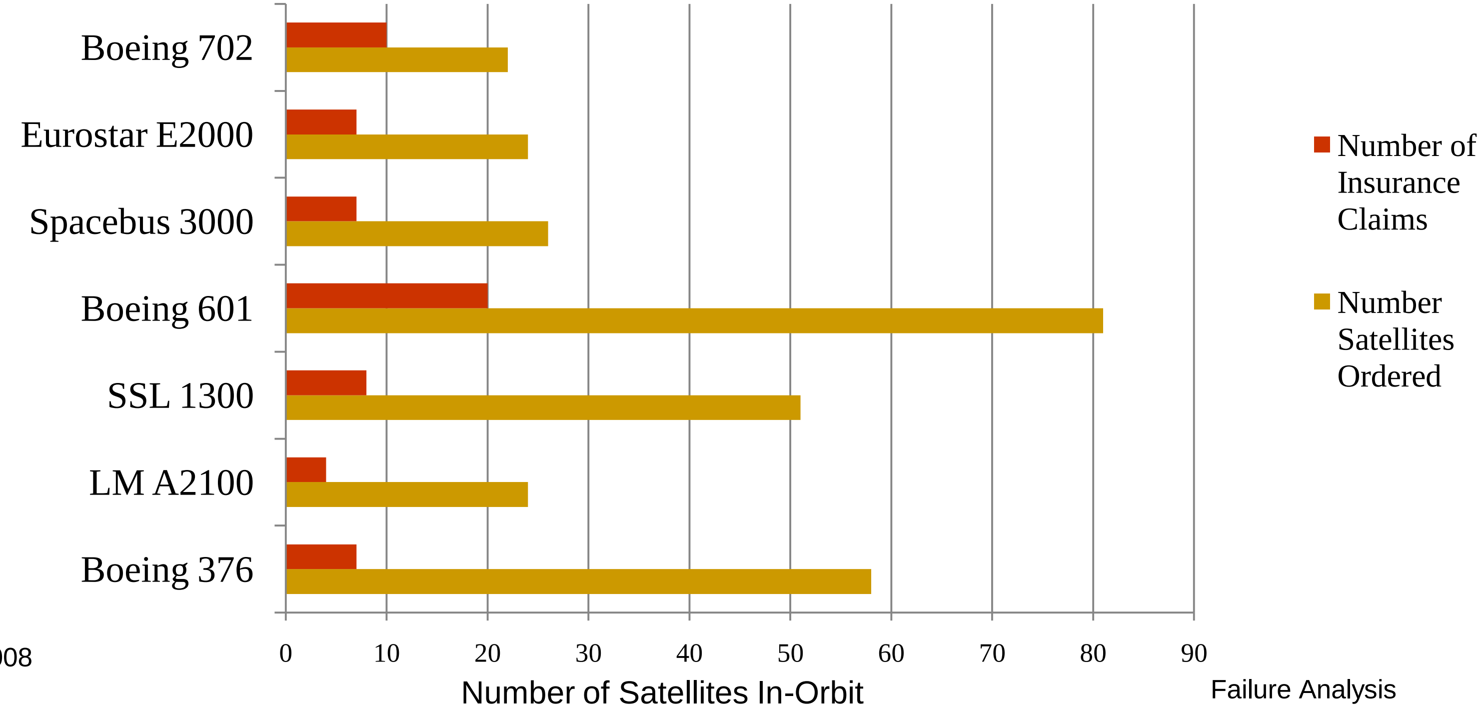
Satellite Times

Number of Launches and Satellite and Launch Vehicle Infant Mortality Failures

Failure Analysis

Engineering Services

- *Commercial Satellite Bus Infant Mortality Rate*
  - *Using best commercial practices, commercial satellite builders may not subject piece-parts to uniform acceptance testing*



Failure Analysis

Engineering Services

- *Commercial Satellite Infant Mortality Failures from 1998 to 2004*

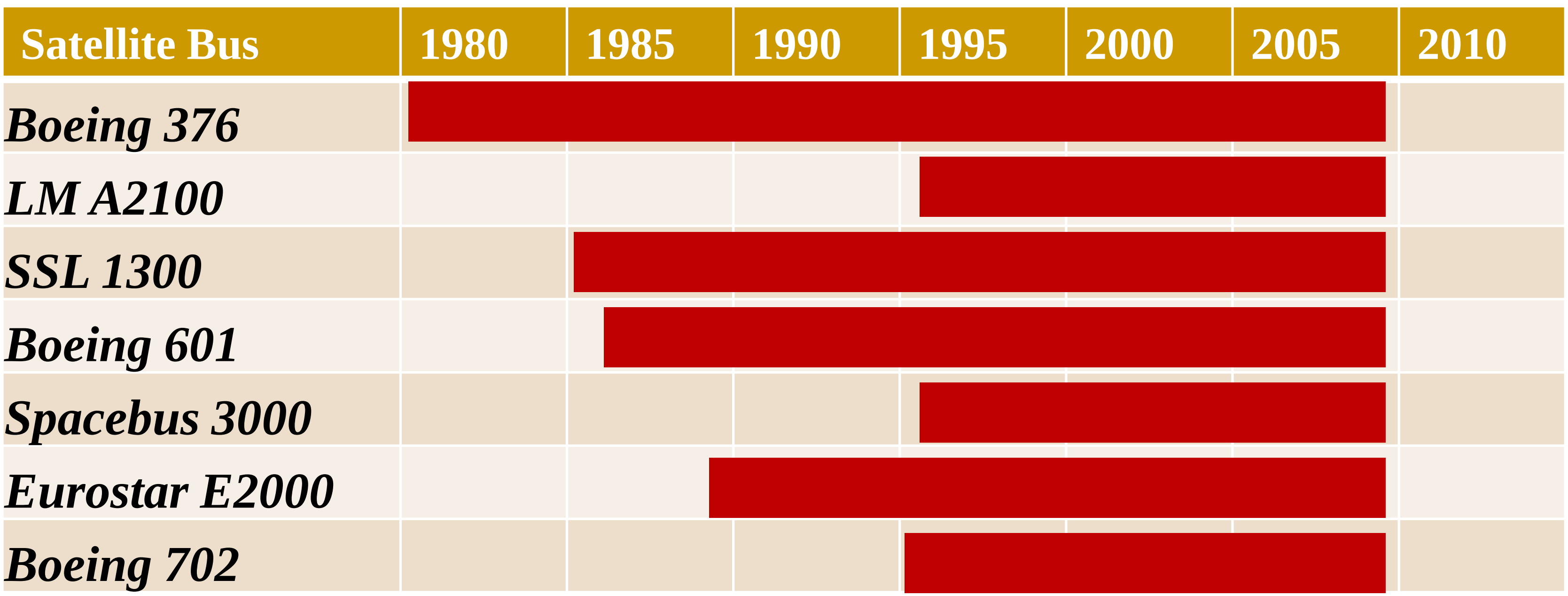
Satellite Bus Name	**Infant Mortality Failure Rate**	**Claims (US$)**
Boeing BSS 376	11%	$125M
Lockheed Martin A2100	17%	$375M
LORAL LS 1300	24%	$791M
Boeing BSS 601	26%	$1,468M
SPACEBUS 3000	28%	$326M
EUROSTAR E2000	32%	$60M
Boeing BSS 702	75%	$1,040M
Totals	***24% (avg)***	***$4,815M***

Frost & Sullivan

Failure Analysis

Engineering Services

- Commercial Satellite Bus Product Line Life

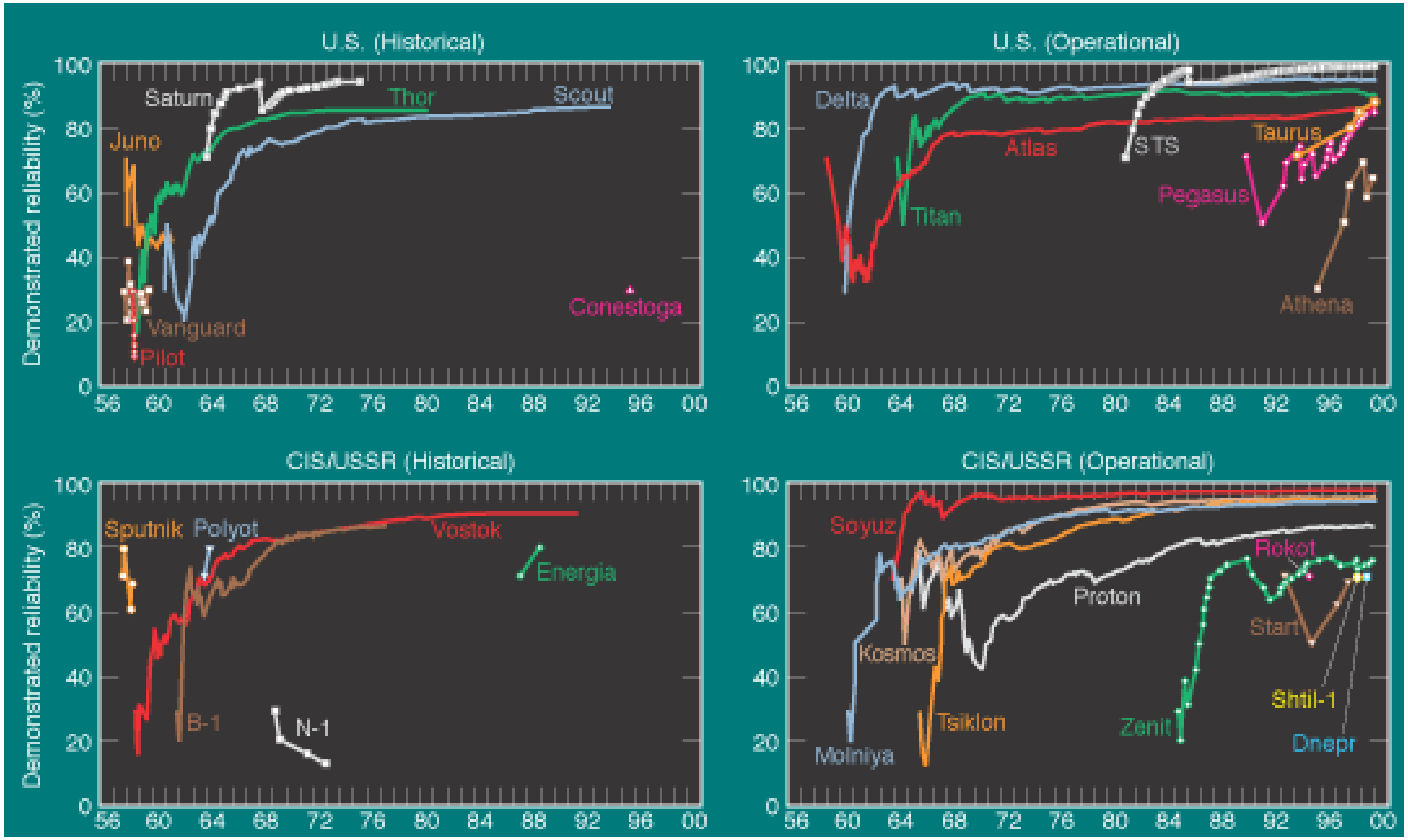


Failure Analysis

Engineering Services

- *Launch Vehicle Success from 1955 to 2000*

- *Launch Vehicle Demonstrated Reliability and Using Diagnostics to Identify Launch Vehicle Failures*



Aerospace Corporation

Failure Analysis

Engineering Services

- *Problem: Spacecraft and launch vehicles fail catastrophically within the first year of use at 24% average rate using diagnostics and acceptance testing for stopping infant mortality failures*
  - *With no other remedy to the high infant mortality rate seemingly possible, space insurance underwriters see space vehicle builders accepting risk after satellite is delivered as solution*
- *Solution: Generate/identify the information necessary to predict what equipment is going to fail within the first year of use and repair/replace it while it is still on the ground*

Failure Analysis

Engineering Services

- *What information/processes are used to eliminate equipment that may cause infant mortality failure?*
  - *Equipment/vehicle acceptance testing*
  - *Piece-part reliability analysis*
  - *Equipment use history*
  - *Equipment failure history*
  - *Changes in company personnel/management*
  - *Changes in design, manufacturing/test process*
  - *Changes in piece-parts*

Failure Analysis

Engineering Services

- *What information is necessary to identify equipment that will suffer from an infant mortality failure?*
  - *Why does equipment fail?*
  - *What causes equipment to fail?*
  - *How does equipment fail?*
  - *When does equipment fail?*
- *Current understanding of the answers to these questions and current technology solutions to mitigate failures gives a demonstrated ~24% average infant mortality failure rate for the past 50 years*

Failure Analysis

Engineering Services

- *Results of Use and Research of Failure Prediction Techniques by Failure Analysis:*
  - *The answer to the questions:*
    - *Why does equipment fail?*
      - *Electrical*
        - *Piece-part normal/premature aging, causing unacceptable electrical stresses on many piece-parts from circuit response*
        - *The actual piece-part that is aging prematurely may not be the piece-part that fails, depends on circuit transient response and the electrical stresses that each piece-part gets during transients*
      - *Mechanical:*
        - *Mechanical assembly fail from normal/premature aging of moving parts developing unacceptable levels of friction and stiction that cannot be overcome*
    - *What causes equipment to fail?*
      - *Electrical*
        - *Transient circuit response as piece-parts age normally/prematurely causing undesirable electrical piece-part stresses*

Failure Analysis

Engineering Services

- *Results of Use and Research of Failure Prediction Techniques by Failure Analysis:*
  - *What causes equipment to fail? (cont'd)*
    - *Mechanical*
      - *A normal/unexpected change in the mechanical system*
  - *How does equipment fail?*
    - *Electrical/Mechanical*
      - *In a methodical process that is identifiable, observable, predictable and manageable*
  - *When does equipment fail?*
    - *Electrical/Mechanical*
      - *Equipment fails after a dynamic process that can be used to predict the day of failure.*
  - *Development of algorithms that illustrate the information in data to identify space equipment that is going to fail*

Failure Analysis

Engineering Services

- *All piece-part reliability analysis is based on the random nature of piece-part failures*
  - *If piece-parts aren't failing from random failures but are being driven to failure by forced transient circuit response from circuit changing piece-part performance changes, all piece-part reliability analysis is invalid*
    - *Need reliability analysis for predicting the likelihood of piece-parts that will change in performance enough to cause transient circuit response large enough to drive piece-parts in the circuit to failure*

Failure Analysis

Engineering Services

- *Failure Analysis' Data-Driven Algorithms*

Algorithm	Flight Equipment Supplier Factory	Satellite Factory	LV Factory	Launch Pad	Mission Control	Mission Control (CCSDS)
Data Integration	X	X	X	X	X	X
Baseline Analysis	X	X	X	X	X	X
Change Analysis		X	X	X	X	X
Comparison Analysis	X					
Data Mining		X	X	X	X	X
Day of Failure	X	X	X	X	X	X
Digital Processing					X	
Discrimination Analysis	X	X	X	X	X	X
Mathematical Modeling	X	X	X	X	X	X
Multi-variant Limit Analysis	X	X	X	X	X	X
Rate Change Analysis		X	X	X	X	X
Remaining Usable Life	X	X	X	X	X	X
Statistical Sampling		X	X	X	X	X
State Change Analysis		X	X	X	X	X
Super Impositioning		X	X	X	X	X
Virtual Telemetry						
Super Precision					X	X
Telemetry Authentication					X	
Virtual Telemetry	X	X	X	X	X	X
Data Base Creation					X	
Data Integration	X	X	X	X	X	X

Failure Analysis

Engineering Services

- *Predicting Failures Is Not Acceptable Engineering/Management in Space Industry*
  - *In 1983, on the Boeing/Air Force Global Positioning System, after completing 25 years of failure analysis using diagnostics on in-orbit satellite equipment and learning what information to use to predict failures across all GPS satellite subsystems accurately and reliably, Boeing GPS Systems Engineering Management ordered a to stop predicting failures on GPS satellites*
    - *Result: NAVSTAR 5 satellite failed catastrophically within weeks of the order, suffering from a dual, reaction wheel failure (predicted but not identified)*

NAVSTAR 5

Reaction Wheel Assembly

Failure Analysis

Engineering Services

- *In 1986, Thiokol SRM Engineering predicted the "O" ring would fail during Challenger launch, Thiokol management over-road engineering's direction not to launch. Management didn't recognize predicting failures was possible, accurate and reliable*
  - *Result: Challenger failure/7 astronauts died*
- *In 2003, NASA management using diagnostics to determined with very high probability that no damage had occurred to Columbia's wing during launch by the main engine tank foam insulation and that there was no damage to repair*
  - *Result: Columbia destruction/7 astronauts died*

Challenger

Columbia

Failure Analysis

Engineering Services

- *Current satellite, spacecraft and launch vehicle industry reliability uses diagnostics to identify space equipment that has failed operating or changed in performance during factory test*
- *Diagnostics is the backbone of understanding equipment reliability, performance, verification, identification, isolation and root cause analysis of all modern electronic and electro-mechanical equipment*
- *Diagnostics includes:*
  - *Data analysis to identify equipment behavior and performance*
  - *Failure analysis to identify equipment that has failed*
  - *Root cause analysis to determine reason of failure*

Failure Analysis

Engineering Services

- *Diagnostics uses passive monitoring of testing activities derived from aircraft and rocket engine builders to collect flight data and evaluate test data after the test is concluded*
  - *The generation and recording of test data for analysis after the test and in the event a failure occurs and failure analysis is done after the test*
  - *Strange, high frequency response behavior in the data can be attributed to system/circuit noise*
  - *If nothing goes wrong during consecutive testing, reduce costs by reducing personnel and record the data for post test performance and failure analysis*

Failure Analysis

Engineering Services

- *After 28 years of predicting failures in equipment and research to understand the source of the information to predict failures, Failure Analysis answered the how, when, what and why equipment fails questions*
  - *Allowing equipment that's going to fail in the future to be identified and replaced/repaired during factory test, before launch*
  - *Research has shown that data is available and has been available in factory test data but requires algorithms to illustrate the information that identifies equipment that is going to fail in the future*
- *Many other industries have recognized that equipment failures can be predicted and the field of prognostics was created to further its use*
  - *The 1st IEEE Reliability Society Prognostic and Health Management (PHM) conference is sponsored by NASA Ames Research Center in Denver, CO 9/2008*

Failure Analysis

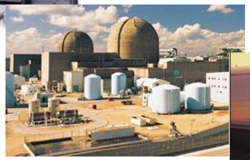
Engineering Services

- *Current Users of Prognostic Technology*
  - *NASA*
    - *Space Shuttle uses prognostics on the launch pad with tank pressure and temperature measurements*
    - *Ames Research Center is the NASA prognostic Center of Excellence (COE)*

  - *Air Force & Navy*
    - *Lockheed Martin F-35 Joint Strike Fighter*

  - *SUN Microsystems*
    - *High-end server families*

  - *Nuclear power plants*



  - *Boeing commercial aircraft programs*

Failure Analysis

Engineering Services

- *Prognostics (pro-active diagnostics) Technology*
  - *The next logical step in a dynamic/evolving process to improve equipment reliability*
    - *Includes all diagnostics and data analysis*
    - *Is the technology to identify equipment that is going to fail*
    - *Identifies future health and status of assets and has been realized by the military to be critical for system readiness*
    - *Various component/parts related prognostic techniques have been developed in laboratories, universities and industry*

Failure Analysis

Engineering Services

- *Prognostic Technology Shifts Liability for Reducing Infant Mortality Failures to Spacecraft and Launch Vehicle Builders*
  - *For the very first time in the space industry, there is a new understanding of equipment failure behavior and prognostic algorithms that illustrate the information necessary to identify equipment that is going to fail during launch and within the first year of use*
  - *After an infant mortality failure, prognostic algorithms can be used to go back to factory test data and identify the information vehicle builders missed after an infant mortality failure, identifying liability forcing an update to the "best effort" vehicle builders use*

Failure Analysis

Engineering Services

- *Telemetry Prognostics*
  - *Includes diagnostics to identify equipment that has failed*
  - *Uses active reasoning*
  - *The use of algorithms that illustrate the information to use to predict equipment that will fail from infant mortality failure*
  - *Actively monitor data to provide knowledge of whether a failure has occurred, is occurring or when a failure is likely to occur*
  - *All events are considered failure information until ruled out by research*
  - *Prognostician doesn't just stand by and watch failures occur, they stop them from occurring*
  - *Requires high skilled personnel - in-depth knowledge of what is being actively monitored is required*
  - *Identifies system readiness for successful deployment*
- *Telemetry Diagnostics*
  - *The use of algorithms to identify equipment that has failed or changed performance*
  - *Developed from ground test environment*
  - *Used for passively monitoring information*
  - *Record data and look at it later*
    - *After the fact response*
  - *Events are recognized but no action is taken*
  - *Diagnostician waits for predefined error message before taking action*
  - *Allows lower skilled personnel - doesn't require in-depth understanding of what's being monitored since data is evaluated post event*
  - *Most common approach throughout many industries*
  - *Inadequate for meeting today's customer expectations*

Failure Analysis

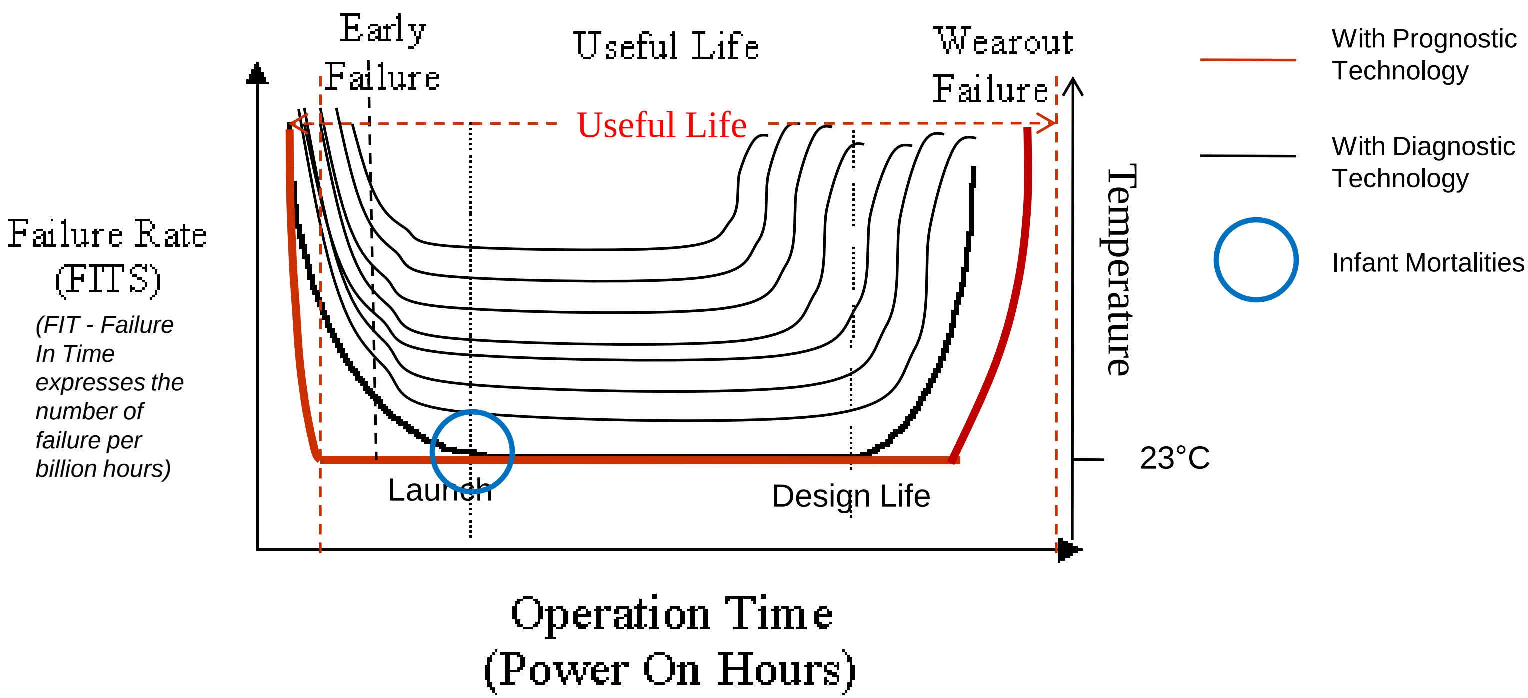
Engineering Services

- *Active Reasoning*
  - *Reduces fault detection time as well as improve the accuracy of fault diagnosis.*
  - *Evaluate symptoms continuously*
  - *Uses fault reasoning*
  - *Uses fidelity evaluation*
  - *Uses action selection*
  - *Takes passively observed symptoms as input and returns fault hypothesis as output.*
  - *Searching for the best fault explanation of the observed symptoms.*
  - *Event-driven fault reasoning technique improves the robustness of fault localization system by analyzing lost, positive and spurious symptoms.*
  - *Assumes each event is a failure precursor*
- *Passive Reasoning*
  - *Evaluates symptoms after the fact*
  - *Spurious symptoms misleads fault localization analysis.*
  - *Spurious symptoms are also regarded as observational noise*
  - *Depends on monitoring agents to detect and report abnormality using alarms or symptom events*
  - *After the fact search for root faults based on the observed symptoms*

Failure Analysis

Engineering Services

- *Prognostics Significantly Increases Usable Life of Equipment*



Traditional Reliability Bathtub Curve

Failure Analysis

Engineering Services

- *Prognostic Approaches*
  - *Data-driven – Algorithms that use real-time and stored data to determine remaining usable life for equipment*
    - *Generic, equipment independent*
    - *Well suited for low volume aerospace equipment*
    - *In-expensive*
  - *Model-based – Uses experts to define future normal behavior well in advance*
    - *Suited for high volume products such as consumer electronics*
    - *Well suited for pattern recognition software*
    - *Well suited for steady-state equipment behavior*
    - *Expensive*
  - *Hybrid*

Failure Analysis

Engineering Services

- *Implementation of Prognostics*
  - *Piece-part suppliers integrate prognostic technology for self-prognosis and makes the information available*
  - *Box/unit level suppliers provide the information*
  - *Vehicle level prognostics*
  - *Replacement or addition to reliability improvement from complex and expensive man-rating programs*

Failure Analysis
Engineering Services

- *How to Leverage Prognostic Technology to Stop Satellite and Launch Vehicle Infant Mortality Failures*
  - *Use prognostic algorithms with current test data generation/collection systems*
  - *Expand future equipment requirements to include prognostics*
  - *During equipment and vehicle design, manufacture, acceptance testing, identify equipment that has failed (prognostics) and are going to fail (prognostics)*
  - *Manage equipment failures*

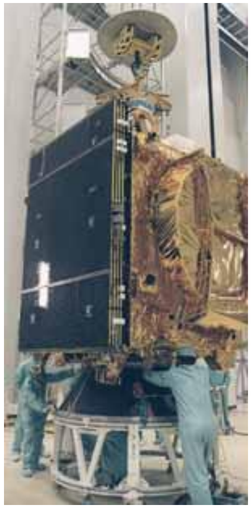
Failure Analysis

Engineering Services

- *Contributions in reducing vehicle production costs & schedules using prognostics for satellites and launch vehicles*

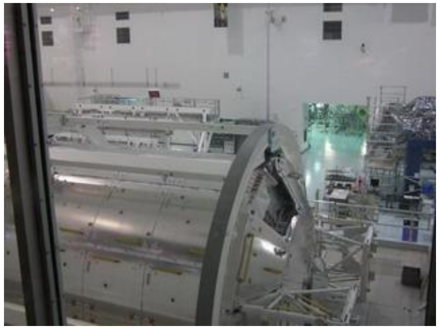
Equipment Manufacturing

Up to 10%



Satellite I&T

Up to 40%



Missile/Launch Vehicle I&T

Up to 40%

Launch Pad Integration

Up to 10%

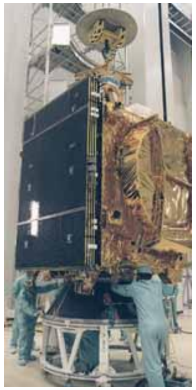
Failure Analysis

Engineering Services

- *Contribution to increasing equipment/vehicle reliability using Telemetry Prognostics*

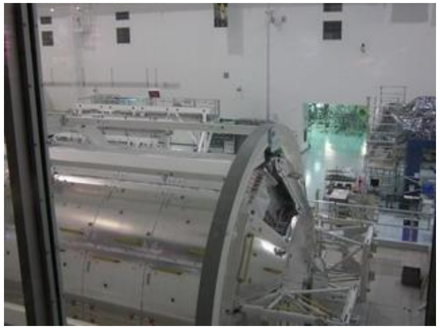
Equipment Manufacturing

Up to 20%



Satellite I&T

Up to 20%



Missile/Launch Vehicle I&T

Up to 20%

Launch Pad Integration

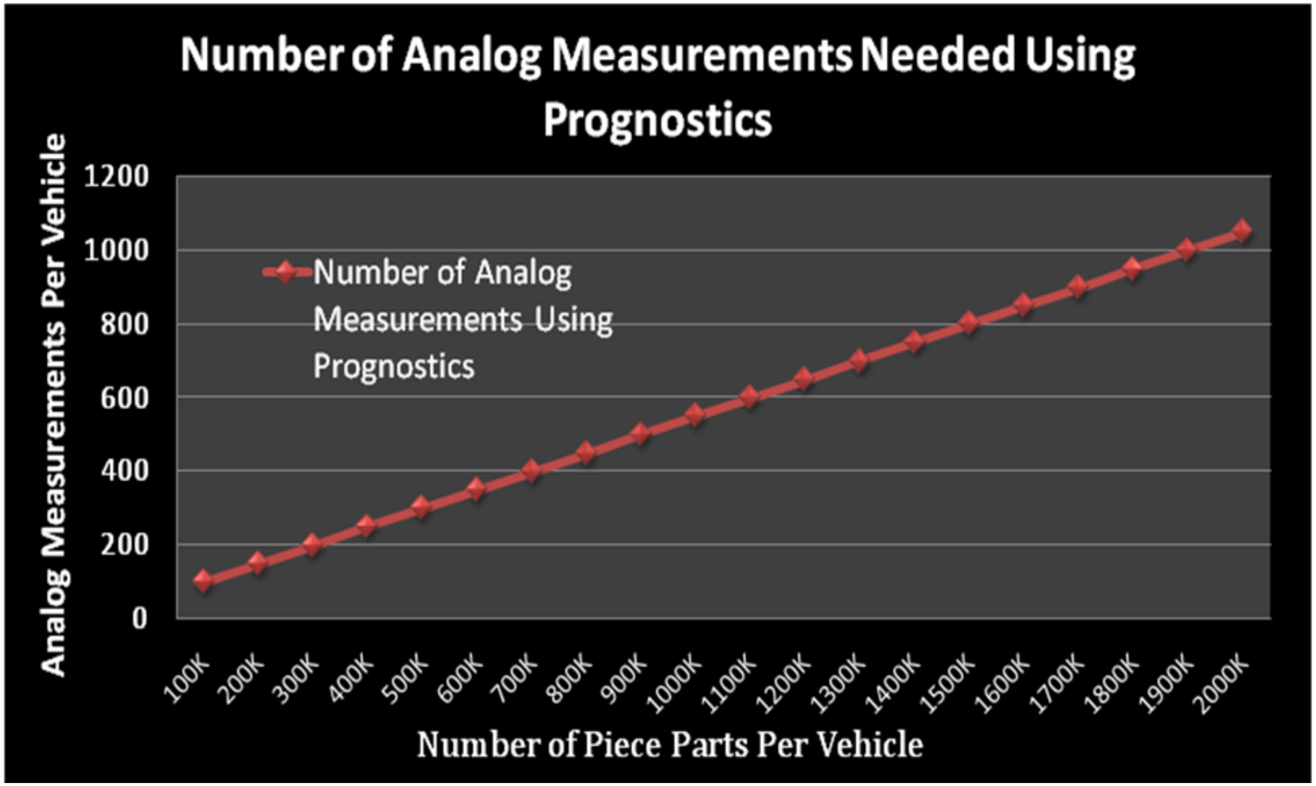
Up to 20%

On Orbit Operations

Up to 40%

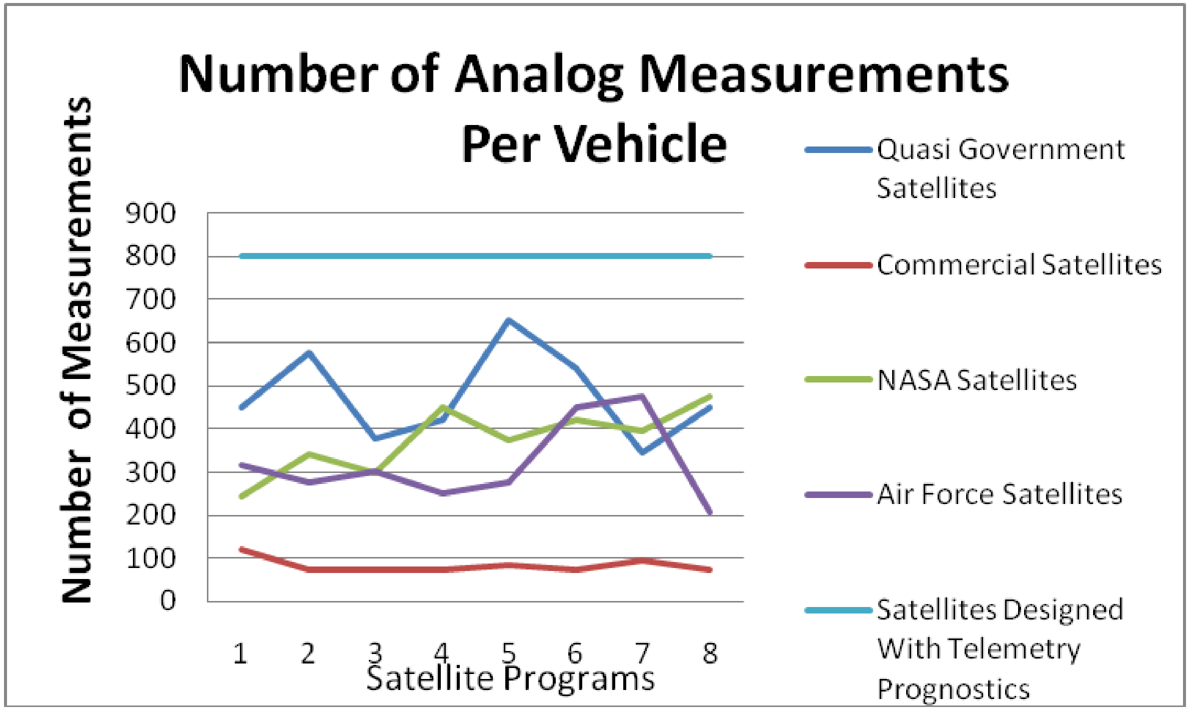
Failure Analysis
Engineering Services

- Prognostic Measurements Needed Per Vehicle



Failure Analysis
Engineering Services

- *Increase Estimates in Prognostic Measurements Per Space Vehicle*



Failure Analysis

Engineering Services

- *Elimination of False Positives*
  - *Prognostics technology developed for applications in which there are enormous penalties associated with false alarms*
    - *False positives reduces the reliability of technology*
      - *People simply ignore alerts*
      - *Space Shuttle*
        - *$5M/day to delay a launch to postpone a launch on the pad*
      - *Commercial Nuclear Industry*
        - *False alarms result in plant shutdowns, which cost $1M per day. EPRI studies have shown that 25% of nuclear plant trips are false alarms from degrading sensors (many sensors have much shorter MTBFs than the assets they are monitoring).*
        - *Result: After a rigorous 2 year evaluation, the US NRC formally approved the use of prognostics for continuous calibration validation of all safety-critical and life critical sensors in all US nuclear plants.*

Failure Analysis

Engineering Services

- *Areas that can be Improved for Predicting Failures*
  - *Vehicle/equipment instrumentation*
    - *Add more vehicle measurements*
      - *Circuit/unit voltage and/or current and/or temperature*
  - *Not real-time, but can be*
    - *If used real-time, the number of false positives increase*
  - *LSB resolution increased to improve accuracy*

Failure Analysis' Satellite, Launch Vehicle, Missile and Upper Stage Summary Using Prognostic Algorithms

Vehicle	Final Orbit	Altitude (nmi)	Final Inclination	Orbit Period	Beta Angle	Attitude Control	Used at	Telemetry Evaluated
Air Force								
GPS 1	Circular	10,900	63°	12 hrs	+/- 86°	Spin	Pad	6 years
GPS 2	(MEO)	10,900			+/- 78°	3-Axis	Early Orbit	6 years
GPS 3		10,900			+/- 78°		On Orbit	5 years
GPS 4		10,900			+/- 86°			5 years
GPS 5		10,900			+/- 86°			3 years
GPS 6		10,900			+/- 78°			2 years
NASA EUVE	Circular	375	28°	1.5 hrs	+/- 51°	3-Axis	On Orbit	3 years
NASA GOES I, J, K & L	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	1.5 years
Japan's SCC SUPERBIRD	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Pad Early Orbit On Orbit	6 weeks
INTELSAT VII&VIIA	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	none
Air Force DMSP Block 6	Circular	450	90°	95 min	+/- 90	3-Axis	Factory	none
Japan's NTT NSTAR	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	none
Canada's ANIK E	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	none
NASA COLDSAT	Circular	19,000	0°	24 hrs	+/- 56°	3-Axis	Factory	none
Space Station Freedom	Circular	275	28°	90 min	+/- 56°	3-Axis	Factory	none
SS/L LS 1300	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	none
GMS-5	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	none
MTSAT	Circular	19,000	0°	24 hrs	+/- 23°	3-Axis	Factory	1 week
Boeing IUS	Circular	19,000	0° – 28°	24 hrs	+/- 56°	3-Axis	Factory	none
Titan Missile	Ballistic	N/A					Factory	1 week
Titan Launch Vehicle	LEO	150	unknown				Factory	1 week
Atlas Missile	Ballistic	N/A					Pad	2 days
Atlas Launch Vehicle	LEO	90	65°	90 min			Pad	2 days
Trident Missile	Ballistic	N/A					Factory	none
Ariane	GTO		3°				Factory	2 days

Failure Analysis

Engineering Services

- *Why Hasn't Prognostics (predicting failures) Been Developed Before?*
  - *No one thought it was feasible to predict failures*
  - *No one increased vehicle reliability requirements to force contractors to investigate new technologies*
  - *Contractors are rewarded with larger contracts for unreliable vehicles, follow-on contracts for replacements vehicles for infant mortality failures, undermining any motivation to look for technologies for eliminating infant mortality failures*
  - *Requires unusual training and experience that design, test and reliability engineers don't get in current academic and industrial career*
    - *Test data behavior illustrated by prognostic algorithms is unique; no 2 are similar, forcing deep understanding, experience and training to accurately identify the information to use to predict equipment will fail in the future*
    - *Very few individuals have the practice, experience, training and confidence to predict equipment failures*
    - *False positives have catastrophic consequences*

Failure Analysis

Engineering Services

- *Telemetry prognostics training includes:*
  - *Signal conditioning*
    - *Filtering*
    - *Amplification*
  - *Linear & non linear DC circuit analysis*
    - *Circuit design*
    - *Troubleshooting*
  - *Satellite communications*
    - *Satellite communications design*
    - *RF Communications*
    - *Digital communications*
  - *Digital signal processing*
  - *Telemetry & Command systems design & test*
  - *Mechanical design*
    - *Thermal control design*
  - *Telemetry software design, development & test*
  - *Command software design*
    - *Validation & verification*
  - *Statistical analysis*
    - *Deterministic*
    - *Bayesian*
    - *Stochastic*
  - *Mathematical modeling*
    - *Harmonic/Fourier Analysis*
      - *Fourier transforms*
      - *FFT*
    - *Kalman filtering*
    - *Neural networks*
    - *Regression analysis*

Failure Analysis

Engineering Services

- *Why Use Failure Analysis' Telemetry Prognostic Technology?*
  - *FA knows what to look for!*
  - *FA knows when to look for it!*
  - *FA knows where to look for it!*
  - *FA knows how to look for it!*
  - *FA knows why it works!*
  - *Flight proven*

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