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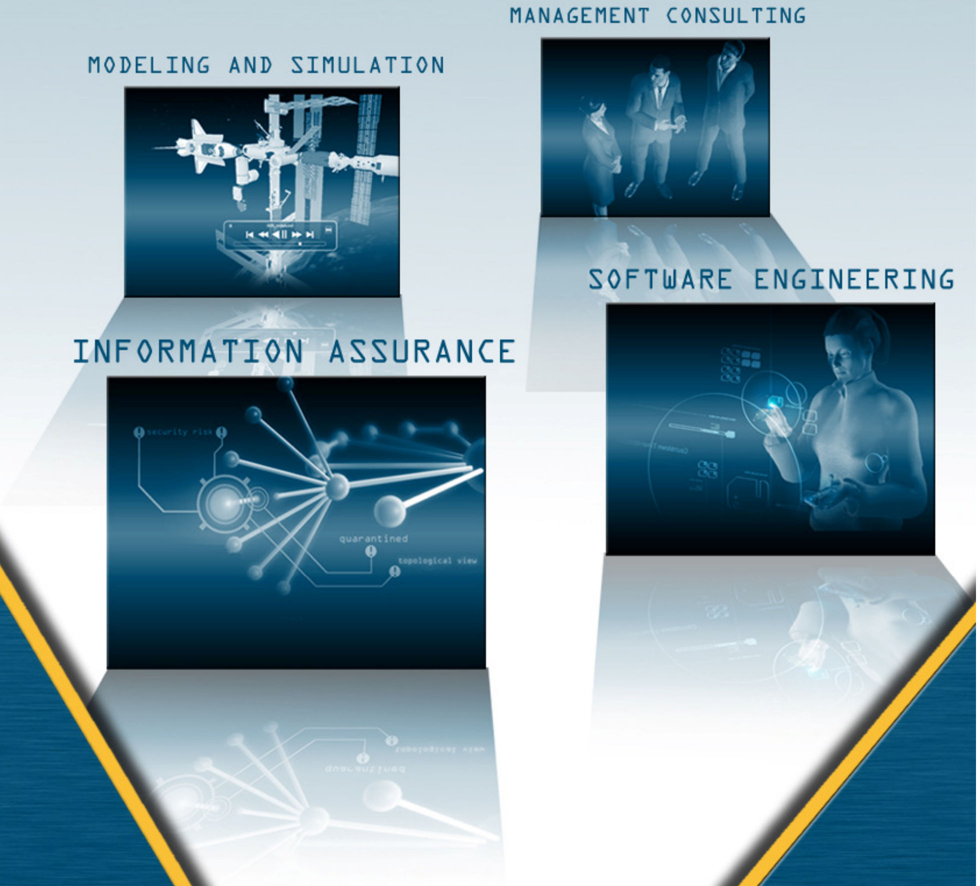

Maintainability: The Forgotten "ility", Essential for Long Term Mission Success

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History of Maintainability

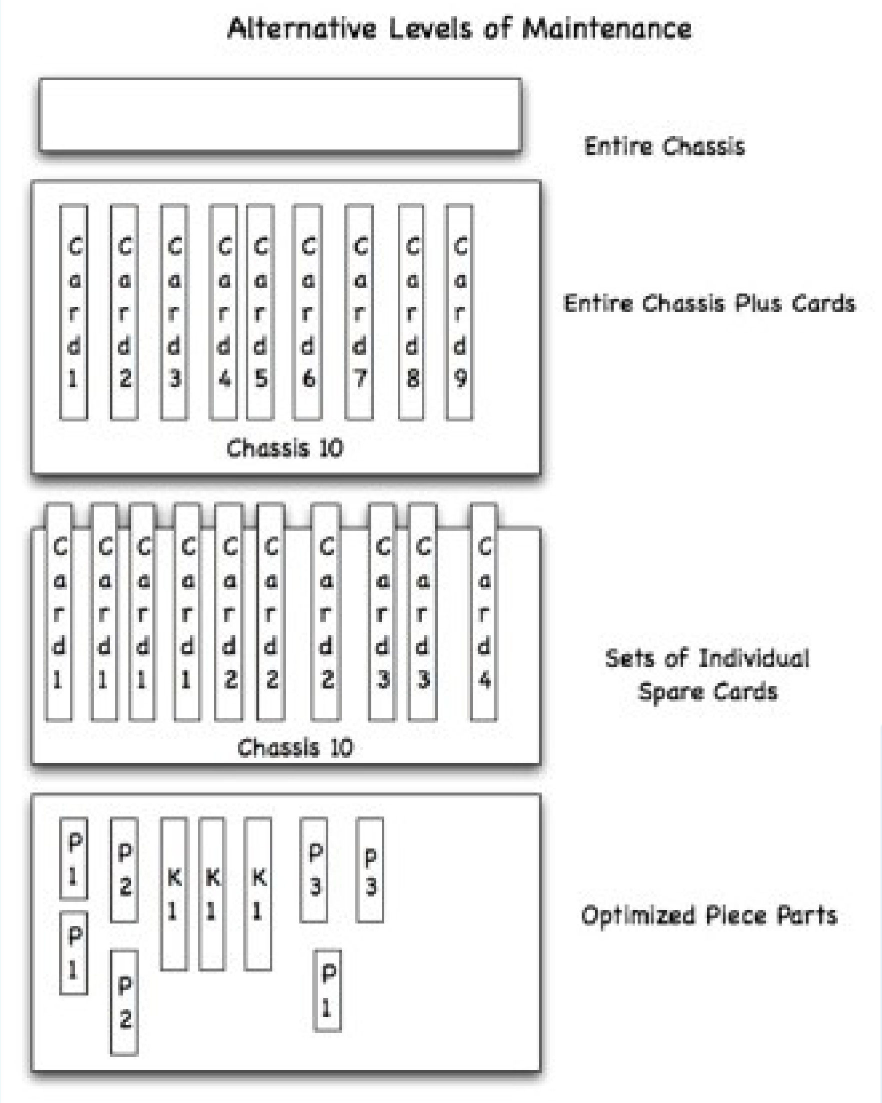
- Past space programs, Apollo and Gemini, used disposable hardware
- Single use spacecraft require little or no maintainability requirements
- During age of the space shuttle, main focus for repair was on ground replacement.
- Limited attention was given to online or in-flight repair known as the Line Replaceable Unit (LRU)
- Restricted ability to repair critical devices such as life support systems can result in Loss of Mission (LOM) or even Loss of Crew (LOC)

Historical Maintainability Shortcomings

- Orbital Replaceable Unit (ORU) level of repair not achievable following Columbia
- Without online repair long duration flights are limited by logistics
- Long-term operation requirements make Lunar outpost tentative and Mars exploration impossible with current design philosophies
- Without a reliable method of maintenance and repair, current missions such as ISS are vulnerable

Analytical Examples

Consider the following System Configuration:



Analytical Examples

Now consider the following Alternative Levels of Maintenance:

- ORU Replacement - This method requires replacement of whole chassis. Multiple spare units will be stored on board.
- Scavenging - When a failure occurs, the replacing of a full chassis is necessary. In event of a second failure, a chassis will be “scavenged” from the remaining workable components (chassis and cards). Multiple Chassis are carried on board.
- Card Replacement - Numerous cards and chassis pieces brought on board. If a failure should occur the defective cards are replaced with spare cards.
- Part Replacement - Individual parts and repair kits will be taken on board. These parts are used to repair individual cards themselves.

Analytical Examples

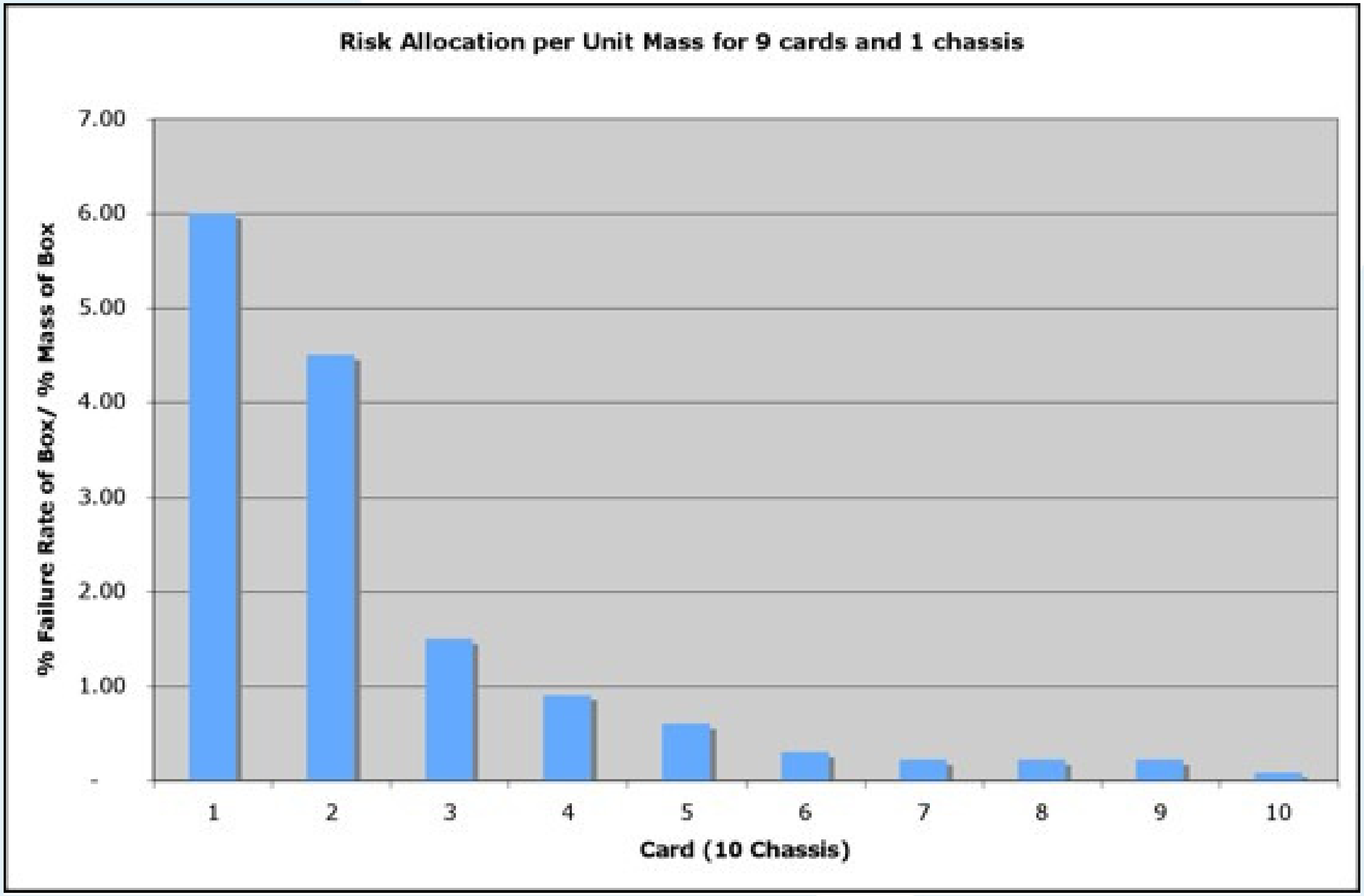
Distribution of Mass and Failure Rates Within the System

Element	% Lambda	% Mass	Pareto (% Lambda/% Mass)
Card 1	40%	7%	6.00
Card 2	30%	7%	4.50
Card 3	10%	7%	1.50
Card 4	6%	7%	0.90
Card 5	4%	7%	0.60
Card 6	2%	7%	0.30
Card 7	2%	7%	0.23
Card 8	2%	7%	0.23
Card 9	2%	7%	0.23
Chassis 10	4%	40%	0.09

Note: Lambda is the failure rate given in a percentage. The lower the Pareto ratio, the lower the concern to bring a replacement.

Analytical Examples

Pareto Chart of Mass and Failure Rates By Card Element



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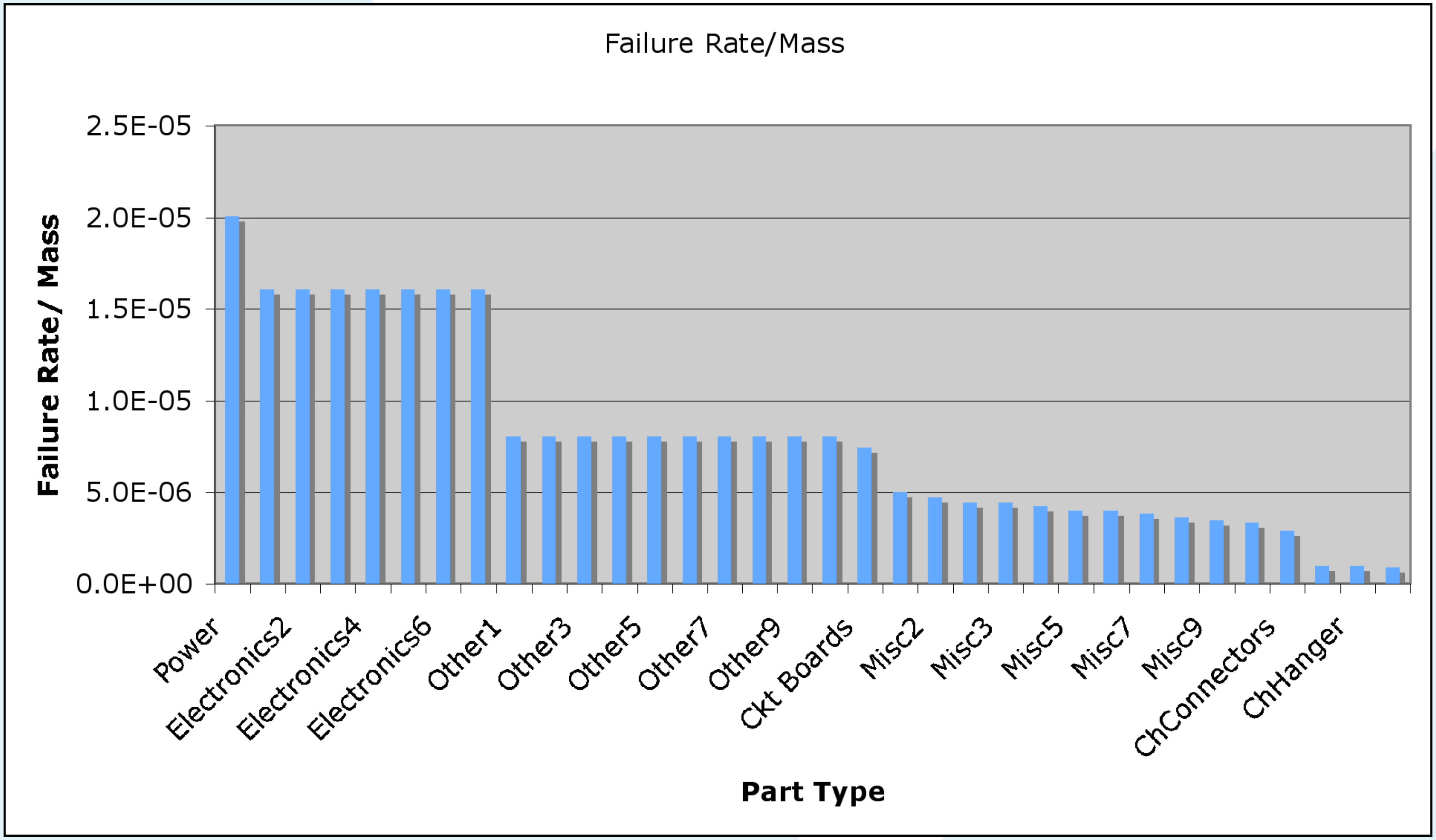
Distribution of Failure Rates and Mass by Part

Item	Number	% Failure Rate/unit	% Mass/unit	Total Failure Contribution	Total Mass Contribution	Pareto Failure Rate/Mass
Chassis	1	0.700%	32.000%	0.7%	38.4%	9.1E-07
ChConnectors	10	0.140%	0.200%	1.4%	2.4%	2.9E-06
ChHarness	10	0.070%	0.300%	0.7%	3.6%	9.7E-07
ChHanger	10	0.070%	0.300%	0.7%	3.6%	9.7E-07
Ckt Boards	9	0.724%	0.450%	6.5%	4.9%	7.4E-06
Processor	18	1.228%	0.764%	22.1%	13.7%	4.5E-06
Power	4	8.292%	5.156%	33.2%	20.6%	2.0E-05
Electronics1	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics2	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics3	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics4	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics5	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics6	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Electronics7	5	0.921%	0.573%	4.6%	2.9%	1.6E-05
Other1	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other2	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other3	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other4	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other5	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other6	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other7	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other8	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other9	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Other10	10	0.012%	0.008%	0.1%	0.1%	8.0E-06
Misc1	16	0.008%	0.005%	0.1%	0.1%	5.0E-06
Misc2	17	0.007%	0.004%	0.1%	0.1%	4.7E-06
Misc3	18	0.007%	0.004%	0.1%	0.1%	4.5E-06
Misc4	19	0.006%	0.004%	0.1%	0.1%	4.2E-06
Misc5	20	0.006%	0.004%	0.1%	0.1%	4.0E-06
Misc6	20	0.006%	0.004%	0.1%	0.1%	4.0E-06
Misc7	21	0.006%	0.004%	0.1%	0.1%	3.8E-06
Misc8	22	0.006%	0.003%	0.1%	0.1%	3.7E-06
Misc9	23	0.005%	0.003%	0.1%	0.1%	3.5E-06
Misc10	24	0.005%	0.003%	0.1%	0.1%	3.4E-06
Total		1	1	100%	109%	

Analytical Examples

Pareto Distribution of Failure Rates and Mass



Analytical Examples

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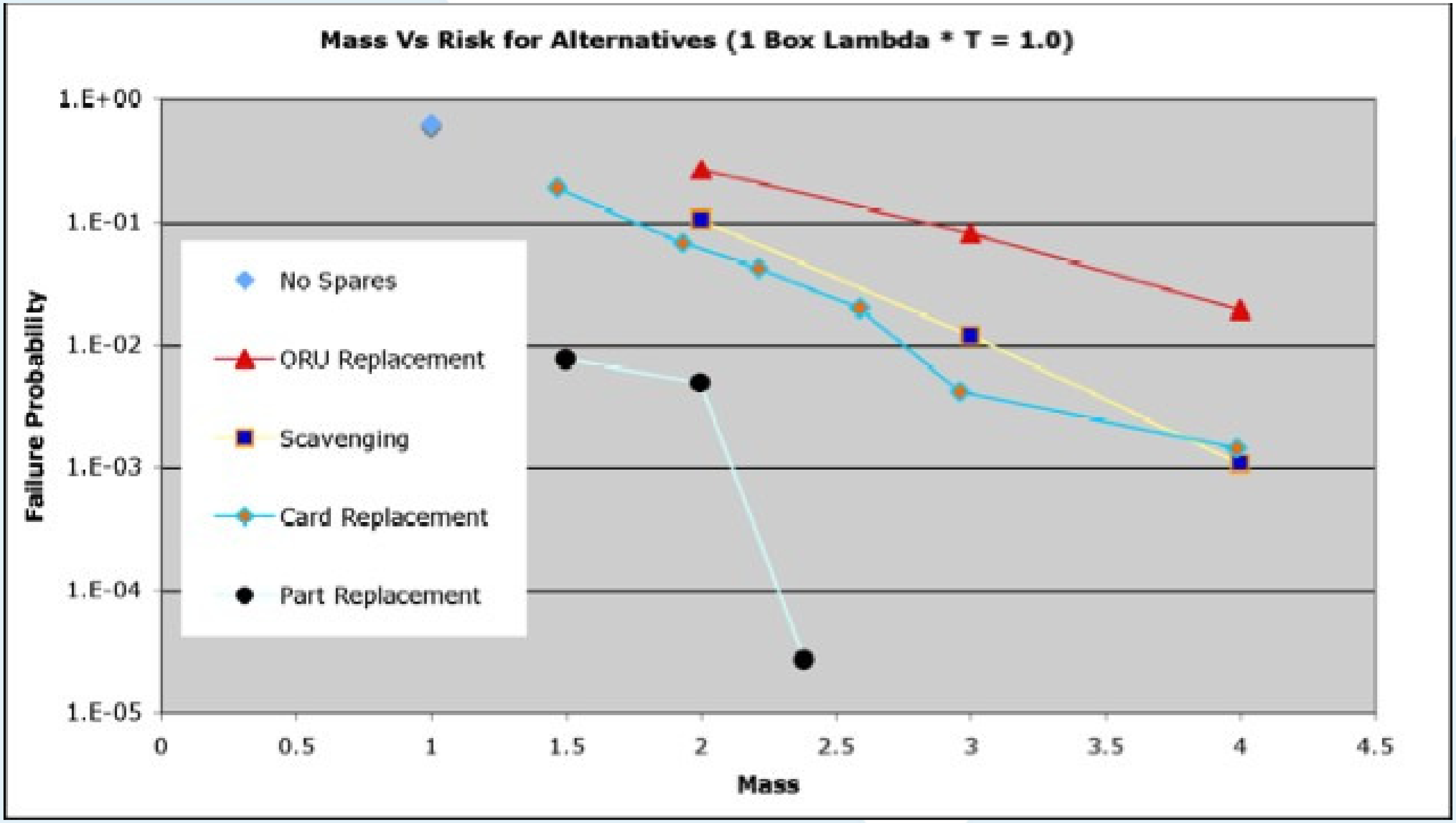
System Reliability as a Function of Mass For Alternative Repair Strategies



Note: Lambda * T = 1.0 is the standard for a typical Long Duration Mission to Mars. T is the time of the mission.

Analytical Interpretation

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Assessment of Maintenance Strategy #1

- Pareto chart indicates that prioritization of spares may be most effective method of maintenance
- Mass efficient strategies should focus on components that tend to have a higher failure rate to mass ratio

Assessment of Maintenance Strategy #2

- Significantly lower probability of failure for a given mass
- Required to carry cards that are less likely to fail
- More feasible when failures are uniformly distributed across elements
- System must be designed to allow crew to disassemble components
- Diagnosing specific failure of a component could be a risk

Analytical Interpretation

Assessment of Maintenance Strategy #3

- Slight failure probability benefit when bringing up optimized sets of elements (cards, etc.)
- Allows more high-priority spares to be carried aboard
- Must have reliable data of relative failure rates of the cards

Assessment of Maintenance Strategy #4

- Optimized to achieve lowest system failure probability with a given mass
- Improvement over the card level maintenance strategy
- Most practical approach for mass constrained maintenance

Maintenance Examples

International Space Station

- Standard procedure for repair practice requires removal of the failed unit and replace it with a spare
- Fairly easy to replace however instructions are said to be too detailed in nature
- This "ancient" process is inefficient, instructions may take longer to read than to execute the repair
- Limited availability of instruction manuals
- Ground crews must anticipate a malfunction in order to write up a detailed instruction manual
- Post Space Shuttle Columbia Accident, this method of repair was put to the test
- Spare parts were not always readily available
- Nearly three years of grounded Shuttle's led to serious issues

Maintenance Examples

Omega Speed Master Watch Failure Example

- Sophisticated Omega watches failed while in orbit
- No other way to accurately tell time
- Time keeping aboard the Shuttle/ISS is a critical part of mission success
- A crew member brought a Casio spare watch which was eventually used for spare parts by astronaut Donald Pettit
- Don has sufficient skills in watch repair and began to “salvage” what he could from both of the watches
- Ground control did not believe a “zero g” repair was possible
- Entire repair was filmed, left ground control crew in shock
- This in flight repair, served as proof for potential low level repair capabilities

Maintenance Examples

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In-flight Component Repair

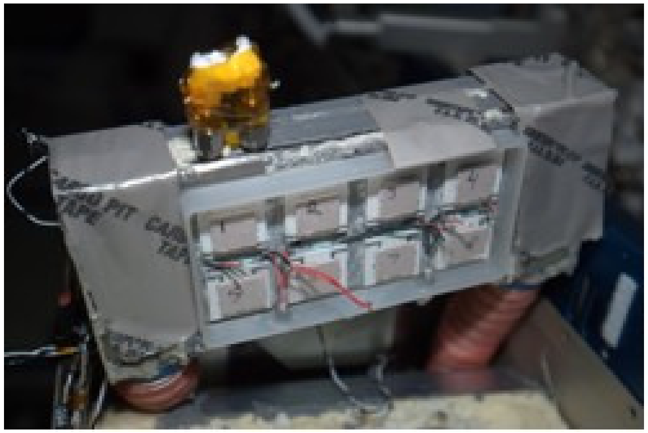
Astronaut Donald Pettit repairing the Omega Watch

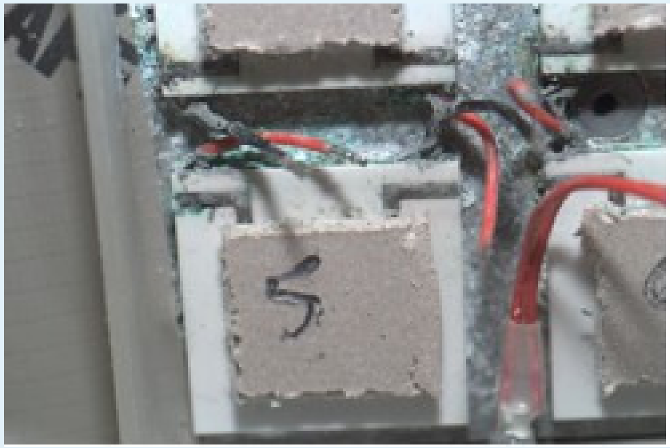
Maintenance Examples

Freezer Failure Example

- ISS freezer used for storing biological samples failed
- Considered a dead ORU
- Could take years before another freezer could be shipped
- It was left up to the crew to attempt to repair the broken freezer
- A general instruction manual was up-linked to the ISS
- During the crews spare time they completed the repair in about two weeks
- Crew improvised and finally fixed six of the eight thermal electric coolers which were malfunctioning

Freezer Repair





Individual screen shots of the defective freezer

Snowmobile Failure in Antarctica

- Antarctic team (ANSMET) searches for meteorites 200 miles from the south pole
- Snowmobiles are used to move camp every two weeks
- An electrical fire caused one of the snowmobiles to be useless
- McMurdo Ops offered little help
- Team decided they would attempt to repair the snowmobile on their own
- Wire was stripped from a backup beeper and used to rewire the ignition.
- Repair was successful despite a few design accoutrements no longer operated

Maintenance Examples

Snowmobile Repair

Burned Wires of the snowmobiles ignition