Reliability, Maintainability, and Availability:

Consideration During the Design Phase in Ground Systems to Ensure Successful Launch Support

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NASA-KSC, Ground Systems Development and Operations (GSDO) Program
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What is GSDO?

- Ground Systems Development and Operations (GSDO) Program
  - 1 of 3 NASA Programs based at Kennedy Space Center (KSC)
  - Established to develop and use the complex equipment required to safely handle rockets and spacecraft during assembly, transport, and launch

Mission:

To prepare KSC to process and launch the next generation of rockets and spacecraft in support of NASA's exploration objectives by developing the necessary ground systems, infrastructure, and operational approaches.
What is RMA?

• RMA is the acronym for Reliability, Maintainability, and Availability
  
  – Reliability (R)
    • The probability (likelihood) that a component or system will perform its intended function with no failures for a given period of time (mission time) when used under specific operating conditions (test environment or operating environment)

  – Maintainability (M)
    • The probability a failed item will be restored or repaired to a specified condition within a given period of time

  – Availability (A)
    • The probability that a repairable system will perform its intended function at a given point in time or over a specified period of time when operated and maintained in a prescribed manner. Thus, availability is a function of reliability and maintainability

• If “R” is enough, then no need for “M” and “A”; if “R” is not enough, then “R” and “M” is needed to make “A”

\[ f(R,M) = A \]
RMA Analysis Purpose

• To reduce lifecycle cost by:
  – Efficiently and effectively identifying limitations within a system that may cause a failure before the intended lifetime
  – Identify unreliable systems that may pose a safety or health hazard
  – Providing specific Reliability requirements for component procurement
  – To identify wasted efforts and hardware that were intended to improve Availability, but are providing little value

• To study, characterize, measure, and analyze the failure and repair of systems in order to:
  – Improve their operational use by increasing their design life
  – Eliminate or reduce the likelihood of failures and safety risks
  – Reduce downtime (maintenance), thereby increasing available operating time
• Ideally, the Reliability Engineering process looks like this:

Start

FFBD = Functional Flow Block Diagram
RBDA = Reliability Block Diagram Analysis
FMEA = Failure Mode & Effects Analysis
FTA = Fault Tree Analysis
PRA = Probabilistic Risk Assessment

Success Space

Failure Space

Engineering

Safety & Mission Assurance

WHAT

WHAT

WHO

WHEN

100% EFFORT

Source: Tim Adams KSC-NE

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• GSDO Program needs to deliver high launch probability
  - Lunar missions and beyond require multiple launches and payloads to achieve mission goals
  - Commercial, DoD, and NASA customers will desire high availability from Ground Systems for launch support
  - The cost of each launch "scrub" is severe
    • De-tanking vehicles, re-synchronizing orbits, rescheduling Range conflicts, resting crew, etc
    • If a GROUND SYSTEM causes this scrub (when the vehicle was otherwise "Available"), then the community's penalty is even more severe

• High Probability of Successful launch is needed; however, challenges were faced:
  - KSC Ground Systems delivered 88% probability of launch during Space Shuttle Program (SSP)
  - KSC Ground Systems Constellation Program (CxP) requirement was 99% probability of launch for the last 10 hours of launch countdown
  - GSDO Program requirement is 98% Inherent Launch Availability for any given launch countdown
GSDO RMA: Solution to a Challenge

- Risk Factors for GSDO:
  - Ground Systems
  - Human Errors
  - Range Conflicts
  - Range Systems
  - Range Intrusions
  - Hurricanes

- Risks for launch probability:
  - GSDO
  - Space Launch System (SLS) – the Launch Vehicle
  - Orion Multi-Purpose Crewed Vehicle (MPCV)
  - Environments – Launch Weather (Wx), Abort Wx, Sea State

Example of Probability of Architecture on Any Given Launch Attempt*

*Does not necessarily represent actual risk probabilities.

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GSDO RMA: Requirement Development

- Needed to put requirements in place to minimize risks to successful launch support
  - Only could control risks to Ground Systems design and upgrades
  - Allocated Availability requirements to Ground Systems
    - Inherent Launch Availability
    - Operational Availability*

*The Operational Availability requirement is not the classical Operational Availability ($A_o$) calculation. It is allocated as Inherent Availability ($A_i$). From a system design point of view, the $A_i$ is of more interest than $A_o$ because spares and repair capability involve resources and trade-offs external to the system design.

Operational availability cannot be controlled by system design, but Inherent Availability can.
Reliability allocations made via improved Reliability Apportionment Method

- Accounts for knowledge of Ground System performance, design, and use

Maintainability allocations made via an improved MIL-HDBK-417A method

- Accounts for knowledge of Ground System design, fault isolation techniques, and maintenance design characteristics, i.e., accessibility on the pad
"Management reserve" is built into each RMA requirement allowing for room for growth in GSDO subsystems:
- Fraction of the overall requirement is unallocated
- If the cost for an availability improvement in a subsystem design outweighs the benefit in increased GSDO launch availability, there is enough management reserve to leave the design as-is, in most cases.

The RMA analyses are completed in parallel with the design and upgrade schedules:
- RMA analysis is a required product for design milestones (30/60/90 or 45/90)
- RMA analyses are performed as requested to assist in trade studies.
Allocation is an iterative process
- As designs are analyzed, allocations may need to be adjusted
RMA Analysis of GSDO Subsystems

1) Develop Component List from Subsystem Drawings

2) Develop Reliability Block Diagram (RBD) from Subsystem Drawings

3) Determine Reliability, Maintainability, and Availability from RBD

4) Determine Cut Sets from RBD

5) Determine Importance Measures from Cut Sets

6) Report Results and Recommendations in Subsystem RMA Reports

Cut Set Analysis

Component Data

Importance Measures

Weibull Analysis
RMA Analysis of GSDO Subsystems

- Example of component data using COTS software:
  PTC Windchill Quality Solutions (WQS)
RMA Analysis of GSDO Subsystems

- Analysis of components will sometimes include Weibull analysis to attempt to determine what type of failures are experienced
  - Used for similar components
  - Used for heritage subsystems to characterize failure types seen:
    - Early failures (burn-in)
    - Useful Life (random failures)
    - Wearout

The Bathtub Curve
• Reliability Block Diagram (RBD) Analysis (RBDA):
  - Predicts reliability (uptime), maintainability (downtime), and availability (mission readiness being a function of uptime and downtime)
  - The RBDA method is used to estimate and analyze the reliability and availability for the systems containing at least two or more elements
    • RBDA is a “top-down” method in success space
    • Analyzes Reliability (and Availability) relationships
  - Quantitative
RMA Analysis of GS DO Subsystems

- RMA Team converts each drawing (mechanical and electrical) into a Reliability Block Diagram (RBD)
  - Verify accuracy and understanding of the components and their connections with the design team
RMA Analysis of GSDO Subsystems

- RMA team determines the RMA of the subsystem by using both analytical and Monte-Carlo simulation calculations with at least 1,000,000 iterations.
  - Confidence Level set at 95%

- Compare results to requirement

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<th>RMA Requirements</th>
<th>Simulation Results</th>
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<tr>
<td><strong>Reliability</strong></td>
<td><strong>Reliability</strong></td>
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<tr>
<td>(for 24 hrs)</td>
<td>(for 24 hrs)</td>
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<tr>
<td>0.99900</td>
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<tr>
<td><strong>Maintainability</strong></td>
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<tr>
<td>(hrs)</td>
<td>(hrs)</td>
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<tr>
<td>48</td>
<td>12.59</td>
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<tr>
<td><strong>Availability</strong></td>
<td><strong>Availability</strong></td>
</tr>
<tr>
<td>( A_{inh} )</td>
<td>( A_{inh} )</td>
</tr>
<tr>
<td>0.998017</td>
<td>0.999529</td>
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</table>

- Perform sensitivity analysis to verify consistency in simulations
  - Different random number seeds for Monte-Carlo simulations

<table>
<thead>
<tr>
<th>Random Seed</th>
<th>Reliability Lower Bound</th>
<th>Reliability Point Estimate</th>
<th>Reliability Upper Bound</th>
<th>Failures per Million</th>
<th>MTTR (hrs)</th>
<th>Availability Lower Bound</th>
<th>Availability Point Estimate</th>
<th>Availability Upper Bound</th>
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<td>0.998564</td>
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<td>0.999561</td>
<td>0.999602</td>
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</table>
RMA Analysis of GSDO Subsystems

- RMA Team performs Cut Set Analysis (CSA)
  - Set of basic events [failures] where the joint occurrence of these basic events results in the failure of the system.
  - Minimal cut set is a set that "cannot be reduced without losing its status as a cut set"
  - Provides clear indication of where most likely failure paths would be depending on the accuracy of the RBD and the accuracy of the failure data of the components
When a small number of failure paths make such large contributions to subsystem unavailability, isolating the key failure paths becomes obvious.

This enables the design team to focus on either:
- Improving the design to correct the high failure nodes (improving reliability), or
- Ensuring that the component is able to be repaired to an operational state as quickly as possible (improving maintainability).
### RMA Analysis of GSD0 Subsystems

#### Example of Cut Set Data

<table>
<thead>
<tr>
<th>CUM UNAVAL %</th>
<th>UNAVAL %</th>
<th>UNAVAL</th>
<th>Component Failure</th>
<th>Component Failure</th>
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<tbody>
<tr>
<td>5.92%</td>
<td>5.92%</td>
<td>0.000146</td>
<td>ICPSU Position Encoder 1</td>
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<tr>
<td>11.83%</td>
<td>5.92%</td>
<td>0.000146</td>
<td>ICPSU Position Encoder 3</td>
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<td>13.13%</td>
<td>1.30%</td>
<td>3.22E-05</td>
<td>4000 PSI Hydraulic Supply Pressure Xducer (36583MT-1)</td>
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<tr>
<td>14.22%</td>
<td>1.08%</td>
<td>2.68E-05</td>
<td>2200 PSI GN2 Supply Valve (36583A12)</td>
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<tr>
<td>15.17%</td>
<td>0.95%</td>
<td>2.36E-05</td>
<td>Fully Extend Switch (36596)</td>
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<tr>
<td>15.97%</td>
<td>0.80%</td>
<td>1.97E-05</td>
<td>Slow Extend/Retrack Valve (36583A9)</td>
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<td>16.67%</td>
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<td>1.72742E-05</td>
<td>CB (GSP to RIO) 50A - Side A</td>
<td>CB (GSP to RIO) 50A - Side B</td>
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<tr>
<td>17.37%</td>
<td>0.70%</td>
<td>1.72742E-05</td>
<td>CB (GSP to RIO) 50A - Side A</td>
<td>Circuit Breaker (CB) 2A - Side B</td>
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<tr>
<td>18.07%</td>
<td>0.70%</td>
<td>1.72742E-05</td>
<td>CB (GSP to RIO) 50A - Side A</td>
<td>Circuit Breaker (CB) to TB - Side B</td>
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<tr>
<td>18.77%</td>
<td>0.70%</td>
<td>1.72742E-05</td>
<td>CB (GSP to RIO) 50A - Side A</td>
<td>Circuit Breaker to Chassis - Side B</td>
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<td>19.47%</td>
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<td>CB (GSP to RIO) 50A - Side A</td>
<td>Circuit Breaker to Ind &amp; Enable - Side B</td>
</tr>
<tr>
<td>20.17%</td>
<td>0.70%</td>
<td>1.72742E-05</td>
<td>Circuit Breaker (CB) 2A - Side A</td>
<td>CB (GSP to RIO) 50A - Side B</td>
</tr>
<tr>
<td>20.87%</td>
<td>0.70%</td>
<td>1.72742E-05</td>
<td>Circuit Breaker (CB) 2A - Side A</td>
<td>Circuit Breaker (CB) 2A - Side B</td>
</tr>
</tbody>
</table>
RMA Analysis of GSDO Subsystems

• GSDO RMA Team performs Importance Measure Analysis (IMA)
  - Assesses the importance of the components in the subsystem or the sensitivity of the subsystem RMA to changes in the components' failure rates
  - Quantify the criticality of a particular component within a system design.
  - Used as tool for identifying system weakness, and to prioritize RMA improvement activities
  - Change in the failure rates of the components (or adding redundancy to account for the high failure rate) with the highest importance measure percent contribution will have the most significant effect on increasing subsystem reliability

• This unique method described in paper written by RMA team, entitled, "Comparison Modeling of System Reliability for Future NASA projects" and presented at International Reliability and Maintainability Symposium (RAMS) in January 2012

Ensure this component/LRU is on hand in order to repair and/or replace when failed.

1. Ensure this component/LRU is on hand in order to repair and/or replace when failed.

2. Ensure personnel are trained in procedures for repair and/or replace.

3. Ensure procedures are optimized for repair and/or replace.
RMA Analysis of GSDO Subsystems

- GSDO RMA Team reports results and recommendations in Subsystem RMA reports

  - Example recommendations for RMA improvement:
    - Have redundant components on separate busses
      - Improved availability by an order of magnitude (0.995 to 0.9994)
    - Move control and monitoring to different Programmable Logic Controller (PLC)
      - Had redundant monitoring on same PLC (see next page)
      - Improved availability by three orders of magnitude (0.9993 to 0.999999)

  - Example recommendations for trades:
    - Tertiary power system provides little to no improvement in availability (0.999995 to 0.999996); does not justify additional weight, space, and cost
    - Avionics architectures: triplex voter improves availability, however, self-checking pair does not
RMA Analysis of GSDO Subsystems

\[ R(10) = 0.999300 \]

\[ R(10) = 0.999999 \]
Effectively monitoring and tracking RMA analysis results for management
  - Management informed of risk to achieving requirements almost immediately

RMA tracking & reporting methodology effective and efficient in communicating recommendations for RMA improvements
  - Can quantify RMA improvements versus cost, scheduling, weight, space impacts
• GSDO requirements allocated to subsystems
  - Inherent Launch Availability is allocated to those subsystems in the launch countdown window
  - Operational Availability is allocated to those subsystems not included in the Inherent Launch Availability allocation, but needed in the event of a launch scrub
• GSDO RMA team performing RMA analysis of subsystem designs and upgrades, as well as heritage subsystems
  - Analysis of heritage subsystems includes Weibull analysis to attempt to determine what type of failures experienced: Early failures (burn-in), Useful Life (random failures), Wearout
• GSDO is tracking and reporting RMA analysis results of ground hardware and software components
• FTA, FMEA, etc are performed as part of the design development cycle to drive out subsystem hazards and single failure points
Other RMA Analyses

- Failure Modes & Effects Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Probabilistic Risk Assessment (PRA)
- Historical Component Failure Rate Determination
- Component Burn-in and Test Time Requirements
Failure Modes and Effects Analysis (FMEAs)

- Inductive (bottom-up) method where a table that describes the way or modes in which each system component can fail and assess the consequences of each of these failures is generated.
- Determines hardware criticality.
- Identifies failure modes that do not meet applicable Program reliability requirements.
- Identifies the potential for single point failures.
- Identifies areas where the design does not meet the failure tolerance requirements.
- Changed from qualitative to quantitative by assigning values to:
  1. Probability of the failure occurring,
  2. Severity of the effect of the failure on the operation of the systems,
  3. Probability that the system controls will detect and eliminate the failure before the design is complete.

- The product of all three values is the risk priority number (rpn).

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<th>Rating</th>
<th>Description</th>
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<td>Very Low or None</td>
<td>Minor nuisance</td>
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<tr>
<td>2</td>
<td>Low or Minor</td>
<td>Product operable at reduced performance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate or Significant</td>
<td>Gradual performance degradation</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>Loss of function</td>
</tr>
<tr>
<td>5</td>
<td>Very High or Catastrophic</td>
<td>Safety-related catastrophic failures</td>
</tr>
</tbody>
</table>
Fault Tree Analysis (FTA)

- Deductive (top-down) method that generates a symbolic logic model that traces and analyzes the failure paths from a predetermined, undesirable condition or event (called the top event) of a system to the failures or faults.
- Can be qualitative or quantitative – *we do quantitative*
- FTA is an event-oriented analysis in contrast to the RBD, which is a structural-oriented analysis.

![Fault Tree Analysis Diagram]
Probabilistic Risk Assessment (PRA)

- Systematic and comprehensive methodology to evaluate risks associated with a complex system
- Risk in PRA is defined as scenarios, associated frequencies, and associated consequences
  - Risk management involves prevention of adverse scenarios and promotion of favorable scenarios
  - NASA uses Risk metrics of probability of loss of vehicle, mission failure, etc
- Goal is to describe how the system and its elements respond to an undesired initiating event, such as lightning or fire
- Quantitative
  - Magnitude of the possible adverse consequence
  - Probability of the occurrence of each consequence
- Include:
  - Human Reliability Analysis (HRA)
  - Common-Cause-Failure Analysis (CCF)
Probabilistic Risk Assessment (PRA)

- Drawings
- Event Tree
- RBDs
- Fault Trees
- System Assurance Analysis (SAA)
- Crew Access Arm (CAA)
- FMEAs
- Hazard Reports
Historical Component Failure Rate Determination

- Using 442 PRACA records:
  - Input into Weibull Analysis
  - Results:
    - It is in its useful life cycle, with random failures
    - $\beta=1.0615$
    - MTBF = 2991 hrs
  - Assumptions
    - Repair Time: 223 hrs
    - Inspection Time: 8 hrs
  - Maintainability
    - Maximum Availability = 87%
    - Inspection Time = 220 hrs
Component Burn-in & Test Time Requirements

- RMA Analysis can determine product testing parameters
  - Reliability life testing can quantify reliability or safety goals
  - Burn-in test times can determine constant failure rates
  - Can determine acceptance test parameters

- The Weibull shape parameter ($\beta$) corresponds to the different failure modes for components
  - Infant mortality when $\beta$ is less than 1
  - Random defects when $\beta$ is equal to 1
  - Wear-out when $\beta$ is greater than 1

- The results of System Reliability analysis can be misleading if components are not properly up-screened (burned-in) or used under a certain bias condition where different failure modes may occur
Why Have RMA Analysis in Design Process?

- RMA Analysis provides quantitative results, which can be used to justify component replacement, system upgrades, cost effectiveness of "abandon in place" concepts for systems, etc.
- GSDO RMA process allows for verification and traceability of RMA requirements.
- GSDO RMA Analysis encompasses entire design life cycle:
  - RBDA
  - FTA
  - FMEA
  - PRA
- RMA Analysis can be used to optimize timeline and launch availability results:
  - Provide MTBF, failure distribution, MTTR, and repair probability to Ground System hardware and software.
- RMA Analysis can be used to optimize Logistics considerations:
  - Spare parts need
  - Logistic Facility space
  - Preventative Maintenance requirements
  - Maintenance Personnel Requirements
GSDO RMA Analysis Papers

- GSDO RMA Team Papers Published:

- Future Papers for Reliability and Maintainability Symposium (RAMS) 2013 (January 2013 in Orlando, FL):
  - "Allocating Reliability & Maintainability Goals to NASA Ground Systems"
    - Paper described GSDO RMA Allocation process for GSDO
  - "Determining Component Probability from Problem Report Data Used in Ground Systems for Manned Space Flight"
    - Describes process of capturing qualitative PRACA failure data for use to determine quantitative component reliabilities
Thank You

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<table>
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<th>Acronym</th>
<th>Definition</th>
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<th>Definition</th>
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<td>A_i</td>
<td>Inherent Availability</td>
<td>KSC-NE</td>
<td>KSC Design Engineering</td>
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<tr>
<td>A_o</td>
<td>Operational Availability</td>
<td>MPCV</td>
<td>Multi-Purpose Crewed Vehicle</td>
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<td>ASQ</td>
<td>American Society for Quality</td>
<td>MTBF</td>
<td>Mean Time Between Failures</td>
</tr>
<tr>
<td>CRE</td>
<td>Certified Reliability Engineer</td>
<td>MTTR</td>
<td>Mean Time to Repair</td>
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<tr>
<td>CSA</td>
<td>Cut Set Analysis</td>
<td>NASA</td>
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<td>CXP</td>
<td>Constellation Program</td>
<td>PLC</td>
<td>Programmable Logic Controller</td>
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# Acronym & Abbreviation List

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<tr>
<th>Acronym</th>
<th>Description</th>
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<td>Science Application International Corporation</td>
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<tr>
<td>SLS</td>
<td>Space Launch System</td>
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<td>Windchill Quality Solutions</td>
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