Reliability Growth Planning and T&E
Module Outline

• Why R&M?
  – Reliability, Maintainability, Supportability, and LCC
  – R&M at the DoD Today

• Policy
  – JCIDS 3170—Sustainment KPP
  – DoDI 5000.02

• Practical R&M Concepts
  – Key Definitions and Measures
  – R&M Engineering Fundamentals
  – Mini Exercise

• R&M Activities by Phase
  – R&M Acquisition Considerations
  – R&M in the Acquisition Lifecycle Discussion
  – Contracting for R&M
**Why R&M?**

- DoD emphasis to increase readiness and reduce life-cycle costs
- Need to understand R&M fundamentals
- Need to ensure R&M principles are properly applied to DoD programs
- Need to tailor R&M disciplines to ensure cost effectiveness for DoD program
R&M and Life-Cycle Cost

Early life-cycle decisions have a large impact on Life Cycle Costs.

Costs driven by R&M considerations not as visible during early phases, but are linked to a large share of the Life Cycle Costs.

CAPE/Army Studies: Two-thirds of program costs come in the O&S phase...90% of those costs are correlated to R&M.
R&M, Supportability, and LCC
R&M in the DoD Today

- Management commitment and attention
- Well defined mission oriented requirements
- R&M design and test activities correctly applied and tailored to all acquisition phases
- Realistic schedule associated with R&M disciplines
- Sustained reliability growth and maintainability maturation
- R&M activities monitored for effective implementation
- R&M assessments to inform decisions at key program reviews and milestones
R&M Policy

JCIDS 3170
- Sustainability Key Performance Parameter (KPP)
- Sustainability Key System Attributes

DoDI 5000.02
- Comprehensive R&M Program
  - R&M Engineering Activities
  - RAM-C Report
  - Reliability Growth
"Prepare a preliminary RAM-C Report in support of Milestone (MS) A decision…"—*DoDI 5000.02*

- Provides early (Pre-MS A) reliability, availability, maintainability, and ownership cost feasibility assessments of alternative concepts
- Includes early formulation of maintenance and support concepts
- Provides an audit trail that documents and supports JCIDS thresholds
- Ensures correct balance between the sustainment metrics (Availability-KPP, Materiel Reliability-KSA, and O&S Cost-KSA)
- Provides early risk reduction by ensuring requirements are realistic and correct
• The Sustainment KPP is intended to ensure an adequate quantity of the capability solution will be ready for tasking to support operational missions.

• At a minimum, the sustainment KPP consists of:
  – Materiel Availability KPP.
  – Operational Availability KPP.
Sustainment KSAs

- Reliability and Operating and Support (O&S) Cost:
  - Ensure that the Sustainment KPP is achievable and affordable in its operational environment.
  - The KPP and supporting KSAs ensure early sustainment planning, enabling the requirements and acquisition communities to provide a capability solution with optimal availability and reliability to the warfighter at an affordable life cycle cost.
Operational Mode Summary/Mission Profile (OMS/MP)

- Required by *DoD 5000.02*. Provides a foundation for R&M design, verification, and validation.
- An OMS/MP projects the anticipated mix of ways a system will be used for each moment of time to include both peacetime and wartime. It also includes the percentage of time the system will be exposed to each type of environmental condition and movement terrain.
- The **Combat Developer** produces the OMS/MP following development of the system CONOPS.
- Provided to industry as an attachment for the next acquisition phase RFP.
- Reliability growth testing and R&M demonstration testing should be reflective of the OMS/MP.
- The combat developer uses the OMS/MP (and Failure Definition/Scoring Criteria) to conduct an analysis to determine the maintenance and support concepts describing the levels of maintenance and the maintenance activities that will be conducted at each level.

### Table 1 - Marine Corps and Army Joint Major Combat Operation (MCO) Scenario with Mission Tasks *

<table>
<thead>
<tr>
<th>Operational Mode Summary (OMS)</th>
<th>Mission Profiles (MP)</th>
<th>Offense</th>
<th>Stability</th>
<th>Defense</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full Spectrum Element</strong></td>
<td>Littoral/Air Attack</td>
<td>Movement to Contact</td>
<td>Attack</td>
<td>Pursuit</td>
<td></td>
</tr>
<tr>
<td>MCO War Game Phases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration (hours)</td>
<td>5.7</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance (miles)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Operations (hours)</td>
<td></td>
<td>0.9</td>
<td>1.2</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Dynamic Operation or Movement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Operation or Idle Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Operating Time (Dynamic + Static)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems &amp; Engine Off Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary Power or Battery</td>
<td></td>
<td>1.8</td>
<td>2.1</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Power (hours)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silent Watch Operating Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exportable Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycles (Number)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine on/off Cycles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Vehicle and Trailer Percent Payload for RAM Testing

<table>
<thead>
<tr>
<th>Payload On-Board the JLTV FOV</th>
<th>Load Condition</th>
<th>No Trailer</th>
<th>Empty Trailer</th>
<th>Half Loaded Trailer</th>
<th>Fully Loaded Trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLV (CW + Crew - All Payload)</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>JLV (G/W + Crew - 1/2 Payload)</td>
<td>35%</td>
<td>1%</td>
<td>8%</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>JLV (GVW + Crew)</td>
<td>24%</td>
<td>2%</td>
<td>3%</td>
<td>15%</td>
<td></td>
</tr>
</tbody>
</table>
• Program Manager will formulate a comprehensive R&M program.
• Program Manager (MDAPs) will prepare RAM-C Report attached to SEP at Milestone A (updated for DRFPRD, MS B, and MS C) to provide a quantitative rationale for R&M requirements.
• Reliability growth curves will be included in the SEP beginning at MS A, and updated in the draft SEP submitted at the DRFPRD, and in the final approved SEP and TEMP submitted at Milestone B.
• The PMO, DT, and OT agencies will assess the reliability growth required for the system to achieve its reliability threshold.
• Reliability growth will be monitored and reported throughout the acquisition process. MDAPs report RG status in DAES.
• **Availability:**
  - Materiel: measure of the percentage of the total inventory of a system operationally capable, based on materiel condition, of performing an assigned mission.
  - Operational: the measure of the percentage of time that a system or group of systems within a unit are operationally capable of performing an assigned mission and can be expressed as (uptime/(uptime + downtime)).
Definitions (2 of 2)

- **Reliability:**
  - The Duration or probability of failure-free performance under stated conditions, or
  - The probability that an item can perform its intended function for a specified interval under stated conditions.
  - Example Metric: Mean Time Between Failure (MTBF)

- **Maintainability:**
  - Is a characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources.
  - Example Metric: Mean Time To Repair (MTTR).
Failure Modes, Effects, and Criticality Analysis (FMECA)

• Systematically identifies the likely modes of failure.
  – The possible effects of each failure and
  – The criticality of each effect on mission completion, environmental impacts, health hazards, and system safety.

• Preliminary Analysis expected by PDR with the Final by CDR (MIL-HDBK-338B Section 7.8, MIL-HDBK-470A Section 4.4.1.3.3)
### Failure Modes Effects and Criticality Analysis (FMECA)

<table>
<thead>
<tr>
<th>System</th>
<th>New Aircraft</th>
<th>Failure Modes Effects and Criticality Analysis</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem</td>
<td>Flight Management</td>
<td></td>
<td>Prepared by I. M. Savvy</td>
</tr>
<tr>
<td>Part</td>
<td>N/A</td>
<td></td>
<td>FMECA date 20 Feb 20XX</td>
</tr>
<tr>
<td>Design lead</td>
<td>J. Doe</td>
<td></td>
<td>Revision date 30 Apr 20XX</td>
</tr>
</tbody>
</table>

#### Failure mode ID

<table>
<thead>
<tr>
<th>Failure mode ID</th>
<th>Item or function</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Mission phase/operational mode</th>
<th>Local effects</th>
<th>Next higher level effects</th>
<th>End effect on mission</th>
<th>Detection methods</th>
<th>Compensating provisions</th>
<th>Severity Category</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flight control computer</td>
<td>Flight control computer freeze</td>
<td>Software fault</td>
<td>Instrument approach</td>
<td>Loss of coupled flight control</td>
<td>Automatic approach non-operational</td>
<td>Abort flight in instrument conditions</td>
<td>Flight Cmprt fail caution light</td>
<td>Back up cmptr takes over</td>
<td>2R</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Altitude sensor</td>
<td>Altitude sensor fail</td>
<td>Electrical short</td>
<td>En route cruise</td>
<td>Loss of altitude indicate</td>
<td>Loss of automatic altitude hold</td>
<td>Abort night mission</td>
<td>Altitude failure caution light</td>
<td>Use of standby altitude indicator</td>
<td>2R</td>
<td>None</td>
</tr>
</tbody>
</table>

**Category 1** Catastrophic—Failure modes that could result in serious injury, loss of life, or damage to equipment.

**Category 1R** Catastrophic—Failure modes of identical or equivalent redundant hardware items that if all failed could result in Category 1 effects.

**Category 2** Critical—Failure modes that could result in loss of one or more mission objectives.

**Category 2R** Critical—Failure modes of identical or equivalent redundant hardware items that if all failed could result in Category 2 effects if all failed.

**Category 3** Significant—Failure modes that could cause degradation to mission objectives.

**Category 4** Minor—Failure modes that could result in insignificant loss to mission objectives.

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### Diagram

- **Pilot**
- **Cockpit Flight Display**
- **Flight Controls**
- **Flight Control Computer**
- **Signal Conditioner**
- **Multiplexer**
- **GPS Receiver**
- **Airspeed sensor**
- **Altitude sensor**
FMECA Feeds Key SE and R&M Areas

- Fault Tree Analysis
- ID Critical Items
- Physics of Failure Analysis

- Human Factors Engineering & Error Proofing
- Risk Management Process
- Test Plans
- Quality Assurance Plans
- Maint Plans
- Process Control Plans
A fundamental concept in reliability engineering, the Bathtub curve plots the TIME DEPENDENT failure rate—sometimes called HAZARD Rate. The curve describes the probability of failing in the next time interval at a certain age given you have survived to that age.

The exponential function (special case of the Weibull function) is used to model equipment and complex systems that exhibit a constant failure rate.

Weibull distribution is commonly used to model a wide range life (time to failure) distributions characteristic of engineered products.
Reliability Prediction

1. Data on similar equipment
2. Engineering Analysis and Modeling
3. Subject Matter Experts
4. Handbooks

- Four prediction methods can be used to produce deterministic or probabilistic predictions for reliability of components.
- First Preference is existing test or field data from a similar system.
- Second preference is analysis and modeling or accelerated life testing. A FMEA process combined with experience can help identify leading causes of failure.
- Third preference is to consult SMEs that can develop a range of likely reliability values in a short time.
- Fourth preference is to use reliability prediction handbooks such as MIL-HDBK-217, Reliability Prediction of Electronic Equipment.
- Note: A combination of the first three methods is the best way to produce accurate predictions.
Systems can be represented as a combination of series, parallel, and complex segments (subsystems). Consequently, by finding the reliability of the distinct segments of the system, the overall reliability of the system can then be found as the product of the segment reliabilities.

\[ R = \prod_{i=1}^{n} R_i = R_A R_B \]

\[ R = 1 - \prod_{i=1}^{n} (1 - R_i) = 1 - (1 - R_A)^2 \]

Construct a truth table (\(2^n\) combinations)

<table>
<thead>
<tr>
<th>Event #</th>
<th>Subsystem Success or Failure</th>
<th>System Event Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>S</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>S</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>(2^n)</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

System reliability is the sum of the probabilities of the events that result in system success.
Reliability Allocation

- Describe the system configuration (identify elements where design is known, i.e., COTS, and elements that are new design).
- Assign complexity or weighting factors to each element below the system level based on complexity, duty cycle, projected environment, etc.
- Allocate the reliability requirement to subordinate elements, basing a components "share" the parent requirement on the assigned complexity factor.
Reliability Growth (RG) Definition

• Reliability growth (RG) is the positive improvement in a reliability parameter over a period of time due to implementation of corrective actions (fixes) to system design, operation or maintenance procedures, or the associated manufacturing process.

• RG of a complex system involves identifying and analyzing failure modes and implementing corrective actions.

More on Reliability Growth in Module 13
Reliability Verification

- Reliability Growth Testing (Part of DT)
- Reliability Demonstration Testing (at the end of DT or part of OT)
- Environmental Qualification Testing
- Accelerated Life Testing (ALT)
- Highly Accelerated Life Testing (HALT)
- Highly Accelerated Stress Screening (HASS)
- Environmental Stress Screening (ESS)
- Production Reliability Acceptance Test (PRAT)
Maintainability Considerations

- Maintenance Concept (Level of Repair)
- Maintenance Environment
- Maintenance Procedures
- Tools and Support Equipment
- Accessibility
- Markings and Labeling
- Scheduled Maintenance
- Fault Detection (FD) and Fault Isolation (FI)
- Personnel/Skill Levels
Maintainability Prediction

- Involves early quantitative estimates for:
  - Maintenance elapsed time factors,
  - Maintenance labor hour factors,
  - Maintenance frequency factors, and
  - Maintenance cost factors.

- Prediction of preventive and corrective maintenance time is accomplished through system element breakdown and determining the maintenance tasks and associated elapsed times in progressing from one element to another.
  - Task times are usually estimated from experience and data from similar systems.
  - The sum of the various individual task times provide a MTTR estimate for a given element. Times applicable to each element are combined to estimate MTTR for the next-higher level elements (subassemblies, assemblies, etc.).
  - Estimates are updated as test data becomes available for the system under development.
  - See MIL-HDBK-472 "Maintainability Predictions."
Built-in-Test (BIT) Measures

- **Probability of Correct Fault Detection (PCD)**
  \[
  PCD = \frac{\text{Number of BIT Detected Failures}}{\text{Number of Failures}} \times 100
  \]

- **Probability of Correct Fault Isolation (PCFI)**
  \[
  PCFI = \frac{\text{Number of Failures Correctly Isolated to One LRU/WRA}}{\text{Number of Failures}} \times 100
  \]

- **Mean Hours Between False Alarms (MHBFA)**
  \[
  MHBFA = \frac{\text{Number of Operating Hours}}{\text{Number of BIT False Indications}}
  \]
• Subsystem/Equipment BIT Assessment Test: Provides an early indication of actual hardware and software BIT capabilities in the areas of fault detection and fault isolation.

• Maintainability Demo: Assesses maintainability critical areas, verifies conformance of system maintainability requirements and maintenance concepts, and identifies installation physical interface problems for correction.

• System-level BIT Demo: Verifies compliance with BIT requirements and the adequacy of all applicable BIT recording, reporting, and display functions for both the operator and maintainer.
Need to replace existing equipment to improve availability. The new equipment must meet an inherent availability ($A_i$) of better than 0.95, have an MTBF greater than 400 hours, and an MTTR of less than 30 hours.

- Three alternative design configurations are considered. All fall within the trade-off area.
- Which alternative configuration do you choose?
- What else must you consider?
FRACAS

FRACAS (Failure Reporting, Analysis, & Corrective Action System)

• To be implemented by the program, for recording, reporting, analysis, correcting, and monitoring of design and production deficiencies and problems revealed in testing, at all levels.

• All failures are analyzed to sufficient depth to identify failure cause and devise corrective actions, which prevents failure recurrence, for incorporation into the system.

• Initiated with the start of the test program (including laboratory, qualification, R&M tests/demonstration, manufacturing, and acceptance tests) and continues through the stages of development through system developmental and operational testing, production, and sustainment.
FRACAS (cont.)

Failure Review Board or Scoring Conference apply Failure Definition/Scoring Criteria (FD/SC) for incidents observed during test events.

Closed Loop FRACAS Diagram
FD/SC is used to determine the classification (e.g., Operational Mission Failure, Essential Function Failure) and chargeability of test incidents which occur during R&M related testing.

Process is applied at a scoring conference by an R&M working group, IPT, or scoring board. The flowchart below is an example approach for a scoring process.
Mini Exercise

10 minutes to discuss—Quick 2 minute presentations

Consider—The automobile

• Team 1—Engine—describe possible failure modes
• Team 2—knocking noise in engine—list possible causes and corrective actions
• Team 3—possible/current uses of BIT in an automobile
• Team 4—possible/current uses of design to improve maintainability
• Team 5—possible/current uses of design to improve reliability
• Team 6—example of specific information that would go into an operational mode summary/mission profile for an automobile.
The type, phase, and acquisition strategy of the program are prime drivers of the R&M disciplines needed to develop a cost-effective R&M program.
R&M Engineering Through the Life-Cycle

- Define R&M Requirements
- Define R&M Risks
- Analyze and Improve R&M Design
- Confirm R&M Performance
- Monitor and Control R&M
Class Discussion

- Develop a list of R&M engineering objectives and key activities for your assigned lifecycle phase. Use the information provided in the Module read ahead and DAG 4.3.18.19 as a guide.
- Team 1—Material Solution Analysis
- Team 2, 6—Technical Maturation and Risk Reduction
- Team 3—Engineering and Manufacturing Development
- Team 4—Production and Deployment
- Team 5—Operations and Sustainment
R&M Engineering Activities Through the Life-Cycle (Notional)

Analyses, Design, & Redesign for R&M
R&M Allocation, Prediction, FMECA, FTA, RBD, Physics of Failure, Trade-offs, Derating, etc.

Supportability Analysis (MTA, LORA, RCM, CBM)

Continuous Assessment of Field Data
- Highly Accelerated Stress Screening (HASS), Burn-in
- IOT&E and Reliability Demo
- Production Reliability Acceptance Test (PRAT)

FRACAS
R&M Planning and Documentation

Initial R&M Investment Modeling, Cost-Benefit Analysis
- Reliability Growth Planning
- Early prototype testing and HALT
- Initial R&M Program Planning (OMS/MP, FD/SC, OC Curve)

Reliability Growth Testing, Tracking, and Projection
- M-Demos/BIT Demos
- Accelerated Life Testing
- Highly Accelerated Life Testing (HALT)
- Environmental & E3 Testing

R&M Program Planning (OMS/MP, FD/SC, OC Curve)

Prototype Development Models
- Engineering Development Models
- Contract Documentation (CPD)

Multiple Baselines
- LRIP
- Multiple Baselines

Product Support Package
- CDD
- CDD
- Draft

System Concept
- ICD
- MDD

MSA
- TMRR
- EMD
- P&D
- O&S
R&M and System Supportability
## Section C (SOW and System Specification)

- List of R&M tasks and deliverable data (CDRLs w/ DIDs) tailored for acquisition phase and nature of the product.
- Quantitative R&M performance requirements.
  - Requirements must be design controllable.
  - Translated from ICD, CDD, CPD, RAM-C analysis, but accounting for differences between operational and design environments.
  - OMS/MP and Failure Definitions included.
- R&M verification provisions to include descriptions of testing and demonstrations, responsibility for test, and rules for the conduct of tests.

## Section L & M (Instructions to Offerors and Evaluation Criteria)

- Section L provides specific instructions on what the contractor should describe in their proposal. Example:
  - "Describe the proposed reliability growth strategy, including the reliability growth planning curve (Evaluation Factor 4)."
- Section M establishes the specific criteria against which the proposals will be evaluated.
  - "Factor 4 – Reliability Growth Plan. The proposed reliability growth plan is technically sound and of adequate scope and detail."

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Sample contract language available from *DoD Reliability and Maintainability Engineering Management Guide* (currently in Draft) and AMSAA
Contracting for R&M Translation of Requirements

Relative Relationship of Reliability Measures

- **FIELD RELIABILITY**: Service ground rules, service logistics reliability measure.
- **CPD OPERATIONAL MISSION FAILURE REQUIREMENT**: OTA ground rules, mission reliability measure.
- **SPECIFIED RELIABILITY**: Design controllable terms, measured during DT.
- **RELIABILITY PREDICTION**: Inherent reliability.

- **FIELD**
  - Service measure
  - Operational test measure
  - Operational mission reliability
- **CPD**
  - Specification
  - Contract measure
- **SPECIFICATION**
  - Design prediction
  - Design measure
Contracting for R&M (cont.)

- Both the contractor and the government have responsibility to ensure that the contract clearly specifies (either as a requirement or goal, depending on the phase of the program), the level of R&M to be delivered (stated in the units appropriate to the system), and the full R&M rationale.
Contracting for R&M: Performance Requirements

- R&M specification requirements must be translated from the thresholds in the Capabilities Requirements Document.
- R&M quantitative performance measures must be realistic.
- Specification requirements are design controllable with a good design margin.
- Use Contractor’s Predictions to assess risk of achieving Operational thresholds.
- Operational Test R&M thresholds must be equal to the thresholds in the Capabilities Requirements Document.
Contracting for R&M

• The specification should define:
  – the level of performance,
  – operating conditions,
  – mission profile,
  – use environment,
  – failure definitions, and
  – design constraints in quantitative terms.

• The R&M thresholds defined in the Initial Capabilities Document (ICD)/Capabilities Development Document (CDD)/Capability Production Document (CPD) and Test and Evaluation Master Plan (TEMP) should be validated via the RAM-C analysis and report, and then these R&M thresholds must be translated to design-controllable R&M requirements for inclusion in the specification.
Contracting for R&M (cont. 2)

• Design-controllable R&M requirements include only those failures that the contractor can influence through design, manufacturing, processing, and integration of the system.

• Quantitative R&M design requirements should be defined in Service terms of:
  – Materiel Reliability (includes all failures to ensure they can describe the demand for maintenance and impact to total ownership cost),
  – Mission Reliability (describes the ability to perform required functions for specified mission profiles),
  – Maintainability (i.e., corrective maintenance and direct maintenance support), and
  – Built-In Test (fault detection, fault isolation, and false alarms rates) to ensure the requirements describe the ability to repair the system and the level of demand required for manpower at all levels of maintenance and storage.
# Failure Definition Factors

<table>
<thead>
<tr>
<th>Failure Source</th>
<th>Failure Type</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Inherent failures</td>
<td>Design specific</td>
<td>Relevant Failures</td>
</tr>
<tr>
<td>Manufacturing related failures</td>
<td>Design Controllable</td>
<td>Total Failures</td>
</tr>
<tr>
<td>Unreported</td>
<td></td>
<td>Proper Identification &amp; reported</td>
</tr>
<tr>
<td>Operation beyond design limits</td>
<td></td>
<td>Non-Relevant Failures</td>
</tr>
<tr>
<td>Maintenance errors</td>
<td></td>
<td>Conditional Malfunctions (Failures)</td>
</tr>
<tr>
<td>Latent induced failures</td>
<td></td>
<td>No Defect</td>
</tr>
<tr>
<td>Field Data Limitations</td>
<td></td>
<td>Mean Time Btw Maint Action</td>
</tr>
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<td>Adjustments</td>
<td></td>
<td>MTBF</td>
</tr>
<tr>
<td>Interface problems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WUC not representative of system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reported</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excesses (operation &amp; environment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance errors</td>
<td></td>
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</tr>
<tr>
<td>Accidental Damage</td>
<td></td>
<td></td>
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<tr>
<td>Handling errors</td>
<td></td>
<td></td>
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<tr>
<td>Accidents</td>
<td></td>
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<tr>
<td>Cannibalization</td>
<td></td>
<td></td>
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<tr>
<td>Facilitate for other maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>False removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unverified failures</td>
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</tr>
</tbody>
</table>
Reliability Growth Curves
Reliability Growth (RG) is the positive improvement in a reliability parameter over a period of time due to implementation of corrective actions (fixes) to system design, operation or maintenance procedures, or the associated manufacturing process.

RG of a complex system involves surfacing (identifying) and analyzing failure modes and implementing corrective actions.
• Reliability growth is possible at any point in the system life cycle.
  – Changes accomplished early in the life cycle cost less and affect reliability more significantly, but the information upon which early changes are based tends to be more uncertain.
  – Design changes made later in the life cycle tend to be better applied as there are fewer unknowns in the information, but tend to be more costly.
  – Programs should not rely solely on testing but should use a number of information sources to grow reliability.
## RG Channels

<table>
<thead>
<tr>
<th>RG via…</th>
<th>Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>External experience and</td>
<td>Historical data, publications, technical experience of personnel, lessons learned, and information from currently operating systems</td>
</tr>
<tr>
<td>lessons learned</td>
<td></td>
</tr>
<tr>
<td>Design techniques</td>
<td>Design simplification, redundancy, margins of safety, probabilistic design, physics of failure techniques, and derating</td>
</tr>
<tr>
<td>Engineering analysis</td>
<td>Block diagrams, predictions, and failure modes, effects, and criticality analysis (FMECA), fault tree analysis, design reviews; saves test time and resources</td>
</tr>
<tr>
<td>Testing</td>
<td>Design verification tests, conventional reliability growth tests, accelerated life tests, highly accelerated life testing (HALT), environmental and functional qualification tests, environmental stress screening, failure reporting, analysis, and corrective action system (FRACAS)</td>
</tr>
<tr>
<td>Production experience</td>
<td>Quality assurance, quality control</td>
</tr>
<tr>
<td>Operational experience</td>
<td>Monitoring fielded systems; least desirable but inevitable in most cases</td>
</tr>
</tbody>
</table>
Evolution of RG Modeling

- **Duane Model: 1962**
  - Logarithmic (power law) growth
  - Formalized "test, analyze, and fix" process
- **AMSAA-Crow Model: 1974**
  - Failures as a stochastic process
  - Allows for statistical evaluation of growth
- **MIL-HDBK-189: 1981**
  - DoD-specific guidelines for planning
  - Yardsticks for assessing growth
- **Planning Model based on Projection Methodology (PM2): 2006**
  - Introduced parameters based on programmatics
  - Combines programmatics and statistics

Failure rates vs. Equipment Operating Time in a test, analyze, and fix scenario. Results in linear relationship when log(failure rate) plotted against log(operating hours)
• Answers the question
  – "What is the initial design reliability needed and how much
test time and resources are needed to meet reliability
goals?"

• Models
  – Planning Model based on Projection Methodology (PM2)
    • PM2-C: continuous
    • PM2-D: discrete
RG Tracking

• Answers the question
  – "What progress has been achieved in RG based on current test data?"

• Model
  – **AMSAA Reliability Growth Tracking Model—Continuous** (RGTMC)
RG Projection

• Answers the question
  – "What is the projected system reliability after the implementation of corrective actions to fix failure modes discovered during test?"

• Models
  – AMSAA-Crow Projection Model (ACPM)
  – AMSAA Discrete Projection Model (ADPM)
  – AMSAA Maturity Projection Model (AMPM)
Some RG Planning Parameters (1 of 2)

- **A-mode**
  - Failure mode that will not be addressed via corrective action

- **B-mode**
  - Failure mode that will be addressed via corrective action
    - **Caution**: B-mode corrective action during test program may not comply fully with planned production model; called interim, short-term or non-tactical fix
    - Final production (i.e., long-term or tactical) fix needs to be tested to assure adequacy

- **Management Strategy (MS)**
  - Fraction of initial system failure intensity (rate of occurrence of failures) due to failure modes that would receive corrective action if surfaced during developmental test

\[
MS = \frac{\text{Initial Failure Intensity Due to B Modes}}{\text{Total Initial Failure Intensity}} = \frac{\lambda_B}{\lambda_A + \lambda_B}
\]
Some RG Planning Parameters (2 of 2)

- **Fix Effectiveness Factor (FEF)**
  - Fraction representing reduction in an individual initial mode failure rate due to implementation of a corrective action.

- **Growth Potential (GP)**
  - Theoretical upper limit on reliability; corresponds to reliability that results if all B-modes were surfaced and fixed with the realized FEF values.

- **Growth Rate \((\alpha)\)**
  - The negative of the graphical slope of cumulative failure rate vs. cumulative test duration plotted on log-log scale,
    - \(\alpha = 0\), no growth; \(\alpha < 0\), reliability decay; \(0 < \alpha < 1\), reliability improvement.
    - Only pertains to growth models that assume a linear relationship for the defined plot.
    - Note: the PM2 Model used for task 3 of this exercise does not use an assumed growth rate \((\alpha)\), but calculates a growth curve shape parameter \((\beta)\) based the planned initial reliability, the reliability growth goal, and total reliability developmental test time.
• Reliability growth curves will be stated in a series of intermediate goals and tracked through fully integrated, system-level T&E events until the reliability threshold is achieved.
• If a single curve is not adequate to describe overall system reliability, curves for critical subsystems, with rationale for their selection, will be provided.
The Reliability Growth Margin is selected based on the cost and level of acceptable risk associated with demonstrating that the required MTBF has been achieved in the final system configuration.

Operating Characteristic Curve analysis is used to determine the goal reliability needed to demonstrate the required reliability has been achieved with a given levels of consumer and producer confidence.
The risk associated with incorrect decisions (accepting an unreliable system—type II risk; or rejecting a reliable system—type I risk) need to be considered in test planning and RG planning.

Operating Characteristic (OC) curve analysis should be used to mitigate risk in demonstrating a reliability requirement.

If the test is passed then there is a \( \leq \beta \) chance the true MTBF \( \leq \) MTBF spec.

If the true MTBF \( \geq \) MTBF goal then there is a \( \leq \alpha \) chance of failing the test.

Risks for reliability demonstration tests should be evaluated quantitatively, and balanced against constraints for cost and schedule.

Using the OC curve method in development of growth curves allows for planning the MTBF goal needed to demonstrate specification requirements at a stated confidence level.

Probability of passing (acceptance) is a function of test time, # of allowable failures, and true MTBF.
Simple 3x requirement rule of thumb underestimates risk by only allowing for one failure.

In general, to achieve higher confidence (or lower consumer and producer risk) in demonstrating a reliability requirement has been met requires increasing demonstration test time or increasing MTBF $\text{Goal}$ for a given MTBF $\text{Required}$. 

Balancing Resources with Consumer and Producer Risk
Managing RG Through Design & Test

Design Phase
Calendar Time

Test Phase
Test Time

Proactive Reliability Management
Design in reliability with multiple corrective action periods

Design for Reliability Objective

Reactive Reliability Management

Reliability Growth Curve with Design for Reliability

Reliability Growth Curve without Design for Reliability

Most programs fail to get on their planned RGC

Planning Model using Projection Methodology (PM2) Basic Procedure

- $M_G$: Determined based on Reliability Demonstration Test Probability of Acceptance (PA) and given requirement level

- $M_i$: The initial reliability that enables reaching $M_G$

\[
M_i \geq (1 - FEF \times MS) \times M_{GP} \quad \text{Design Margin} = \frac{M_G}{M_{GP}} \leq 0.8
\]

- $\beta$: The planning curve shape parameter (calculated by AMSAA PM2 spreadsheet)

\[
\beta = \frac{1}{T} \left( \frac{1 - \frac{M_i}{M_G}}{MS \times FEF - \left(1 - \frac{M_i}{M_G}\right)} \right)
\]

- $M(t)$: The expected reliability, in terms of cumulative time and planning parameters (plotted in AMSAA PM2 spreadsheet)

\[
M(t) = \frac{M_i (1 + \beta \times t)}{1 + \beta \times t \times (1 - MS \times FEF)}
\]
ATEC Example of Using RG Curve to Integrate DT/OT

Planned 10% reduction in MTBF due to transition from a DT to an OT environment.

Costs in Current 2008 Dollars ($M)

- $2,457 M
- $1,701 M
- $1,103 M
- $894 M
- $869 M

ASA(ALT) Threshold is 70% of the 146 hour requirement (i.e., 104 hours). If there are 12 failures or less in the planned 2,400 hour IOT event, the MTBF requirement will be demonstrated with at least 80% statistical confidence, as required.

PM's assumed 80 hour initial MTBF. Customer test planned for 3QFY09.
The endpoint of the Design for Reliability (DfR) program ($M_i$) determines the starting point of the RG planning curve.

- Assumptions:
  - Smooth curve assumes instantaneous fixes
  - Step-function based on number of corrective action periods
  - Fixing a problem increases reliability
  - Testing will usually reveal biggest (most frequent) problems first
  - Fixing biggest problems increases reliability most
• Make sure the requirement makes sense—a promise we can keep:
  – Are failures clearly defined in the Failure Definition/Scoring Criteria (FD/SC)?
  – Why is the requirement what it is? Analytically valid?
  – Realistic? Doable compared with other analogous systems?
  – Does the mission profile make sense? It drives the whole show?

• Plan Design for Reliability (DfR) efforts such that Reliability Goal (Mg) > Reliability Requirement (Mr)—Consult your reliability analyst to determine the relationship between Mg and Mr.
Must Have A Realistic Plan (cont.)

• Plan a Reliability Growth Testing (RGT) program that:
  – Starts at a realistic Initial Reliability (Mi),
  – Is developed using realistic management metrics from comparable system,
  – Is designed to grow beyond the requirement in order to demonstrate the requirement with high statistical confidence in IOT&E,
  – Includes a sufficient amount of test assets and test time,
  – Includes periods of non-test for corrective action implementation, and
  – Is conducted in accordance with the Operational Mode Summary/Mission profile (OMS/MP).
Reliability Growth/Reliability Growth Testing (RGT)

• Uncovering failure modes is good
• Watch out for many Fix Effectiveness Factors (FEFs) better than .7
  – FEF = the fraction decrease in a problem mode Average Failure Intensity after a corrective action
  – Fertile ground for wishful thinking
  – Software is one exception
• Program decisions need to be made about when to apply the fixes
• Note: Mission Reliability is only measured during mission profiles
• Failure Definition and Scoring Criteria (FDSC) and conferences
  – All stakeholders must come to consensus on the FDSC as the system design matures
  – The OT Agency considers the technical advice of the PM and the Requirements Officer (RO), **BUT MUST** maintain independence for the suitability assessment—DOT&E memo 5 October 2012

• Other Stuff
  – Failure Reporting Analysis and Corrective Action System (FRACAS)
    • Closed loop system
    • A "process" that really needs to be efficient and effective
  – Failure Prevention and Review Board (FPRB) makes sure the process works and corrective actions are good ones
Reliability Program Scorecard

• Answers the question
  – "How well will a specific supplier use best practices to achieve the program’s reliability requirements?"

• Models
  – AMSAA Reliability Scorecard: for hardware with or without software
  – AMSAA Reliability Scorecard (Software): for software only
Summary

• R&M planning starts with establishing requirements derived from balancing life-cycle cost with mission needs.
• A R&M program comprises an integrated set of activities that include analysis, design, and test; supported by a robust FRACAS.
• A formal RG program involves the systematic identification of failure modes through analysis/testing/implementation of corrective actions to improve reliability performance.
• RG models are used for planning, tracking, and projection of a system’s estimated reliability; actual growth comes from executing DfR activities.
• Both the contractor and the government have responsibility to ensure that the contract adequately addresses R&M activities and requirements.
Reliability Growth Exercise
# PM2 Mini-Exercise

<table>
<thead>
<tr>
<th>PM2 Input Type</th>
<th>Input Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement</td>
<td>80 hours MTBF @ 80% confidence</td>
</tr>
<tr>
<td>Mi:</td>
<td>35 hours</td>
</tr>
<tr>
<td>MTBF Degradation</td>
<td>10%</td>
</tr>
<tr>
<td>MGT Strategy</td>
<td>0.95</td>
</tr>
<tr>
<td>FEF</td>
<td>0.70</td>
</tr>
<tr>
<td>DT Hours</td>
<td>10,000 hours total</td>
</tr>
<tr>
<td>DT Phases</td>
<td>5 @ 2,000 hours each</td>
</tr>
<tr>
<td>CAP</td>
<td>Yes, one per phase</td>
</tr>
<tr>
<td>CAP Length</td>
<td>300 hours</td>
</tr>
<tr>
<td>Confidence Level for IOT LCB</td>
<td>0.8 (20% Consumers Risk)</td>
</tr>
<tr>
<td>Prob. of Accept. in IOT using LCB</td>
<td>0.8 (20 % Producers Risk)</td>
</tr>
<tr>
<td>IOTE Training Time</td>
<td>400 hours</td>
</tr>
<tr>
<td>IOTE Test Hours</td>
<td>1000 hours</td>
</tr>
</tbody>
</table>
Open the PM2 tool, and enable content

Enter the numbers given
- It’s an unacceptable plan

What things could you change, to help obtain an acceptable plan?
- List at least 5 things you could change

What numbers/things are you going to change, to obtain an acceptable plan?
- Try out different options, using the PM2 tool
- What is your recommended plan?

How will your recommended changes affect the test and evaluation program?