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Setting Programs Up for Reliability Evaluation Success: A Systems Engineering Approach

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NDIA Test and Evaluation Conference; Wednesday, 14 March 2012; Session R

Mr. Grant Schmieder
gschmieder@drc.com
301-305-6727

Disclaimer

- The contents of this brief are the opinion of the presenter and do not reflect the policy or guidance of DASD(SE)
- This brief is designed to open dialog on the benefits of re-instituting evaluation approaches from MIL-HDBK-781 and MIL-HDBK-108 that reflect:
  - Potential savings in schedule and cost during test events where Reliability is significantly above or below requirements
  - Potential to reach decisions more quickly and with controlled risk in schedule and/or resource constrained environments
  - Implementation of commercial best practices
- Use of the PM2 Growth Model is by expedience and any similar model may have been used
- Introduce idea of unscored (for Reliability) “training” period at introduction of IOT&E
  - Reduces failures due to inadequate documentation and/or familiarity with system
- Discusses Reliability evaluation only and does not address other MOS/MOE evaluation

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Outline

- Objective
- Definitions
- Discussion of "Key Issues in Reliability Growth" by Dr. Gilmore
- Importance of Producer's Risk
- Test Issues and Concerns
- Proposal for Applying Commercial (and Pre-Acquisition Reform Defense) Approach to Reliability Evaluation During Testing

Briefing Objective

- Provide One Reliability Professional's Perspective on Gaining Efficiencies in Testing without Losing Needed Accuracy
- Provide Overview of Current State According to DOT&E
- Review Basics of Reliability Test Design
- Identify Issues Requiring Decisions Early During Development Cycle to Achieve Test Success
- Evaluate "Design to Test" Approach Pros and Cons
- Initiate Discussion Regarding Utilizing Sequential Testing to Reduce Cost and Schedule Effects

Definitions Used

- From MIL-HDBK-108:
  - Length of Life: The terms “length of life” and “time to failure” may be used interchangeably and shall denote the length of time it takes for a unit of product to fail after being placed on life test. The length of time may be expressed in any convenient time scale such as seconds, hours, days, etc.
  - Mean Time to Failure: The terms “mean time to failure” and “mean life” may be used interchangeably and shall denote the mean (or equivalently, the average) length of life of items in the lot. Mean life is denoted by θ.
  - Acceptable Mean Life: The acceptable mean life, θ_0, is the minimum mean time to failure which is considered satisfactory.
  - Unacceptable Mean Life: The unacceptable mean life, θ_1, ($\theta_1 < \theta_0$), is the mean time to failure such that lots having mean life less than or equal to θ_1 are considered unsatisfactory. The interval between θ_0 and θ_1 is a zone of indifference in which there is a progressively greater degree of dissatisfaction as the mean life decreases from θ_0 to θ_1.
  - Operating Characteristic Curves: The operating characteristic (OC) curve of a life test sampling plan is the curve which shows the probability that a submitted lot with a ***given mean life*** would meet the acceptability criterion on the basis of that sampling plan.
  - Producer’s Risk: The producer’s risk, α, is the probability of rejecting lots with mean life θ_0. …the producer’s risk may also be defined as the probability of rejecting lots with acceptable proportion of lot failing before specified time, p_0. (Note: AKA Type I Failure)
  - Consumer’s Risk: The consumer’s risk, β, is the probability of accepting lots with mean life θ_1. …the consumer’s risk may also be defined as the probability of accepting lots with unacceptable proportion of lot failing before specified time, p_1. (Note: AKA Type II Failure)

The key is balancing the size of the “zone of indifference” through test design and assignment of Producer’s and Consumer’s Risks!

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Current State: Discussion of “Key Issues in Reliability Growth” Presented by Dr. Gilmore

- The Honorable Dr. Michael Gilmore, D,OT&E, presented “Key Issues in Reliability Growth” to the National Academy of Science Panel on the Theory and Application of Reliability Growth Modeling in Defense Systems on September 22, 2011
  - URL: http://www.dote.osd.mil/pub/presentations/Gilmore-NAS-presentation-finalv1.pdf

- The following slides extract applicable background information from Dr. Gilmore’s briefing…

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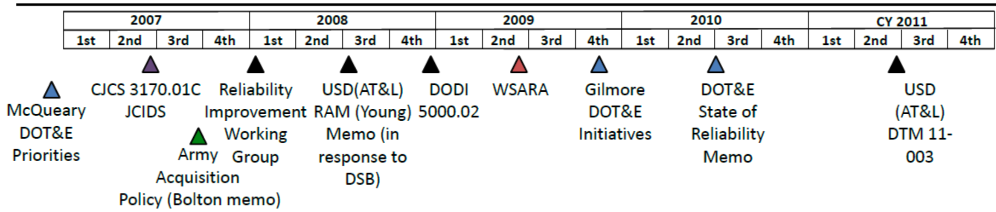
Chronology of Reliability Improvement Steps Since 2007

DoD Steps Taken to Improve Reliability



- Reliability (MTBF) is a key factor in O&S costs of systems
  - Additional burden to user in unscheduled maintenance and down time
- DOT&E top priority since 2006 has been to improve suitability of fielded systems, in addition:
  - Army Acquisition Policy
  - Joint Staff Directive
  - Defense Science Board Study
  - Congressional Language
  - USD (AT&L) policy updates

DoD needs systems that are effective when needed, not just effective when available

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From my perspective:

- CJCS 3170.01 "Grandfathered" programs from the Sustainment KPP leading to a delay in realizing improvements
- USD(AT&L) Memo Highlights: "Further, effective immediately, it is Department policy for programs to be formulated to execute a viable RAM strategy that includes a reliability growth program as an integral part of design and development."
- USD(AT&L) DTM 11-003 issued to establish proscriptive steps required for R&M during program acquisition and operation

There is a minimum time to results required when Reliability Policy changes are made—we should be seeing these improvements soon as programs that were initiated after 2007 proceed through OT&E, but expectations of immediate improvement may be unfounded.

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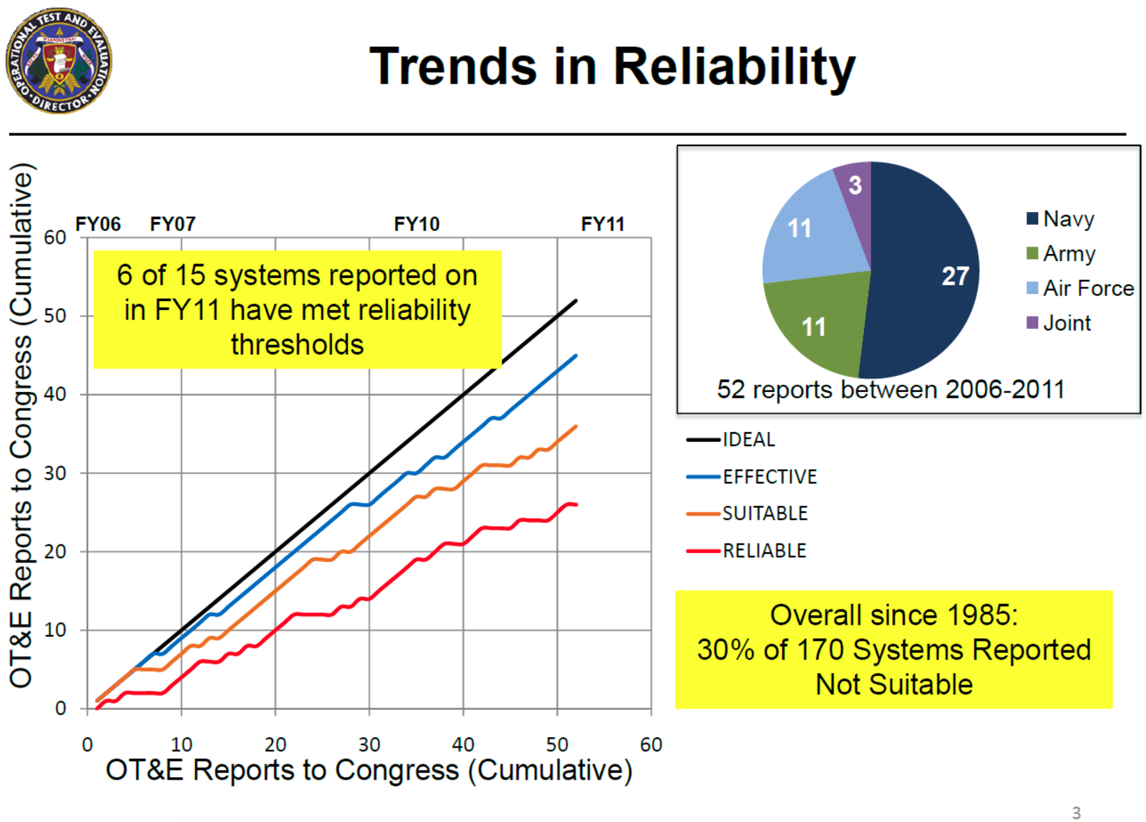
D,OT&E Analysis of Trends in Reliability Test Results



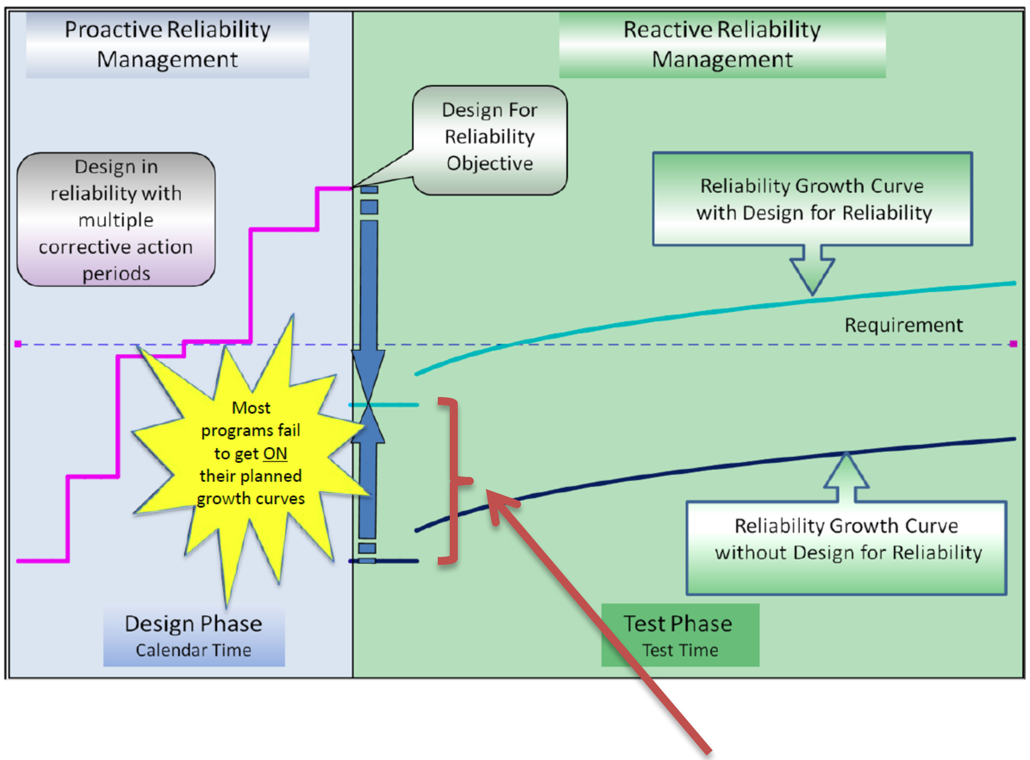
From my perspective:

- Similar trends were detailed in the DSB report
- Issues with determining Reliability during OT events include:
  - Was the test properly designed?
  - Was the Producer's Risk acceptable? (aka probability of type I error)
  - Was the FD/SC consistent with the CONOPS?
  - Was the test conducted under realistic operational scenarios?

Cancellation of MIL-HDBK-108 on 31 January 2002 has led to loss of rigor in test design especially with respect to properly applying Producer's Risk through the use of the Operating Characteristics Curve

D,OT&E Reliability Management Approach

Reliability Management



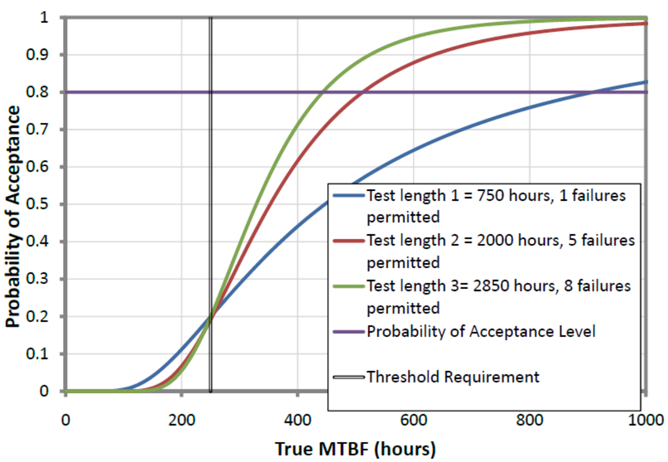
From my perspective:

- One major reason programs fail to get on their planned growth curves is setting unrealistic $MTBF_i$ values when planning growth
- Proactive Reliability Management is one of the objectives of DTM 11-003!

Without proactive management, achievement of the required MTBFi has proven to be high risk!

D,OT&E Test Design Concepts

Test Design Concepts



Simple 3x requirement rule of thumb underestimates risk by only allowing for one failure

- **The risk associated with incorrect decisions (accepting a unreliable system or rejecting a reliable system) need to be considered in test planning.**
- **Operating Characteristic (OC) curve analysis should be used to mitigate risk in demonstrating reliability requirement.**
  - Used to determine risks (Type I and Type II errors)
  - Comparison across multiple curves helps gauge sample size as a function of allowable failures and risk.
- **Risks for reliability demonstration tests should be evaluated quantitatively, and balanced against constraints for cost and schedule**

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From my perspective:

- Proper application of these concepts is necessary to re-establish rigor in Reliability evaluation
- For a Unit Under Test (UUT) with a given true MTBF, the Producer's Risk is a function of the requirement, the true MTBF (aka "the true state of nature"), the confidence level specified, and the test length
- Thus Producer's Risk and Consumer's Risk are not independent!!!!!

Many programs set the Consumer's Risk (1 – confidence) and test length separately leading to unacceptable Producer's Risk!

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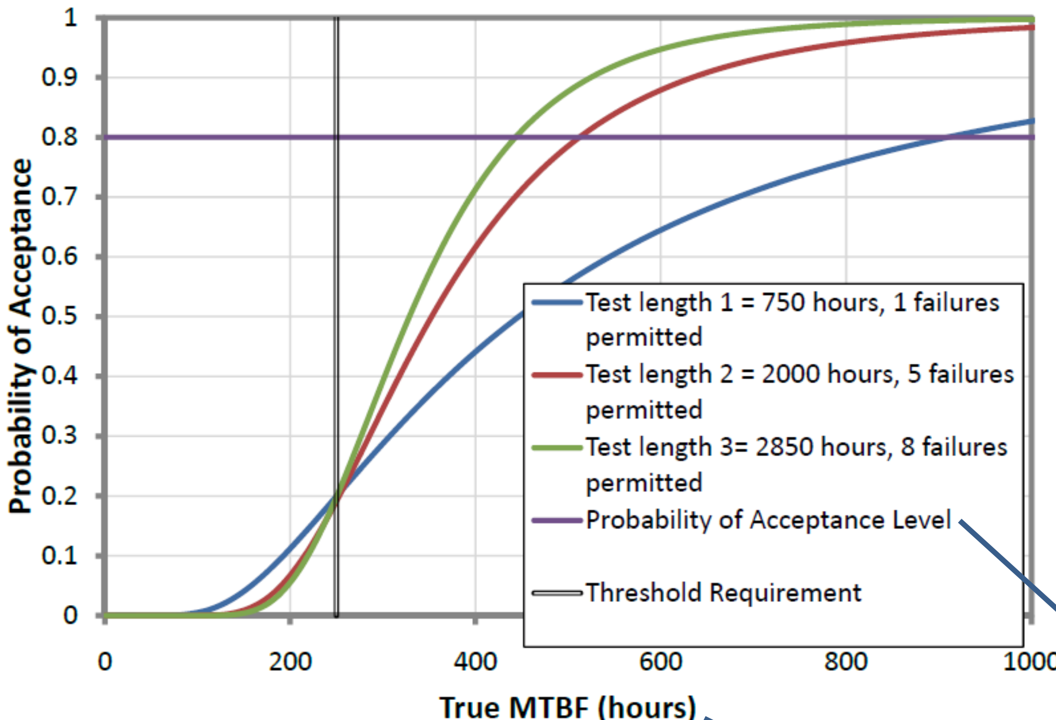
Importance of the Operational Characteristics Curve (OC)

Simple 3x requirement rule of thumb underestimates risk by only allowing for one failure

The issue is the probability of seeing only "x" failures in a test of a given length



"True State of Nature"

Different Test Plans

From my perspective:

- The system has to achieve a True MTBF above the requirement if having an 80% Probability of Acceptance is the goal
- Programs have made statements like:
  - "80% confidence will be demonstrated when the test is completed with x or fewer failures"
- One program had a 25% chance of seeing x or fewer failures given their design and test plan
- Another program had less than a 5% chance of seeing x or fewer failures

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Explanation of Producer's Risk (AKA Type I Error)

- In any test of a parameter that is conducted on a subset of a population the result of the test will be a random variable based on the true value of the parameter throughout the population
  - As an example, a reliability test on a missile system might be structured like this:
    - N = 1000 Where N is the total population of missiles
    - n = 10 Where n is the total number of missiles tested
    - $R_{hat} = 1 – (k/n)$ Where k is the observed number of failures during the n test events
    - $R_{rqt} = 0.80$ Where R_{rqt} is the reliability value to be demonstrated
    - $R^* = X.XX$ True unknown state of nature
  - This can be shown to be a hypothesis test with:
    - $H_O: R^* \geq R_{rqt}$ vs. $H_1: R^* < R_{rqt}$
    - The possible test results fall in the set k = {0, 1, 2, …, 10}
    - The random variable, k, can take on any value in this set for any possible value of $0 < R^* < 1$
      - Because if $R^* = 1$, then k = 0 since the missiles are perfect; alternately, if $R^* = 0$, then k = 10 because the missiles will not work

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Explanation of Producer's Risk (AKA Type I Error) (Cont.)

- The decision cube for this is:

DECISIONS		True State of Nature	
		H_O is true	H_1 is true
	Reject H_0	Type I error	Correct Decision
	Fail to Reject H_0	Correct Decision	Type II error

- The test result we observe is k—and we only observe it after the test
- We do not know the value of R* and cannot know it unless we test all 1000 missiles in the population—of course this would leave us with no missiles for actual use in the field
- What we can do is determine the probability that k will take on each value in the result set given various potential values of R*

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Explanation of Producer's Risk (AKA Type I Error) (Cont.)

- This is done using the Poisson distribution and the resulting analysis for selected values of R* is:

<table>
<tr><th></th><th colspan="3">Value of R*</th><th rowspan="3">Value of R_{hat} = {1 – (k / n)} * 100%</th><th colspan="6">Test Result Given R* Value</th></tr>
<tr><th></th><th>0.70</th><th>0.80</th><th>0.90</th><th colspan="2">R* = 0.70</th><th colspan="2">R* = 0.80</th><th colspan="2">R* = 0.90</th></tr>
<tr><th>Observed Value of k</th><th colspan="3">Cumulative probability that the test result is ≤ k</th><th>R* = 0.70</th><th>Prob. of T-II Error</th><th>R* = 0.80</th><th>Prob. of T-I Error</th><th>R* = 0.90</th><th>Prob. of T-I Error</th></tr>
<tr><td>0</td><td>4.98%</td><td>13.53%</td><td>36.79%</td><td>100%</td><td rowspan="3">Type-II Error</td><td rowspan="3">42.32%</td><td rowspan="3">Correct</td><td rowspan="3">NA</td><td rowspan="3">Correct</td><td rowspan="3">NA</td></tr>
<tr><td>1</td><td>19.91%</td><td>40.60%</td><td>73.58%</td><td>90%</td></tr>
<tr><td>2</td><td>42.32%</td><td>67.67%</td><td>91.97%</td><td>80%</td></tr>
<tr><td>3</td><td>64.72%</td><td>85.71%</td><td>98.10%</td><td>70%</td><td rowspan="8">Correct</td><td rowspan="8">NA</td><td rowspan="8">Type-I Error</td><td rowspan="8">32.33%</td><td rowspan="8">Type-I Error</td><td rowspan="8">8.03%</td></tr>
<tr><td>4</td><td>81.53%</td><td>94.73%</td><td>99.63%</td><td>60%</td></tr>
<tr><td>5</td><td>91.61%</td><td>98.34%</td><td>99.94%</td><td>50%</td></tr>
<tr><td>6</td><td>96.65%</td><td>99.55%</td><td>99.99%</td><td>40%</td></tr>
<tr><td>7</td><td>98.81%</td><td>99.89%</td><td>100.00%</td><td>30%</td></tr>
<tr><td>8</td><td>99.62%</td><td>99.98%</td><td>100.00%</td><td>20%</td></tr>
<tr><td>9</td><td>99.89%</td><td>100.00%</td><td>100.00%</td><td>10%</td></tr>
<tr><td>10</td><td>99.97%</td><td>100.00%</td><td>100.00%</td><td>0%</td></tr>
</table>

Explanation of Producer's Risk (AKA Type I Error) (Cont.)

- If we simply use the point estimator to determine the test result, then if $k \leq 2$ the test result will be a pass since $1 - (k/n) \geq R_{rqt}$
  - The problem with this is that for $R^* = 0.70$, for which the test should be failed, there is a 42.3% chance that $k \leq 2$
    - This is the chance of Type II error, failing to reject H_O when it is in fact false
    - This probability, 42.3%, is called the Consumer's Risk of the test because the consumer would suffer the effects of lower reliability than desired
  - Conversely, for $R^* = 0.80$, the chance of rejecting H_O even though it is actually true, is 32.33% (for $R^* = 0.90$ this probability is reduced to 8.03%) which is the chance of Type I error
    - Type I error is also known as the Producer's Risk of the test because the producer suffers from the rejection of H_O when it is actually true
- These values will change with the length of the test—if the test is shortened while Consumer's Risk is held constant the Producer's Risk will increase.
- If the test is lengthened while the Consumer's Risk is held constant the Producer's Risk will decrease

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Test Example, Issues, and Concerns

- The example is for an imaginary system with a requirement for a 20 hour MTBF
  - Initial MTBF (M_I) is anticipated to be 14 hours entering the contractor test phase
  - The program has agreed to a management strategy (MS) of 95% and a fix effectiveness (μ_G) of 75%
  - Test plan includes 80% Consumer's Risk and 80% Producer's Risk
- The described test program is fully viable
- The initial event of 250 contractor test hours is followed by a corrective action period (CAP)
  - All corrective actions are performed after the test event (i.e. all fixes are delayed)
- Development Testing consists of two formal DT events with a reliability growth test in between
  - Initial reliability evaluation will be performed during DT event #1
- IOT&E consists of a 50 hour training period followed by a 300 hour test

Test Example, Issues, and Concerns (Continued)

PM2 Reliability Growth Planning Curve

AMSAA Continuous Model - Version 1.0

*** Blue font indicates input ***

About PM2

Test Schedule Input Option: (•) General Schedule ( ) Detailed Schedule

Reliability Growth test broken into four phases encompassing 850 test hours with corrective action periods (CAPs).

Developmental Test - Schedule Summary

	Test Phase Name	Mission Time in Test Phase	Cumulative Test Time	CAP at End of Phase?	Corrective Action Lag Time for Individual CAP	Cumulative Time at CAP minus Lag
TP 1 Schedule	Contractor Test	250	250	Yes	0	250
TP 2 Schedule	DT Test Event #1	150	400	Yes	0	400
TP 3 Schedule	Reliability Growth Test #1	250	650	Yes	0	650
TP 4 Schedule	DT Test Event #2	200	850	Yes	0	850
TP 5 Schedule	IOT&E	350	1,200	No		850
TP 6 Schedule						
TP 7 Schedule						
TP 8 Schedule						
TP 9 Schedule						
TP 10 Schedule						

IOT&E consists of 50 training hours followed by a 300 hour test. IOT&E is included in growth curve.

Is IOT incorporated in the Planning Curve?	Yes

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Test Example, Issues, and Concerns (Continued)

IOT Inputs	
IOT Training Test Time	50
IOT Phase Test Time	300
Assumed DT to IOT Degradation Factor	0.10

Requirement MTBF (M_R)	20
Initial MTBF (M_I)	14
Management Strategy (MS)	0.95
Average FEF (μ_d)	0.75
Confidence Level for IOT LCB	0.80
Prob. of Accept. in IOT using LCB	0.80
Prob. of Accept. In IOT using Pt. Est.	0.98
Goal MTBF in IOT (M_R^*)	33
Goal MTBF in DT (M_G)	37
Growth Potential (M_{GP})	49
M_G/M_{GP} Ratio	0.76

IOT&E consists of 50 training hours followed by a 300 hour test.

Degradation factor of 10% intended to account for use in new environments and with operational testers.

Planning Curve

Suggestions to Lower Ratio

- Confidence level for IOT LCB is 80%
  - In order to pass IOT with the stated confidence, the design goal (M_G) during the development testing events is 37 hours
  - If the 37 hour MTBF is achieved, then the resulting IOT entry MTBF (M_R*) will be 33 hours after the 10% degradation factor
    - The 33 M_R* provides a 98% probability that the MTBF point estimate during IOT will be above the 20 hour MTBF requirement but only an 80% probability that the lower confidence bound will be above 20 hours

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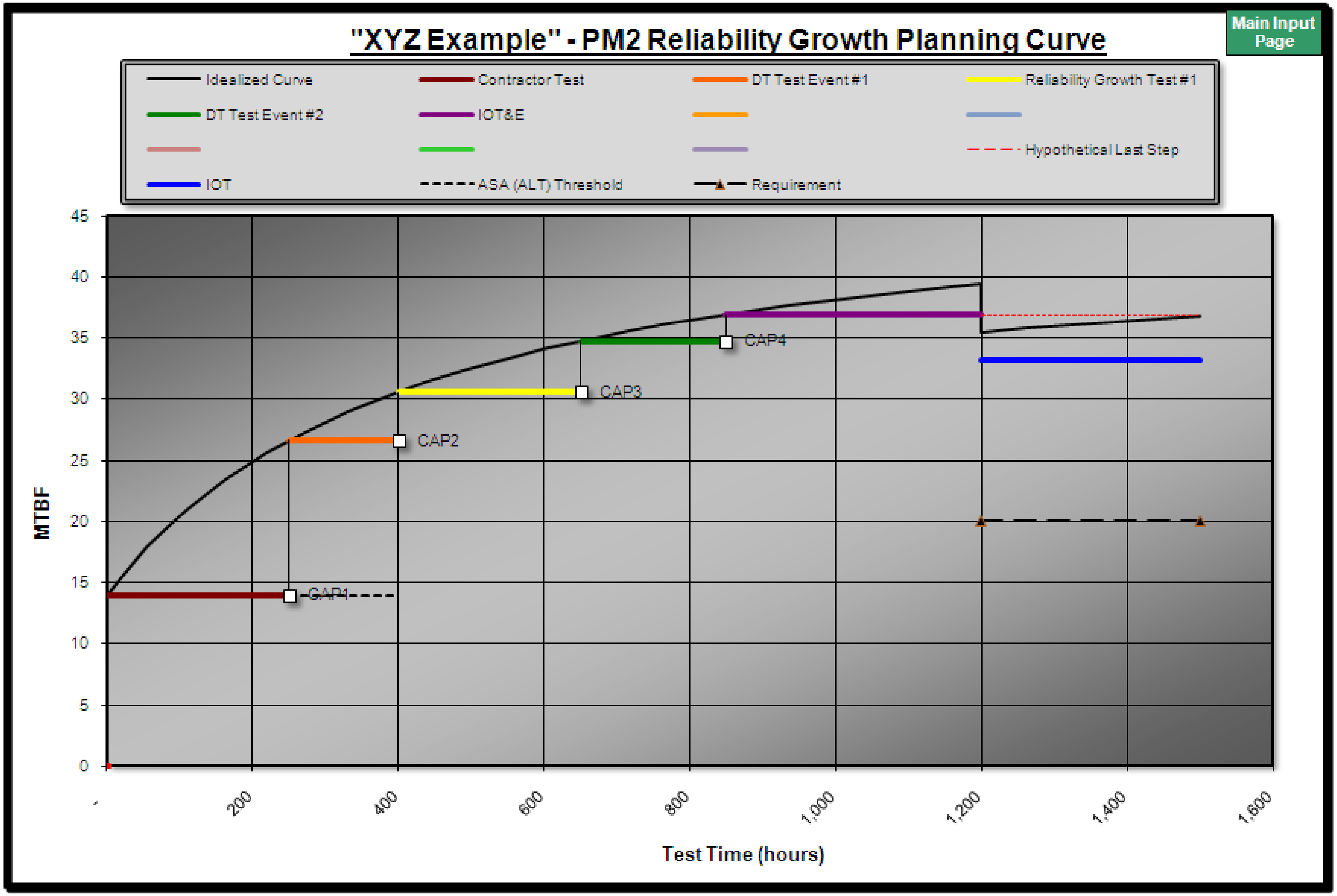
Test Example, Issues, and Concerns (Continued)



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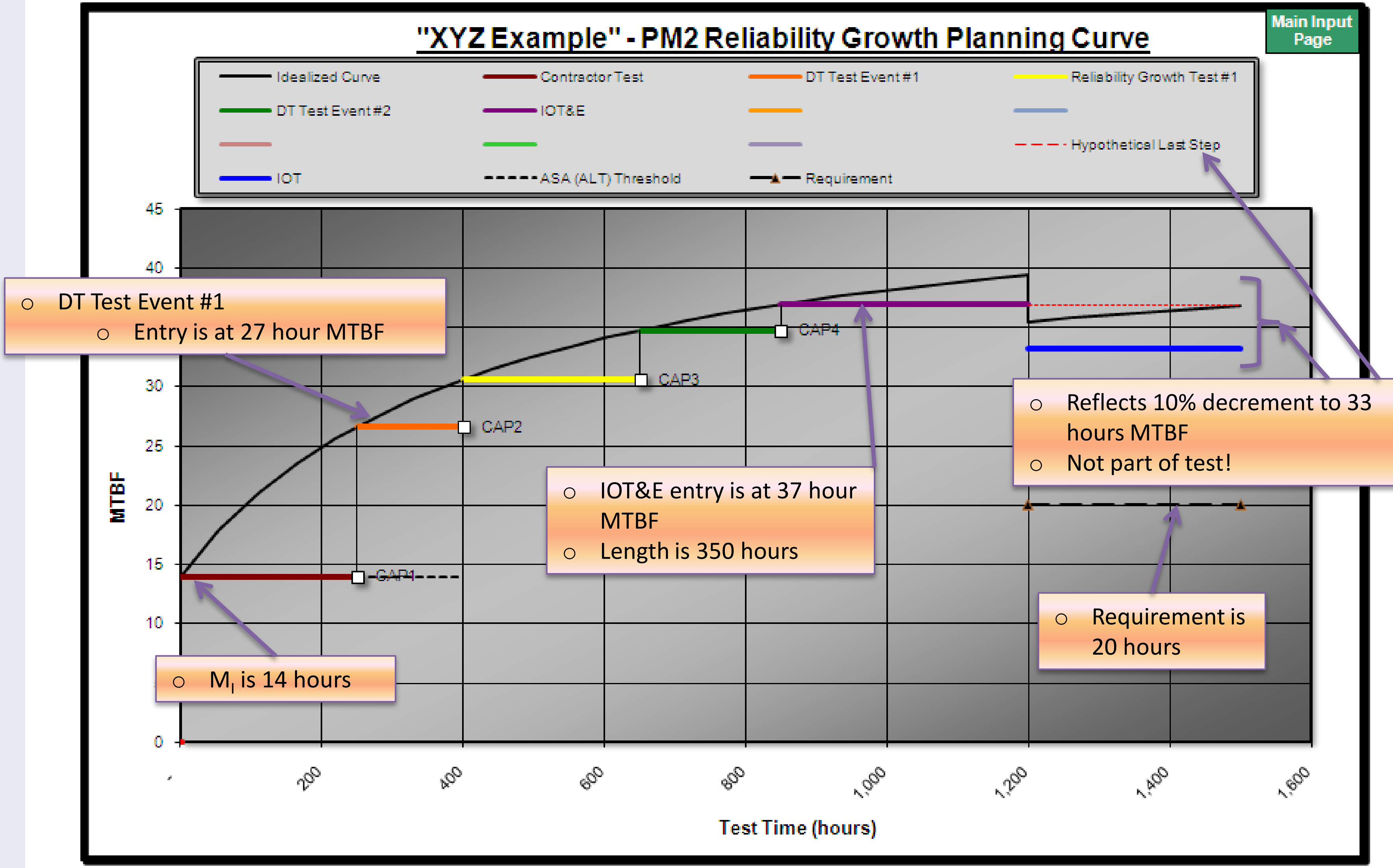
Test Example, Issues, and Concerns (Continued)



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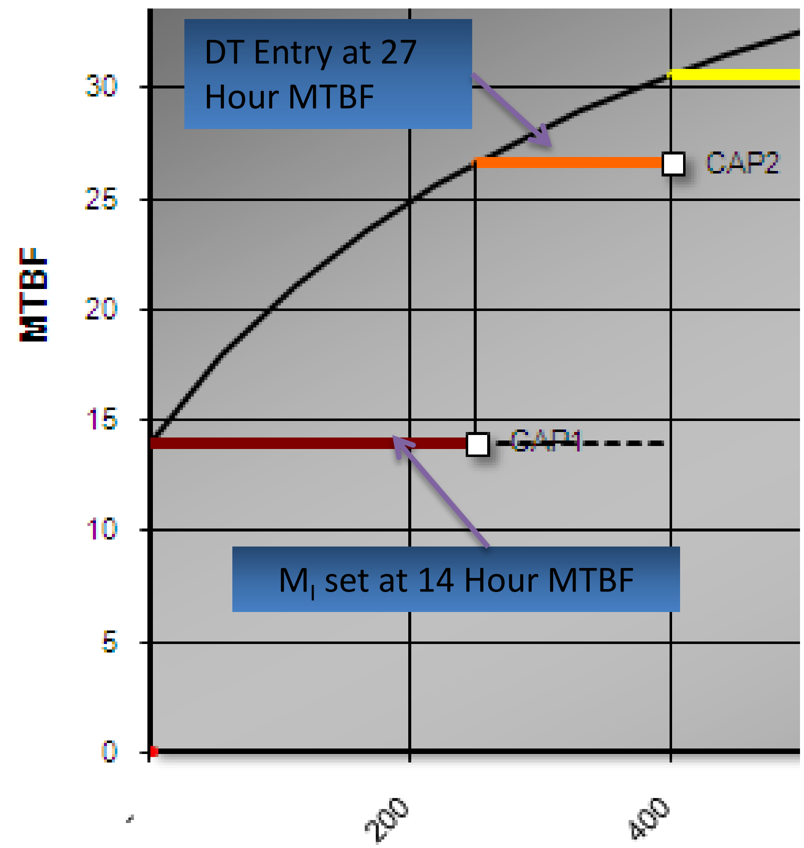
DT Event #1 Probability of Acceptance Explanation

- DT Event #1 is 150 hours long
- Event is failed Upper Control Bound (UCB) is below growth curve (i.e. less than 27 hours)
  - ***This is the only statistically valid use of the test results due to being in the "Zone of Indifference" if the UCB is above and the LCB below***
  - If the UCB is above the curve, then the test result cannot exclude the possibility that the program is on the curve at the given confidence level!
- The test fails if 10 or more failures occur:
  - UCB: 24.1 Hours < 27 Hours
  - Point Estimate: 15.0 Hours
  - LCB: 9.74 Hours
- The test Passes if 9 or fewer failures occur:
  - UCB: 27.61 Hours
  - Point Estimate: 16.67 Hours
  - LCB: 10.56 Hours



Customer Test and DT Event #1 Portion of Growth Curve

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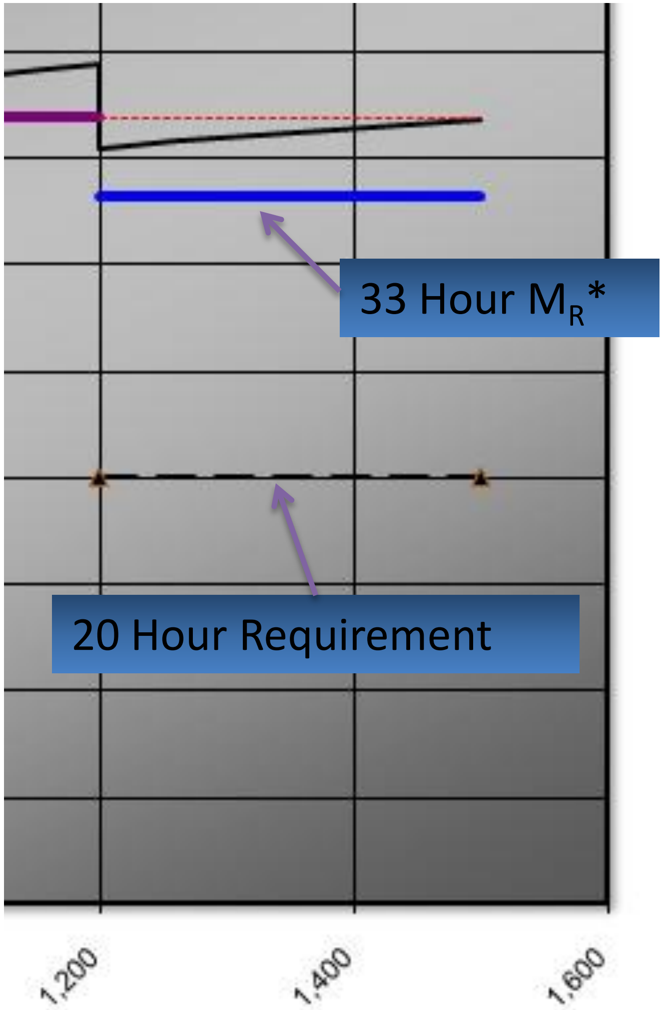
IOT&E at 80% Confidence (Designed)

- IOT&E is 300 hours long
- Event is failed if Lower Control Bound (LCB) is below requirement (i.e. less than 20 hours)
  - *This is the only statistically valid use of the test results due to being in the "Zone of Indifference" if the UCB is above and the LCB below*
  - If the LCB is below the requirement, then the test result includes the possibility that the MTBF is less than 20 hours at the given confidence level
- The test fails if 10 (or more) failures occur:
  - UCB: 48.2 Hours
  - Point Estimate: 30.0 Hours
  - LCB: 19.5 Hours < 20 Hours
- The test Passes if 9 (or fewer) failures occur:
  - UCB: 55.2 Hours
  - Point Estimate: 33.3 Hours
  - LCB: 21.1 Hours
- This puts the Program Manager and Sponsor in a Difficult Position:
  - We are interested in proving that the 20 hour system requirement is met with 80% confidence
  - The growth curve is designed to result in a 33 hour M_R*--which provides the necessary 80% confidence that the test result will be an LCB above 20 hours
  - Do they design to the requirement (20 hours) or to the test (33 hours)?



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Example Reflects A "Design to Test" Approach…and has Pros and Cons

- Policy is to design to the test
  - This decision best supports the need to quickly field systems without repeated OT events
- Being "on" the growth curve means the test result contains the corresponding value on the curve
  - Analysis is performed at the specified confidence level
  - A lower confidence level (say 50% versus 80%) makes the test easier to fail
    - This is because the 80% UCB is ALWAYS greater than the 50% UCB
- A properly designed growth curve, like the one in this example, provides a reasonable probability that the desired requirement will be evaluated as being met during IOT
  - System reliability is grown to the proscribed M_R* value which is sufficiently above the requirement to ensure the PLANNED test will be passed at the specified confidence
- ***Note that this means we are designing the system to significantly exceed the stated reliability requirement (in the example, the system is developed to have a 33 hour MTBF versus the 20 hour requirement)***
  - If the field requirement is actually as stated, then this is an inefficient approach to ensure "suitability" for our systems as it requires overdesign and longer development cycles for no reason other than passing a single test event
  - A more efficient method would be implementation of sequential testing to limit both the consumer's and producer's risks with continuing follow-on evaluation after IOC

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Proposal for Applying Commercial (and Pre-Acquisition Reform Defense) Sequential Test Approach to Reliability Evaluation

- MIL-HDBK-108 and MIL-HDBK-781 both include sequential test methodologies
  - Since the cancellation of MIL-HDBK-108 (31 January 2002) and the Guidance Only status change to MIL-HDBK-781 (1 April 1996), the use of sequential testing has virtually ceased within the DoD
  - Sequential testing is the method of choice within Industry when getting a product to market is crucial
    - Sequential tests are designed to identify when the test result moves out of the "Zone of Indifference" within accepted risk levels
  - MIL-HDBK-781, Paragraph 5.9.2, p. 37:
    - "PRST plans will accept material with a high MTBF or reject material with a very low MTBF more quickly than fixed-duration test plans having similar risks and discrimination ratios"

Program time and schedule pressures may force the Program Manager to consider and early termination of test AND/OR accepting a high producer's risk due to inadequate planned test times—truncated sequential testing is one way to deal with these issues

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Proposal for Applying Commercial (and Pre-Acquisition Reform Defense) Sequential Test Approach to Reliability Evaluation

- **Recommendation:**
  - Test plans for OT events should include sequential test "off-ramps" built in
  - Traditional test plans can be developed and implemented as they are currently
    - Data analysis during testing should include sequential test analysis, per MIL-HDBK-781, so that tests will be shortened when reliability is much better than needed (passing test) or when reliability is much worse than needed (failing test)
    - If an estimate of UUT reliability is necessary, the base test can be run to completion even after a sequential test related decision is implemented
  - Industry uses sequential test decision points to establish system suitability for release as quickly as possible
  - When necessary (usually due to economically based warranty needs), tests will be run past a sequential test decision in order to establish the best estimate of MTBF possible

From a time and cost standpoint, sequential testing is the way to determine initial reliability suitability through test

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Considerations for Test Plans

- Private industry understands that time to market is key to success
  - In Defense, this is equivalent to reduced development times needed to support Urgent Operational Needs or simply to optimize cost and schedule
- Cost and Schedule pressures plus loss of rigor since Acquisition Reform of the 1990's has led to execution of inadequate and/or high risk test plans usually based on time truncated testing
  - Could this be the source of at least some system failures in meeting their Reliability thresholds?
- Designing systems to pass OT events can result in significant cost, schedule, weight, etc. overruns from what is really necessary for the warfighter
  - Note the example:
    - Warfighter asked for 20 hr MTBF during operational use
    - Test plan required achievement of a 33 hr MTBF so that there would be an 80% chance that the LCB would be more than 20 hrs
  - *Did the Warfighter need a 33 hr MTBF?*
  - *If so, why was the requirement set to 20 hrs?*
  - *If a 20 hr MTBF is suitable, why are we designing the system to meet 33 hrs?*
  - *Are the increased cost, schedule, complexity, and weight of a 33 hr MTBF system justified?*

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In an era of austerity and rapidly changing threats, reduction of time to field through minimum required testing is good for the Warfighter, the Taxpayer, and the Country

Questions?

- Contact Information:
  - Grant Schmieder
  - gschmieder@drc.com
  - 301-305-6727

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Backup

- **Abstract ID: 13957**
- **Title:** Setting Programs Up for Reliability Evaluation Success: A Systems Engineering Approach
- **Abstract Text:** Across the spectrum of DoD Acquisition, one constant seems to keep occurring: programs are evaluated as "unsuitable" due to Reliability shortcomings uncovered during Operational Testing. How does this continue to happen given the Acquisition Community's extensive efforts to correct the issue over the past few years? And, more importantly, what can be done to fix the problem? The presentation will discuss the requirements generation process for Reliability, from the definition of the Operational Need through the completion of IOT&E. Examples will be shown to illustrate developmental issues. These will include initial requirement definition, incomplete or inaccurate translation to system specifications, inadequate coverage of chosen Reliability metrics, poor Failure Definitions and Scoring Criteria development, etc. As a proposed solution, a Systems Engineering based approach, based on guidance in the RAM-C Report Manual and policy driven by DTM 11-003, will be presented. The solution includes involving all stakeholders in the development and planning of the system's Sustainment KPP (Availability, both Materiel and Operational) and its associated KSAs (Reliability and Ownership Cost), FDSC, and proposed test plan. Finally, the presentation will include a discussion of Commercial versus Defense test approaches including the value of sequential testing normally used in industry.

Presenter's Related Background

- **Education:**
  - BS Engineering, Santa Clara University, 1983
  - MS Systems and Industrial Engineering, University of Arizona, 1998
- **Certifications:**
  - American Society for Quality Certified Reliability Engineer since 2000
  - Holder of Professional Certificate in Reliability and Quality, University of Arizona, 1998
- **Applicable Experience:**
  - 1984 to 1995 Logistics Engineer, Hughes Missile Systems, Tucson, Az
  - 1995 to 2000 Reliability Engineer, Hughes/Raytheon Missile Systems, Tucson, Az
  - 2000 to 2007 Reliability Lead, IGEN/BioVeris Corporation, Gaithersburg, MD
  - 2007 to Present Senior Reliability Engineer, High Performance Technologies Group
  - Member of RIWG, 2008
  - Provided input to USD(AT&L) RAM Memo, 2008
  - Provided DODI 5000.02 and CJCS 3170.01 inputs, 2008 and 2009
  - Principle author of RAM-C Report Manual, 2009
  - Provided technical support to RSSG, 2010
  - Reviewed or supported more than 100 DoD Acquisition programs, 2007 to present

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