Reliability Growth Planning with PM2

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Agenda

- Terminology
- Test-fix-test reliability growth process
- Relationship between reliability demonstration and reliability growth planning
- Planning curve development
- Risk assessments for planning curve
- Model demo

Terminology

- **Failure Mode**
  - The manner by which a failure is observed
  - Generally describes the way the failure occurs and its impact on equipment operation
- **Corrective Actions (fixes)**
  - Changes to the design, manufacturing process, operating or maintenance procedures for the purpose of improving reliability
- **Repair**
  - The refurbishment or replacement of a failed part with an identical unit in order to restore the system to be operationally capable

Reliability Growth Process

(It's more than just developing a curve)

Design for Reliability (DfR)

- Component-level Testing
- Physics of Failure (PoF)
- Results in initial system design

Developmental Testing (DT)

- Enter DT with Initial MTBF (M_I)
- Discover Failure Modes
- Grow to Goal MTBF in DT (M_G)

Demonstration Test (IOT)

- Fixed Configuration Test to Demonstrate Req't w/ Confidence
- Enter with Goal MTBF in IOT (M_R^+)

Failure Mode Analysis & Corrective Action Implementation

Root Cause Analysis → Development of Corrective Actions

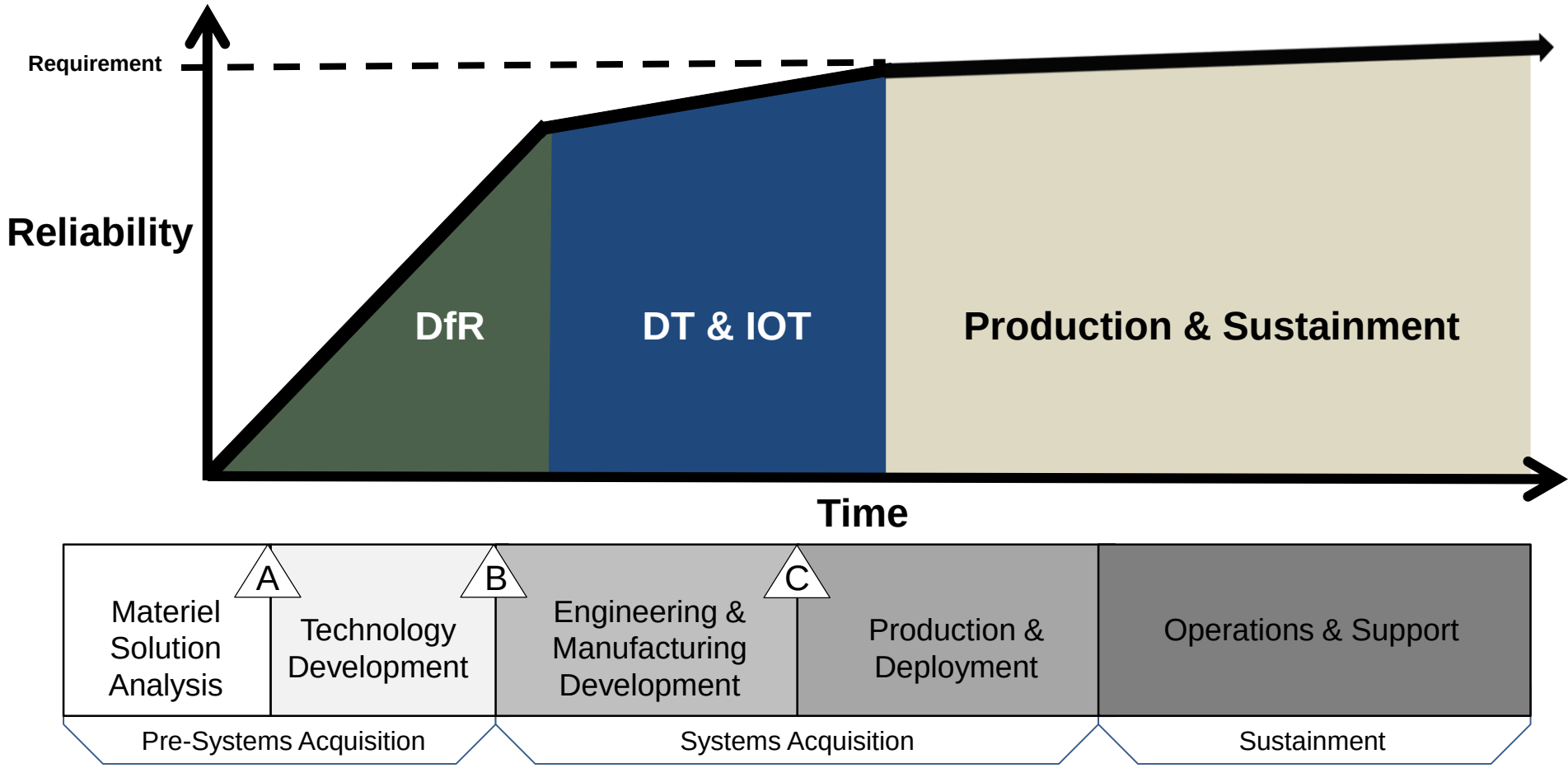
Reject

Failure Prevention and Review Board
- Corrective Action Review and Approval
- Assignment of Fix Effectiveness Factors

Accept

Corrective Action Implementation to Prototypes → Verification of Corrective Actions

Reliability vs. Time

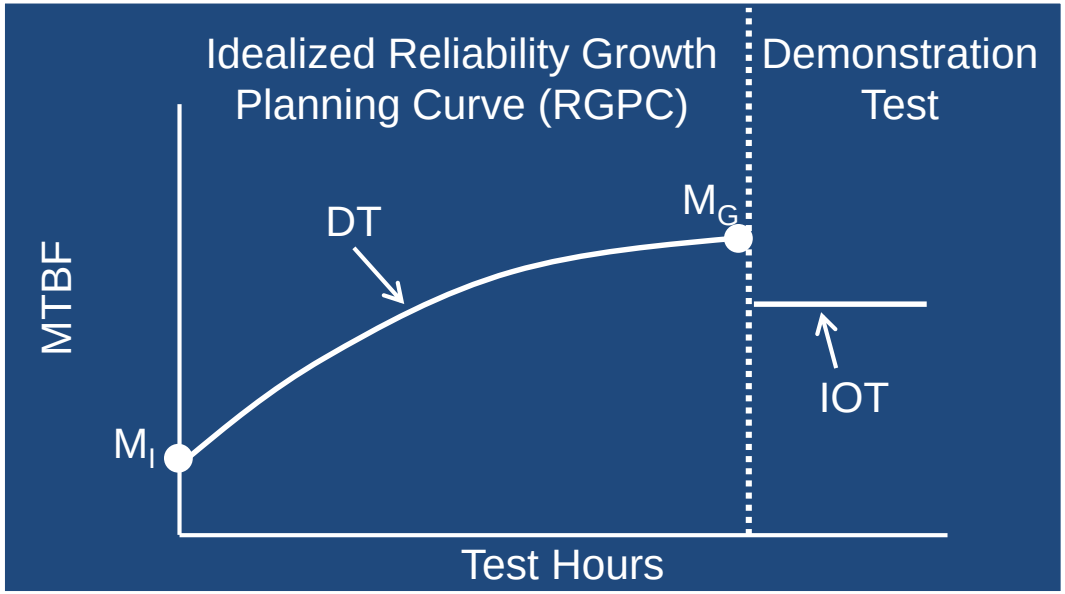


DfR can provide the most reliability improvement in the shortest time

Importance of Rel. Growth Planning

- Establish a realistic RGPC that provides interim reliability goals and serves as a baseline against which reliability assessments can be compared
- Determine the extent of DfR activities that need to occur prior to system-level DT
- Establish a test schedule and corrective action strategy that optimizes test resources
- Obtain necessary resources (test articles, facilities, support equipment, test personnel, data collectors, analysts, engineers, etc.)
- Identify and mitigate potential risks in order to increase the likelihood of passing the demonstration test
- Estimate O&S costs

Relationship Between Planning and Demonstration



Planning:

- Establish goals for surfacing failure modes and implementing corrective actions to allow the system to grow from an initial reliability (M_I) to a goal reliability (M_G)
- Multiple test phases followed by Corrective Action Periods (CAPs), evolving configuration, stressed per OMS/MP

Demonstration:

- Demonstrate the reliability requirement with high statistical confidence
- Fixed length, fixed configuration, stressed per OMS/MP

Planning Process

Step 1: Determine a DT reliability goal (M_G) that provides a high probability of demonstrating the requirement in IOT

Step 2: Develop a feasible reliability growth plan that uses management metrics and DT test time to achieve M_G

PM2 uses a backwards planning approach

Planning Process

Step 1: Determine a DT reliability goal (M_G) that provides a high probability of demonstrating the requirement in IOT

Step 2: Develop a feasible reliability growth plan that uses management metrics and DT test time to achieve MG

Risks Associated with Reliability Demonstration Testing

- Before developing a reliability growth plan, program management needs to establish how the reliability requirements will be demonstrated
- Typically, programs conduct a demonstration test (e.g. IOT) to allow the Government to determine if the system meets the MTBF requirement, M_R
- IOT should be designed to mitigate the risk of making a wrong decision

Decision at end of Demonstration Test

System's True MTBF	Pass	Fail
At or Above M_R	Probability of Acceptance (P(A))	Producer's (Contractor's) Risk
Below M_R	Consumer's (Government's) Risk	Confidence

Use OC Curve to mitigate risks

= Right Decision = Wrong Decision

Determine Test Duration & Max Failures

MTBF Requirement (M_R):

- 148 hr MTBF to be demonstrated with 80% confidence

What is "confidence"?

- Confidence = 1 – Consumer's Risk
- Consumer's (Govt's) Risk = probability that Govt accepts a system that has a true MTBF < M_R
- Consumer's Risk is mitigated by designing an IOT that utilizes a LCB to demonstrate M_R

Question:

- What test durations and max number of failures allow M_R to be demonstrated with 80% confidence?

Answer:

- For a desired IOT Duration, find the maximum number of allowable failures, *c*, where *c* is the largest positive integer *k* such that

$$\sum_{i=0}^{k} \frac{\left(\frac{\text{IOT Duration}}{M_R}\right)^i \exp\left(-\frac{\text{IOT Duration}}{M_R}\right)}{i!} \leq \text{Consumer's Risk} \qquad \text{(Equation 1)}$$

- For a 2,400 hour IOT, the maximum number of allowable failures is 12

$$\sum_{i=0}^{12} \frac{\left(\frac{2{,}400}{148}\right)^i \exp\left(-\frac{2{,}400}{148}\right)}{i!} \leq 0.20$$

Failures	Equation Results
11	0.117
12	0.179
13	0.257

Determine MTBF Goal in IOT (M_R^+)

Question:

- For a 2,400 hour test with a max of 12 failures, what should the MTBF goal in IOT (M_R^+) be?
  - The answer depends on the desired probability of acceptance

What is "Probability of Acceptance"?

- P(A) = 1 – Producer's Risk
- The Producer's (Contractor's) Risk = probability that Gov't rejects a system that has a true MTBF ≥ M_R
- Producer's Risk is mitigated using OC Curve to determine MTBF Goal when entering IOT (known as M_R^+)
  - The OC Curve is the P(A) plotted as a function of the system's MTBF, *M*

Answer:

- Plot the OC Curve for the selected IOT Duration and maximum number of allowable failures, *c*:

$$\sum_{i=0}^{c} \frac{\left(\frac{\text{IOT Duration}}{M}\right)^{i} \exp\left(-\frac{\text{IOT Duration}}{M}\right)}{i!} \qquad \text{(Equation 2)}$$

- For a desired P(A) of 70%, determine the *M* that corresponds with 70%; this is the system's M_R^+

$$\sum_{i=0}^{12} \frac{\left(\frac{2{,}400}{221}\right)^{i} \exp\left(-\frac{2{,}400}{221}\right)}{i!} = 0.70$$

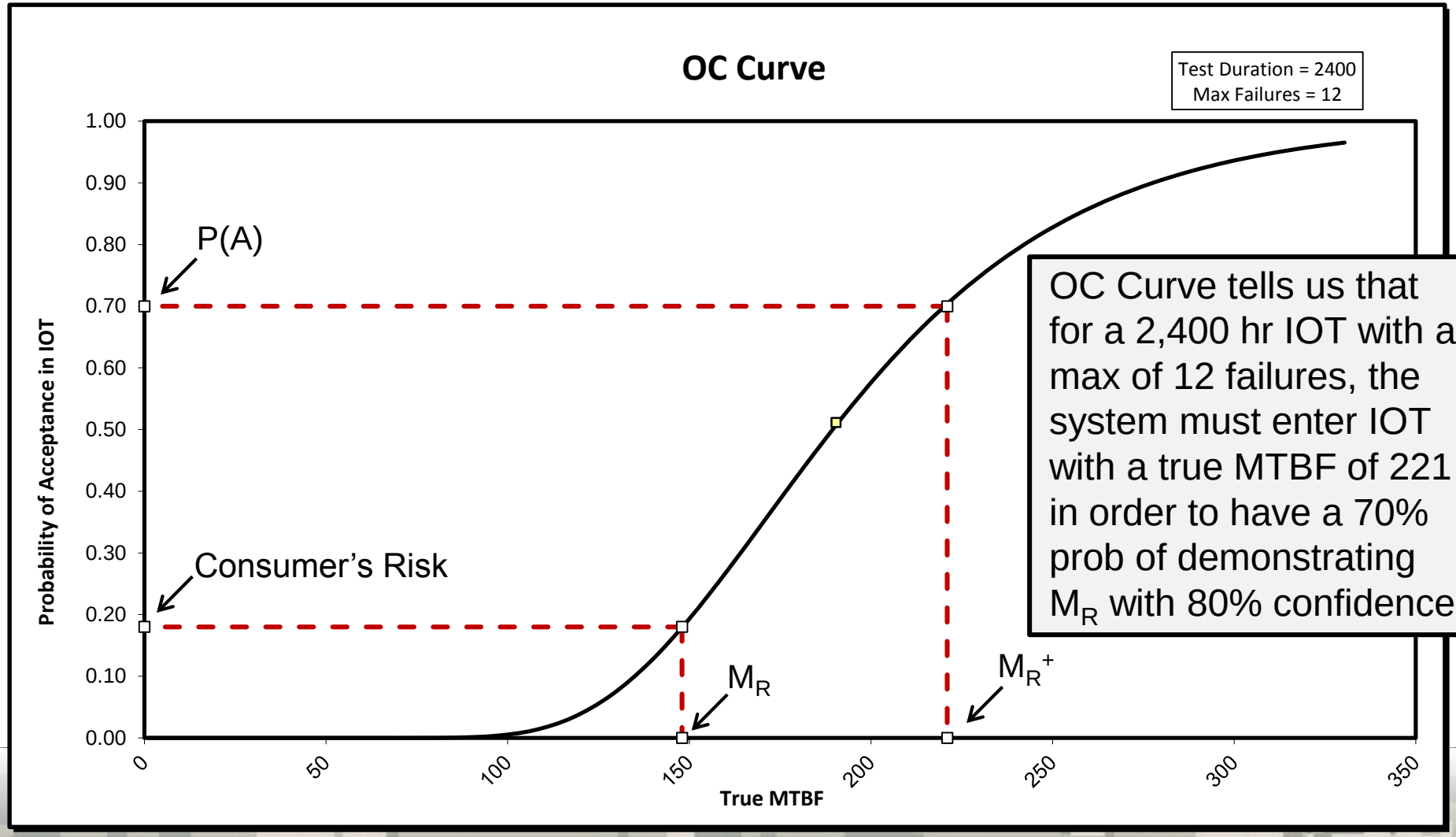
M_R^+	Equation Results
200	0.576
210	0.641
220	0.699
221	0.704

- Therefore, in order to have a 70% P(A) in IOT, the system's M_R^+ must be at least 221 MTBF

OC = Operating Characteristic

Solution Using OC Curve

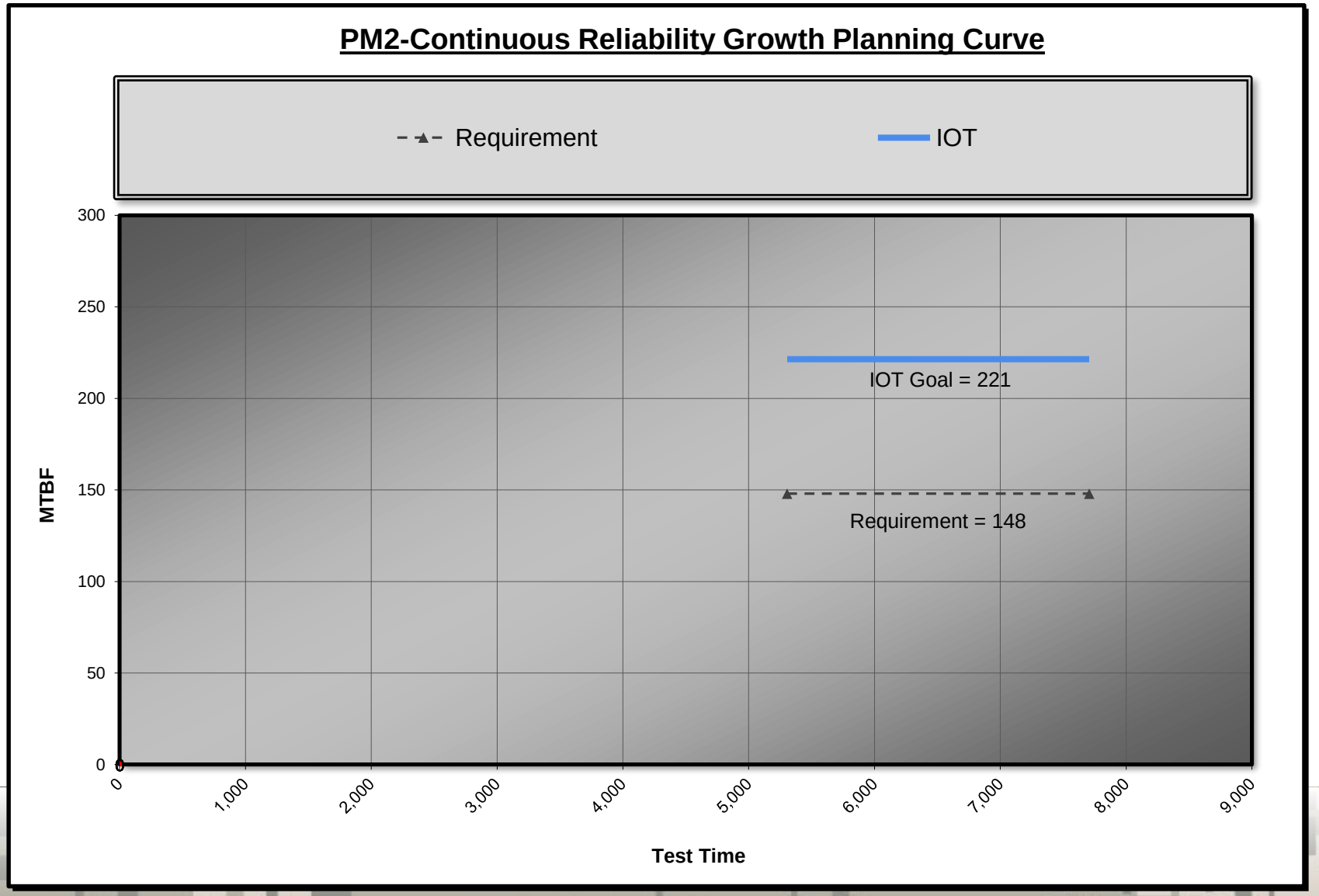
M_R = 148	Consumer's Risk = 0.20	Producer's Risk = 0.30	IOT Duration = 2,400	Max Failures = 12



OC Curve tells us that for a 2,400 hr IOT with a max of 12 failures, the system must enter IOT with a true MTBF of 221 in order to have a 70% prob of demonstrating M_R with 80% confidence

If the system enters IOT with an M_R^+ of 190 (instead of 221), the P(A) is reduced to 0.50. Even though 190 > 148, the system would fail the test half of the time. **Passing the test at the specified confidence level would be like flipping a coin!**

Building the RGPC



Determine Goal MTBF in DT (M_G)

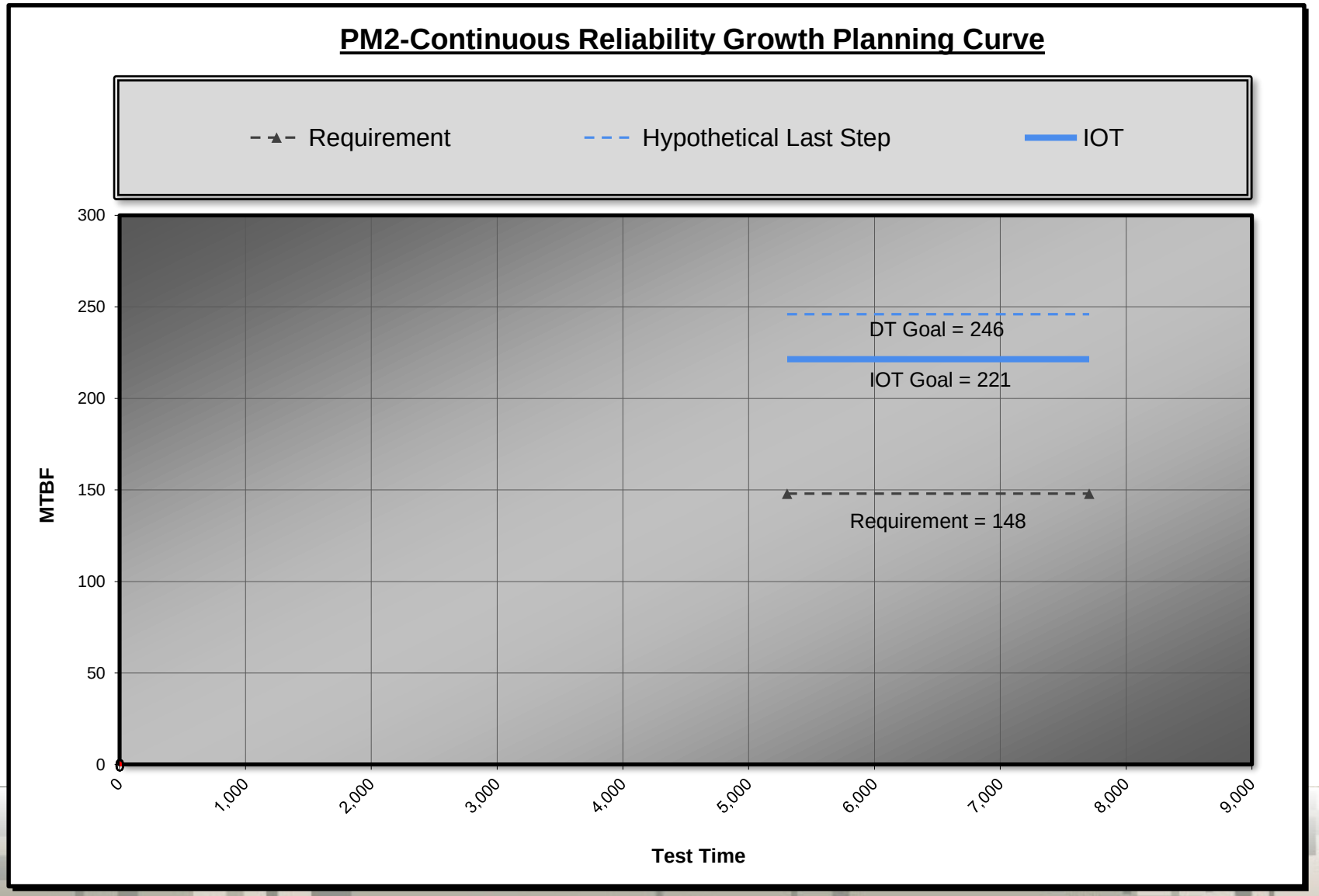
1) Determine Goal MTBF in IOT (M_R^+) using OC Curve
   - M_R^+ = 221 hours from previous chart

2) Determine expected degradation factor to account for drop in reliability when moving from DT environment to IOT environment
   - Should be based on what can realistically be expected
   - 10% for this example

3) Solve for DT Goal by applying degradation factor to M_R^+

$$M_G = \frac{M_R^+}{1\text{-Degradation}} = \frac{221}{0.90} = 246$$

Building the RGPC



Planning Process

Step 1: Determine a DT reliability goal (M_G) that provides a high probability of demonstrating the requirement in IOT

Step 2: Develop a feasible reliability growth plan that uses management metrics and DT test time to achieve M_G

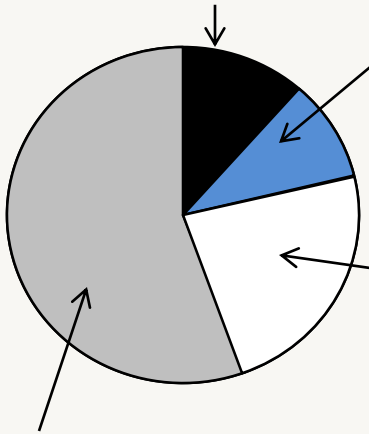
Determine Management Strategy (MS) & Fix Effectiveness Factor (FEF)

- Should be chosen based on what can realistically be achieved
  - Based on past performance, type of system, etc.
- MS is the proportion of total failure intensity that is addressed with corrective actions
  - Let MS = 0.95 for this example
- FEF is the fraction reduction in the failure rate for a failure mode that has been addressed via corrective action
  - Average FEF (μ_d) used for planning
  - Let μ_d = 0.70 for this example

MTBF Growth Potential (1 of 2)

System Failure Intensity After Testing (at time t)

λ_A: contribution from A-modes



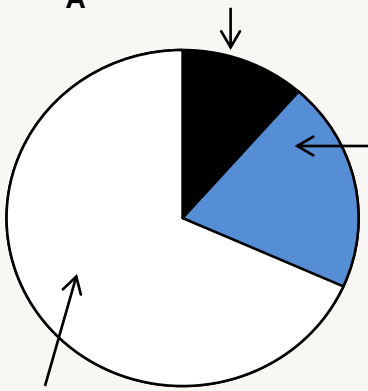
$(1-\mu_d)\,[\lambda_B - h(t)]$: contribution from observed B-modes <u>remaining</u> after corrective actions

$\mu_d\,[\lambda_B - h(t)]$: contribution from observed B-modes <u>removed</u> after corrective actions

$h(t)$: contribution from unseen B-modes

System Failure Intensity at Growth Potential

λ_A: contribution from A-modes



$(1-\mu_d)\,\lambda_B$: contribution from observed B-modes <u>remaining</u> after corrective actions

$\mu_d\,(\lambda_B)$: contribution from observed B-modes <u>removed</u> after corrective actions

- The System Growth Potential failure intensity (ρ_{GP}) is the rate of occurrence of failures that would occur if <u>all</u> potential B-modes are mitigated
  - Contribution from unseen B-modes is completely removed
- For *k* failure modes, can represent as $\rho_{GP} = \lambda_A + \sum_{i=1}^{k} (1-d_i)\lambda_i$

MTBF Growth Potential (2 of 2)

- M_{GP} is the upper bound on the MTBF that can be achieved if <u>ALL</u> failure modes in the system that can be addressed are corrected with the specified FEF, μ_d

- M_{GP} is a function of M_I, MS, and μ_d

$$M_{GP} = \frac{M_I}{1 - MS \times \mu_d}$$

- Ratio of Goal MTBF in DT (M_G) to M_{GP} should be less than or equal to 0.80

$$\text{Ratio} = \frac{M_G}{M_{GP}} \leq 0.80$$

Determine Initial MTBF (M_I)

- M_I is the system's initial MTBF when entering DT
  - DfR activities should result in a high M_I
  - M_I should be chosen based on what can realistically be achieved

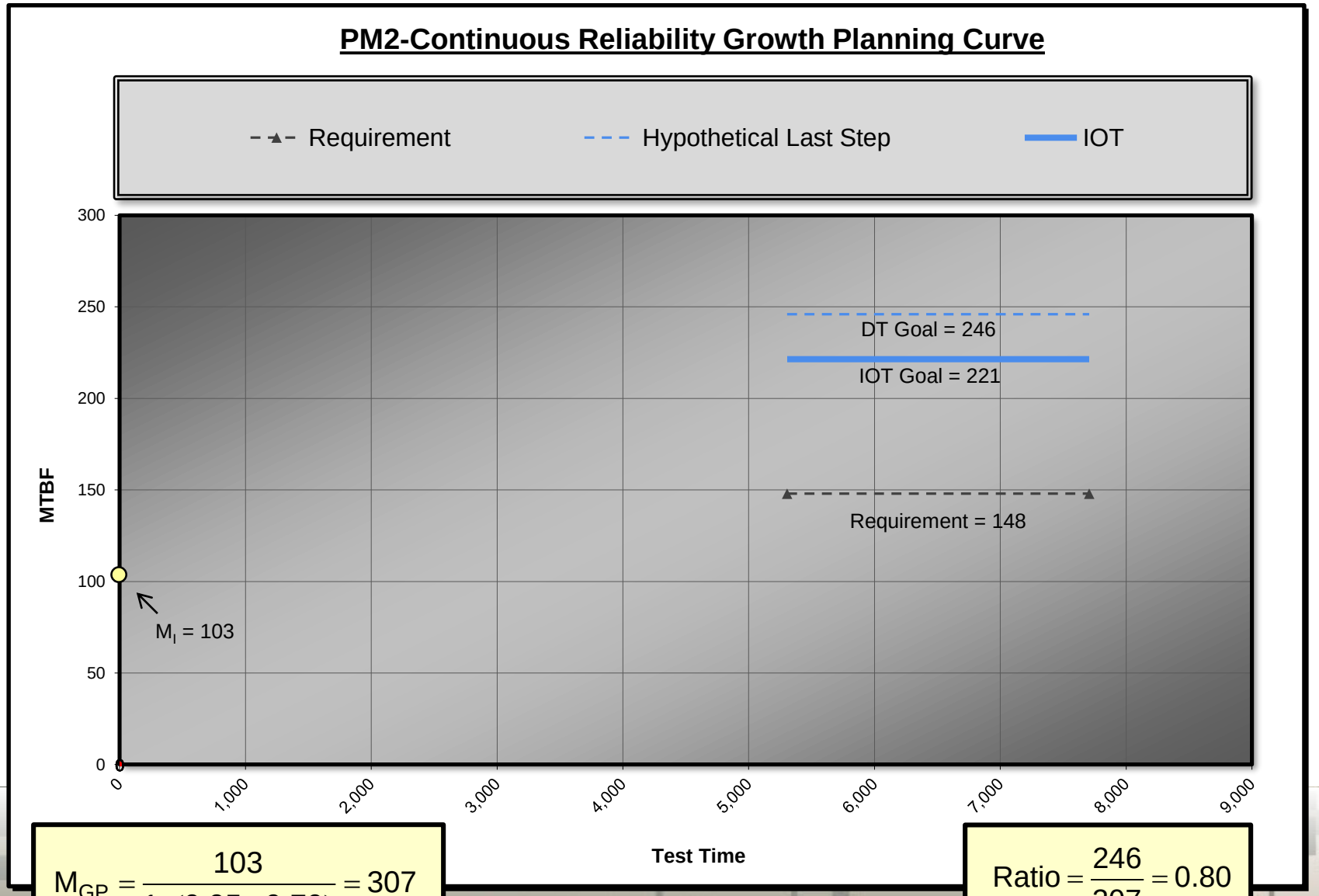
- M_I can be obtained 2 ways
  1) Estimate M_I based on insights from reliability models, previous test results, M_I for similar systems, etc.
  2) Establish a lower bound for M_I using the planning parameters (MS and μ_d) and the desired M_G/M_{GP} Ratio

$$M_I \geq \left(1 - MS \times \mu_d\right) \times \frac{M_G}{Ratio}$$

$$M_I \geq \left(1 - 0.95 \times 0.70\right) \times \frac{246}{0.80}$$

$$M_I \geq 103$$

Building the RGPC



$$M_{GP} = \frac{103}{1-(0.95 \times 0.70)} = 307$$

$$\text{Ratio} = \frac{246}{307} = 0.80$$

Test Schedule

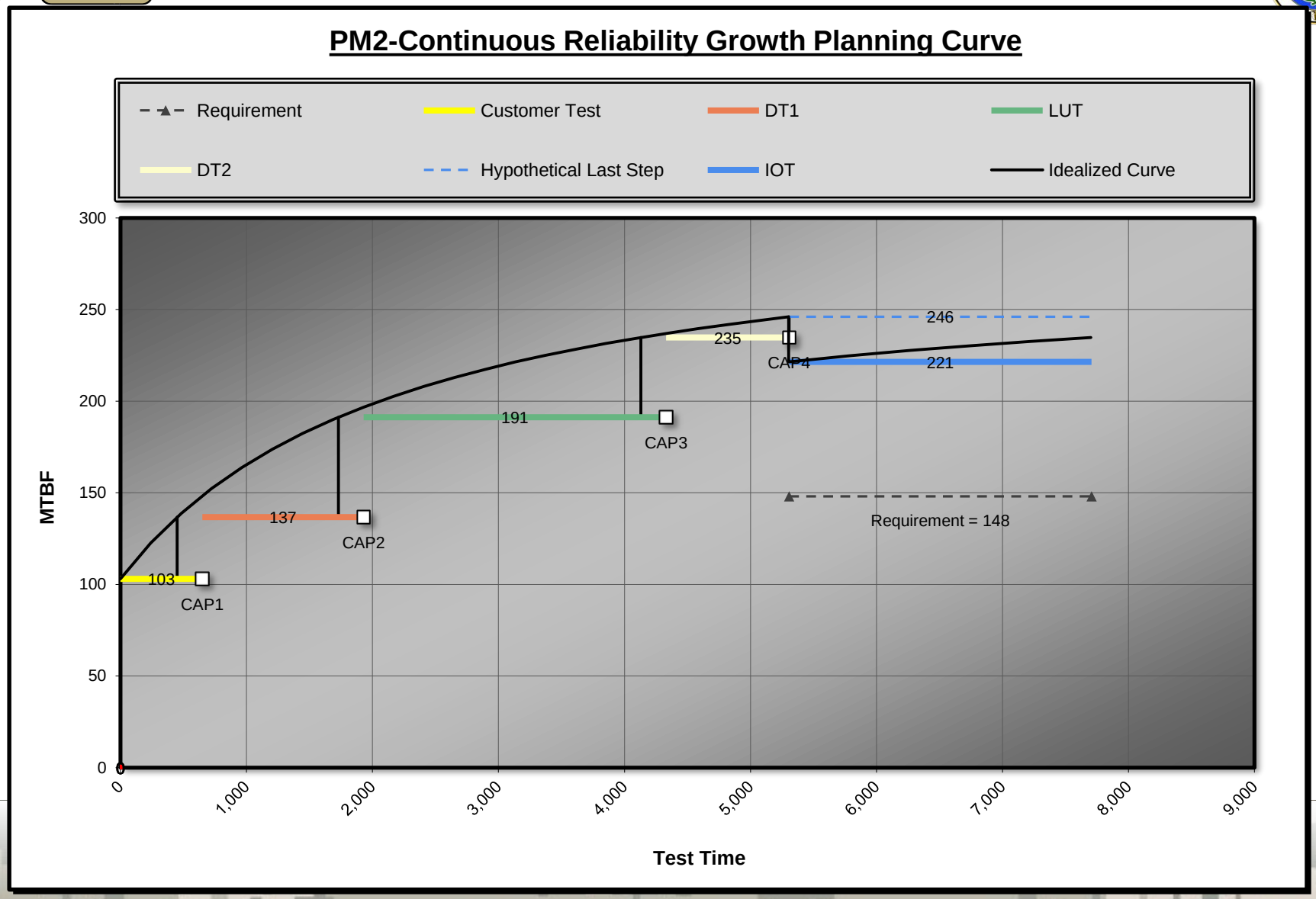
- 4 Developmental Test (DT) events totaling 5,306 hours
  - Customer Test: 650 hrs
  - DT: 1,280 hrs
  - LUT: 2,400 hrs
  - DT2: 976 hrs
- Corrective Action Periods (CAPs) after each event
- 2,400 hour Initial Operational Test (IOT)

Corrective Action Periods and Lag Time

- Growth cannot occur without corrective actions, which either occur during test or during CAPs
  - CAPs are calendar periods where testing stops and CAs are implemented
  - Important for maintaining configuration control
- For example, assume the following 12 month test scenario:
  - 8 month test phase – 100 test hours per month
  - 4 month CAP after test phase
  - 6 month delay for incorporating CAs into CAP 1
- Failure modes surfaced in the final 2 months of the test phase cannot be addressed until the following CAP.
  - Lag Time = 6 month Delay – 4 month CAP = 2 months = 200 hours
  - Only failures surfaced in the first 6 months will be addressed in CAP 1

	DT Test Phase 1 (8 months)								CAP 1 (4 months)			
Cum. Months	1	2	3	4	5	6	7	8	9	10	11	12
Cum. Hours	100	200	300	400	500	600	700	800	800	800	800	800
	Reduced Test Phase						Lag Time					

Building the RGPC



Continuous Reliability Growth Planning Curve Risk Assessment (1/2)

Category	Low Risk	Medium Risk	High Risk
$\frac{\text{MTBF Goal (DT)}}{\text{MTBF Growth Potential}}$	< 70%	70 - 80%	> 80%
IOT&E Producer's Risk	≤ 20%	20^{+} - 30%	> 30%
IOT&E Consumer's Risk	≤ 20%	20^{+} - 30%	> 30%
Management Strategy	< 90%	90 - 96%	> 96%
Fix Effectiveness Factor	≤ 70%	70^{+} - 80%	> 80%
$\frac{\text{MTBF Goal (DT)}}{\text{MTBF Initial}}$	< 2	2 - 3	> 3
Time to Incorporate and Validate Fixes in IOT&E Units Prior to Test	Adequate time and resources to have fixes implemented & verified with testing or strong engineering analysis	Time and resources for almost all fixes to be implemented & most verified w/ testing or strong engineering analysis	Many fixes not in place by IOT&E and limited fix verification

$^{+}$ indicates strictly greater than

Continuous Reliability Growth Planning Curve Risk Assessment (2/2)

Category	Low Risk	Medium Risk	High Risk
Corrective Action Periods (CAPs)	5 or more CAPs which contain adequate calendar time to implement fixes prior to major milestones	3 - 4 CAPs but some may not provide adequate calendar time to implement all fixes	1- 2 CAPs of limited duration
Reliability Increases after CAPs	Moderate reliability increases after each CAP result in lower-risk curve that meets goals	Some CAPs show large jumps in reliability that may not be realized because of program constraints	Majority of reliability growth tied to one or a couple of very large jumps in the reliability growth curve
Percent of Initial Problem Mode Failure Intensity Surfaced	Growth appears reasonable (i.e. a small number of problem modes surfaced over the growth test do not constitute a large fraction of the initial problem mode failure intensity)	Growth appears somewhat inflated in that a small number of the problem modes surfaced constitute a moderately large fraction of the initial problem mode failure intensity	Growth appears artificially high with a small number of problem modes comprising a large fraction of the initial problem mode failure intensity

Conclusions

- Reliability growth planning curves can be powerful management tools
  - Portray the planned reliability achievement as a function of program resources
  - Serve as a baseline against which demonstrated reliability estimates may be compared
  - Illustrate and quantify the feasibility of the test program in achieving the interim and final reliability goals
- Curves possess a series of management metrics that may be used to:
  - Assess the effectiveness of potential reliability growth plans
  - Assess the reliability maturity of complex systems as they progress through DT program

Model Demo

Backup

Operating Characteristic (OC) Curve Analysis

- Set consumer (government) risk

  α = 1 - confidence = 0.20 for this example

- Determine maximum number of allowable failures (12 for example)

$$c \equiv \text{largest } k \text{ s.t } \sum_{i=0}^{k} \frac{\left(\frac{T_{Dem}}{M_R}\right)^i \exp\left(-\frac{T_{Dem}}{M_R}\right)}{i!} \le \alpha,$$

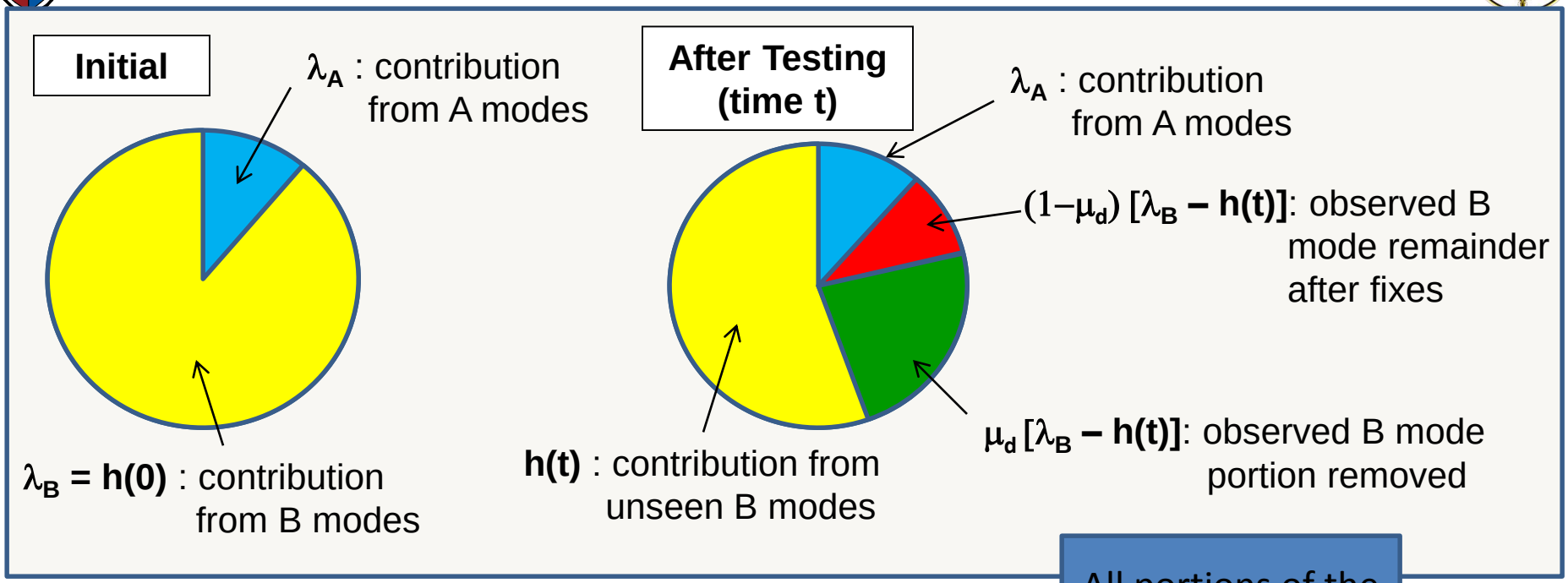
where T_{Dem} = IOT Test Length,

M_R = MTBF Requirement

- Develop probability of acceptance based on allowable failures, requirement, and test time

$$\text{Plot } \sum_{i=0}^{c} \frac{\left(\frac{T_{Dem}}{M}\right)^i \exp\left(-\frac{T_{Dem}}{M}\right)}{i!} \text{ as function of } M$$

PM2 Failure Intensity



All portions of the system failure intensity are well-defined

Definitions:

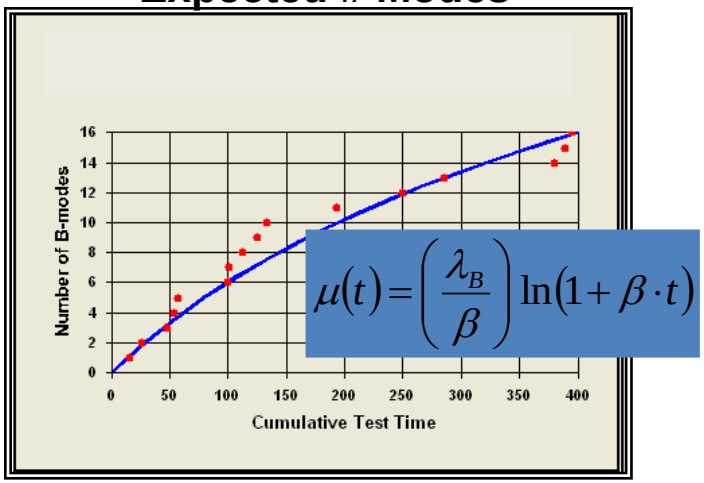
A mode: No corrective action made
B mode: Corrective action made if discovered
Planned average fix effectiveness factor: μ_d

Idealized curve for PM2 model based on

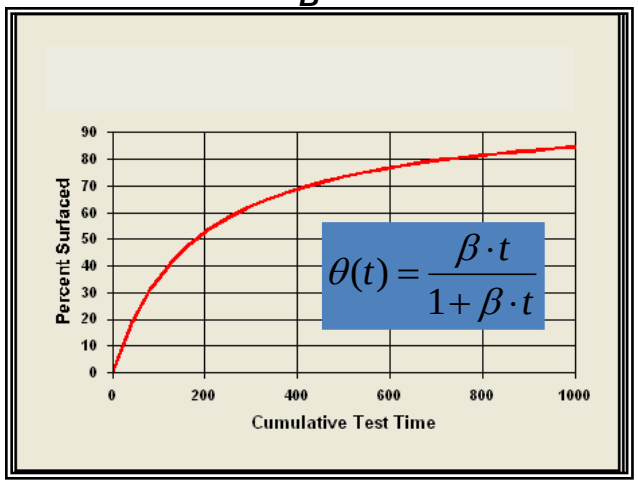
$$M(t) \equiv \frac{1}{\rho(t)} = \left[\lambda_A + (1-\mu_d)\cdot\left[\lambda_B - h(t)\right] + h(t)\right]^{-1} \text{ for } t \in [0,\infty)$$

PM2 Planning Metrics

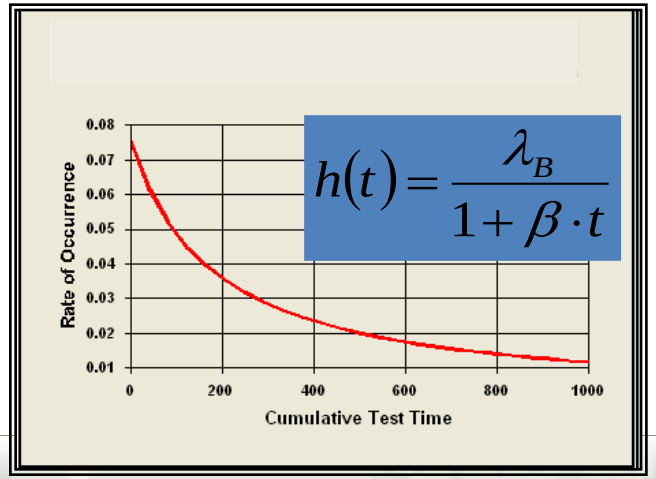
Expected # Modes



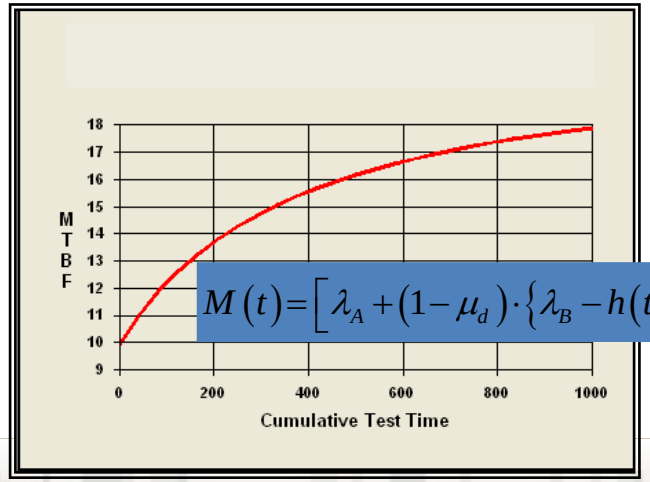
Percent λ_B Observed



Rate of Occurrence of New Modes



Mean Time Between Failures



PM2 planning metrics can be used to determine feasibility of growth plan

PM2 Inputs

Help | Print | About

AMSAA PM2-CONTINUOUS - Version 3.0

MAIN INPUTS

Your System Name

Blue font indicates user inputs

Step 1: Identify the Purpose of your Developmental Test (DT)	Help
Do you wish to grow to a level of reliability that will allow you to demonstrate the requirement with confidence in a follow-on demonstration test (e.g., IOT)?	Yes

Step 2: Input the Program Requirements	Help	
MTBF Requirement (M_R)	148.00	
Confidence Level for IOT LCB	0.80	
Prob. of Acceptance In IOT using LCB	0.70	
Consumer's (Government's) Risk	0.20	← Low Risk
Producer's (Contractor's) Risk	0.30	← Medium Risk

Step 3: Determine the IOT Profile Using OC Curve Methodology	Help
IOT Test Duration	2,400
Max Failures in IOT	12
Goal MTBF in IOT (M_R^+)	221
Actual Confidence Level for IOT LCB	0.820
LCB for Requirement	151
Prob. of Acceptance In IOT Using LCB	0.70
Prob. of Acceptance In IOT Using Pt. Est.	0.95

IOT Planner

OC Curve

Step 4: Determine the DT Goal	Help
Assumed DT to IOT Degradation Factor	0.10
Goal MTBF in DT (M_G)	246

PM2 Inputs

Step 5: Input the DT Planning Parameters		Help	
Initial MTBF (M_I)	103	M_I Solver	
M_G/M_I Ratio	2.4	← Medium Risk	Suggestions to Lower Ratio
Management Strategy (MS)	0.95	← Medium Risk	
Average FEF (μ_d)	0.70	← Low Risk	
Growth Potential (M_{GP})	307		
M_G/M_{GP} Ratio	0.80	← Medium Risk	Suggestions to Lower Ratio

Step 6: Input the DT Schedule Help

Select an Input Option for the DT Schedule: (●) General Schedule ( ) Detailed Schedule

DT Phase	Test Phase Name	Mission Time in Test Phase	Cumulative Test Time	CAP at End of Phase?	Corrective Action Lag Time for Each CAP	Cumulative Time at CAP minus Lag (Backoff Time)
Phase 1	Customer Test	650	650	Yes	200	450
Phase 2	DT1	1,280	1,930	Yes	200	1,730
Phase 3	LUT	2,400	4,330	Yes	200	4,130
Phase 4	DT2	976	5,306	Yes	0	5,306
Phase 5						
Phase 6						
Phase 7						
Phase 8						
Phase 9						
Phase 10						

PM2 Inputs & Feasibility Metrics

Step 7: Apply the ASA(ALT) Threshold	Help
Test Phase for ASA(ALT) Threshold	2nd Phase
Percent of M_R to be Demonstrated	0.70
Confidence Level for ASA(ALT) LCB	0.50
MTBF Goal for ASA(ALT) Threshold	104
Max Failures	11
Test Length	1,280
LCB for ASA(ALT) Threshold	110
Prob. of Acceptance Using LCB	0.766
Prob. of Acceptance Using Pt. Est.	0.848

PM2 Planning Curve

Risk Assessment Matrix

PM2 Feasibility Metrics — Help

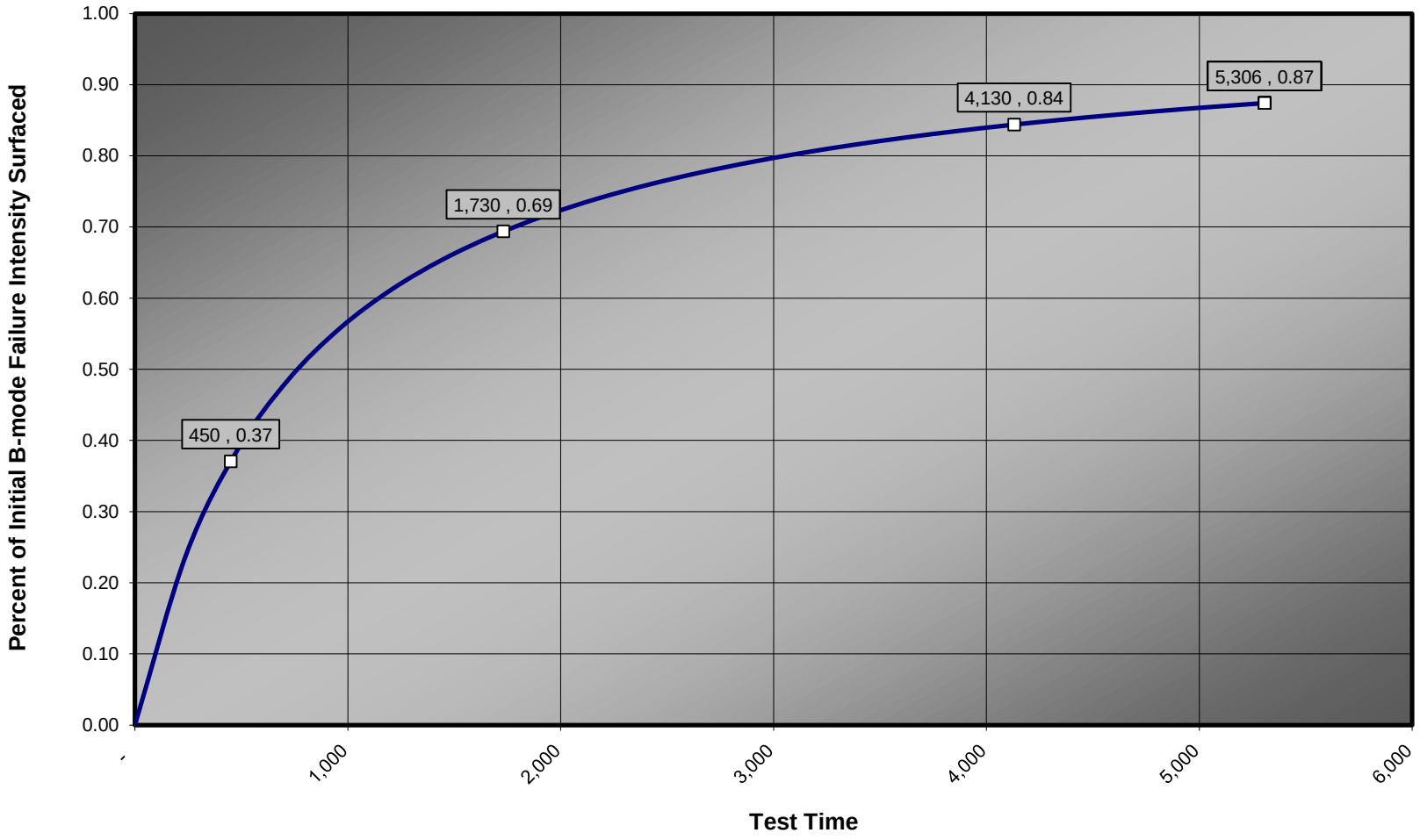
Test Phase Name	Cumulative Time at CAP minus Lag (Backoff Time)	Percent of Initial B-mode Failure Intensity Surfaced at Backoff (View θ(t) Curve)	Expected Number of B-modes at Backoff (View μ(t) Curve)	Expected Rate of Occurrence of New B-modes at Backoff (View h(t) Curve)	Expected Number of B-mode Failures at Backoff (View Exp. # of Failures Curve)	Expected Number of Total Failures at Backoff
Customer Test	450	0.37	3	0.005804	4	4
DT1	1,730	0.69	8	0.002825	13	14
LUT	4,130	0.84	13	0.001440	24	26
DT2	5,306	0.87	15	0.001161	29	31

3 failure modes encompass 37% of the failure intensity

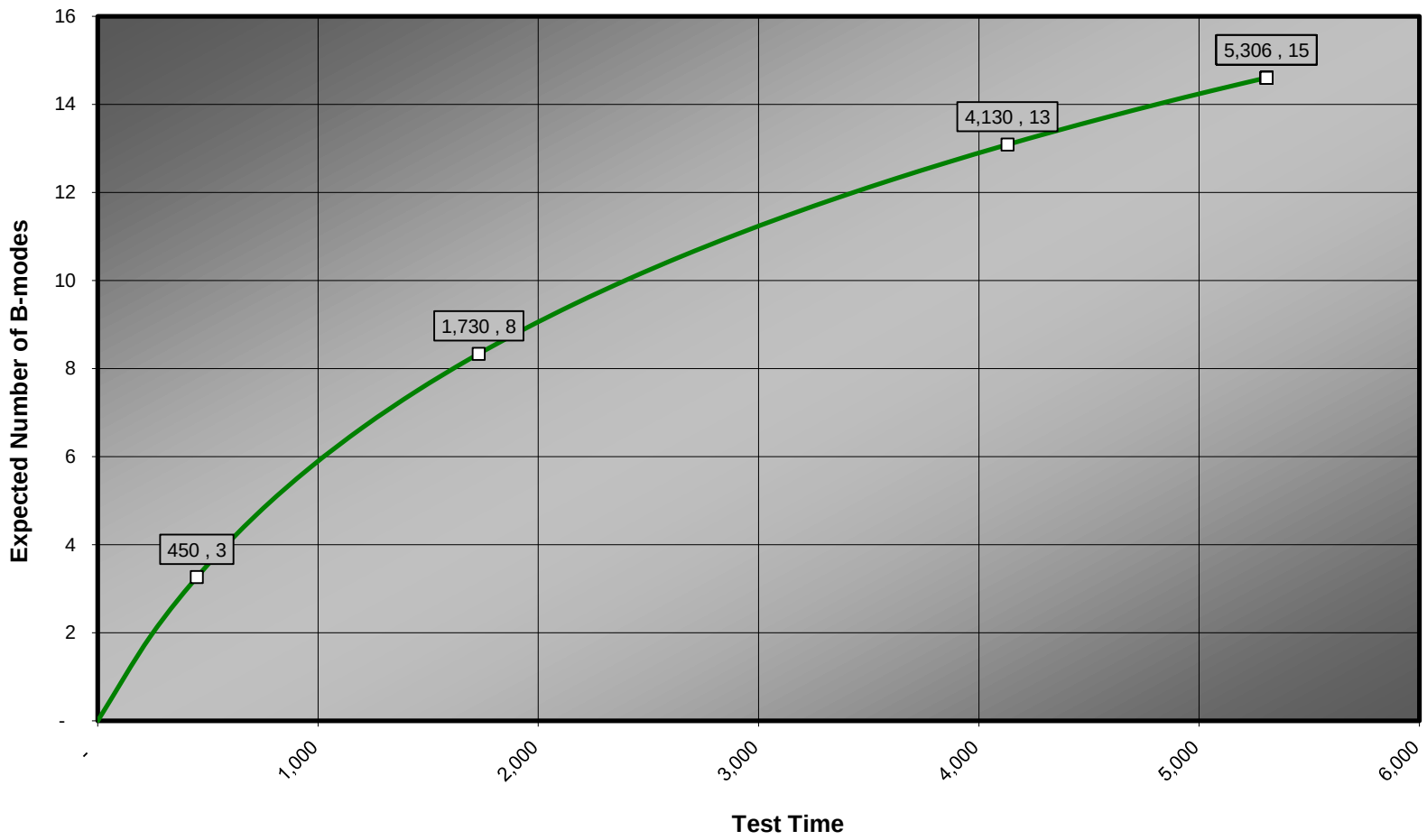
15 failure modes encompass 87% of the failure intensity

Feasibility Metrics

Percent of Initial B-mode Failure Intensity Surfaced by Time t
θ(t) Curve



Feasibility Metrics



Risk Assessment Matrix

Help | Print | Main Inputs

AMSAA PM2-CONTINUOUS
RISK ASSESSMENT MATRIX

PURPOSE: To help the user assess the level of risk associated with the proposed reliability growth plan.

INSTRUCTIONS:
1) Refer to the Risk Assessment Matrix, which includes 10 critical categories. Each category has an associated Low, Medium, and High Risk Criteria.
2) Refer to the Risk Assessment , which includes the appropriate risk rating & rationale for each of the 10 categories. The risk ratings for categories 1-6 are automatically filled out by PM2. The risk ratings for categories 7-10 need to be completed by the user.

NOTE: This matrix identifies the technical risks associated with the chosen planning parameters. It does not identify the cost and schedule risks associated with achieving the planning parameters. Therefore, programs should find an acceptable balance between these technical risks and their associated cost/schedule implications.

Reliability Growth Planning Curve Risk Assessment Matrix

#	Category	Low Risk Criteria	Medium Risk Criteria	High Risk Criteria	"Program Name" Risk Assessment	
1	M_G / M_{GP}	< 0.70	0.70 - 0.80	> 0.80	0.80	← Suggestions to Lower Ratio
2	IOT&E Producer's Risk	≤ 0.20	0.20* - 0.30	> 0.30	0.30	
3	IOT&E Consumer's Risk	≤ 20	20* - 30	> 0.30	0.18	
4	Management Strategy	< 0.90	0.90 - 0.96	> 0.96	0.95	
5	Fix Effectiveness Factor	≤ 0.70	0.70* - 0.80	> 0.80	0.70	
6	M_G / M_I	< 2	2 - 3	> 3	2.4	← Suggestions to Lower Ratio
7	Time to Incorporate and Validate Fixes in IOT&E Units Prior to Test	Adequate time and resources to have fixes implemented & verified with testing or strong engineering analysis	Time and resources for almost all fixes to be implemented & most verified w/ testing or strong engineering analysis	Many fixes not in place by IOT&E and limited fix verification		
8	Corrective Action Periods (CAPs)	5 or more CAPs which contain adequate calendar time to implement fixes prior to	3 - 4 CAPs but some may not provide adequate calendar time to implement all fixes	1- 2 CAPs of limited duration		
9	Reliability Increases after CAPs	Moderate reliability increases after each CAP result in lower-risk curve that meets goals	Some CAPs show large jumps in reliability that may not be realized because of program constraints	Majority of reliability growth tied to one or a couple of very large jumps in the reliability growth curve		
10	Percent of Initial Problem Mode Failure Intensity Surfaced	Growth appears reasonable (i.e. a small number of problem modes surfaced over the growth test do not constitute a large fraction of the initial problem mode failure intensity)	Growth appears somewhat inflated in that a small number of the problem modes surfaced constitute a moderately large fraction of the initial problem mode failure intensity	Growth appears artificially high with a small number of problem modes comprising a large fraction of the initial problem mode failure intensity		

Risk Assessment

* indicates strictly greater than