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SIMULATION BASED RELIABILITY GROWTH PLANNING MODEL FOR THE ARMY

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ABSTRACT

The current reliability growth planning model used by the US Army, the Planning Model for Projection Methodology (PM2), is insufficient for the needs of the Army. This paper will detail the limitations of PM2 that cause Army programs to develop reliability growth plans that incorporate unrealistic assumptions and often demand that infeasible levels of reliability be achieved. In addition to this, another reliability growth planning model being developed to address some of these limitations, the Bayesian Continuous Planning Model (BCPM), will be discussed along with its own limitations. This paper will also cover a third reliability growth planning model that is being developed which incorporates the advantageous features of PM2 and BCPM but replaces the unrealistic assumptions with more realistic and customizable ones. The internal workings of this new TARDEC developed simulation-based model will be delved into with a focus on the advantages this model holds over PM2 and BCPM.

INTRODUCTION

One of the most important requirements for a US Army system is its reliability requirement. Any failing equipment puts both the mission and the soldier's life and the lives of other soldiers who depend on him at risk. Historically however, the Army has often failed to treat reliability with the importance that it deserves which has led to many systems being deployed without operationally suitable reliability levels. Figure 1 shows how over the period of 1997 to 2006, over two thirds of Army systems undergoing operational testing failed to demonstrate their reliability requirements [1].

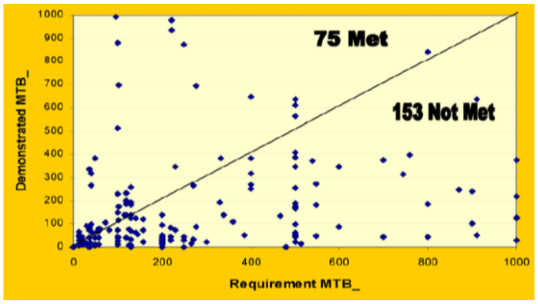

Figure 1: Reliability Operational Test Results [1].

One of the reasons for these high suitability failure rates was due to the requirement for a reliability growth program during development being deemphasized or eliminated as a result of the implementation of Acquisition Reform in the late 1990s [1]. Design for Reliability (DfR) activities were not always mandated for the contractors developing the systems often leading to them treating reliability as an afterthought. Proper planning of reliability testing activities was also not performed as reliability growth planning was not required either. Without these two critical activities, failing to meet reliability requirements became much more likely. The results from figure 1 ultimately led to the Department of Defense (DoD) passing a memorandum in 2011 stressing the importance of DfR and mandating that a reliability growth planning curve be developed for all programs [2].

This led to the Army and Marine Corps latching on to the Planning Model for Projection Methodology (PM2). This model was developed by the Army Materiel Systems Analysis Activity (AMSAA) to allow for developing reliability growth planning curves for any given program [3]. While it was a definite step forward that reliability growth planning was now being addressed within the Army and Marine Corps, there were significant issues with PM2 because of unrealistic assumptions that often led to inflated reliability requirements among other issues. This led to the development of the Bayesian Continuous Planning Model (BCPM) by AMSAA. BCPM was structured to make its interface largely similar to PM2 but the inner workings of BCPM were built to allow for combining data from different phases of testing in a way PM2 was not structured for [4].

While BCPM has not yet been formally signed off on for use as a reliability growth planning tool for the Army and Marine Corps, it has shown significant promise for addressing some of the issues that are present in PM2. There are still some significant issues with BCPM however which lead to some unrealistic results. This is what led to TARDEC working to develop a new simulation-based reliability growth planning model that would incorporate the positive aspects of both PM2 and BCPM while also allowing for the inclusion of a much more realistic set of assumptions that would ensure the reliability growth plans that are created are truly realistic and meaningful [5].

This paper will examine both PM2 and BCPM, focusing on their structure, how they are different from one another and also the issues that are present with both. It will also touch on a case study for an example system where both PM2 and BCPM were employed to demonstrate how these differences lead to different sets of risks for a program. The paper will conclude with a discussion of the simulation-based reliability growth planning model being developed by TARDEC that will focus on the structure of this model, how this structure makes it advantageous over both PM2 and BCPM, and what work still needs to be done to complete this model.

AMSAA's PM2 Model

AMSAA's PM2 model is a Microsoft Excel based tool that takes in various inputs in order to set risk levels and develop a reliability growth curve for a vehicle system.

PM2 Inputs

The first set of inputs is the overall test profile for the vehicle which is entered in as shown in figure 2.

Developmental Test - Schedule Summary

Input Test Schedule for Each Test Phase (TP)	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	RG1	4,000	4,000	Yes	0	4,000
TP 2 Schedule	RG2	4,000	8,000	Yes	0	8,000
TP 3 Schedule	RG3	4,000	12,000	No		8,000
TP 4 Schedule	RG4	4,000	16,000	Yes	500	15,500
TP 5 Schedule	RG5	4,000	20,000	Yes	0	20,000
TP 6 Schedule						
TP 7 Schedule						
TP 8 Schedule						
TP 9 Schedule						
TP 10 Schedule						

Is IOT incorporated in the Planning Curve?	Yes

IOT Inputs	
IOT Training Test Time	0
IOT Phase Test Time	5,000
Assumed DT to IOT Degradation Factor	0.10

Figure 2: PM2 Test Profile Inputs

This is where all of the reliability growth test phases get fully defined. For each Developmental Test (DT) phase, the length of the test needs to be specified along with whether or not there will be a Corrective Action Period (CAP) at the conclusion of that phase. These CAPs are when the fixes are implemented to address issues that have been identified during the earlier test phases and therefore, where the reliability growth occurs. The input also allows the option to define CAP lag times in the event that all fixes for one phase of testing might not be able to be implemented by the start of the next phase.

The Initial Operational Test (IOT) information must also be provided here. This is where the reliability of the system is formally measured against the user requirement. The important inputs here are the length of IOT and the assumed degradation factor in going from DT to IOT. The test length itself is important because the requirement typically needs to be demonstrated with statistical confidence. As such, lengthier tests typically equate with lower levels of reliability needing to be achieved and lower risks for the system's overall reliability growth plan. The degradation factor helps to account for the different types of testing being carried out. While both DT and IOT generally follow the vehicle's defined mission profile, IOT results have historically shown lower levels of reliability than DT results. Including a degradation factor is how PM2 incorporates this empirically observed trend.

The second set of inputs is where the different levels of risk are defined as shown in figure 3.

Requirement MTBF (M_R)	500
Initial MTBF (M_I)	450
Management Strategy (MS)	0.95
Average FEF (μ_d)	0.70
Confidence Level for IOT LCB	0.80
Prob. of Accept. in IOT using LCB	0.70
Prob. of Accept. In IOT using Pt. Est.	0.98
Goal MTBF in IOT (M_R^+)	924
Goal MTBF in DT (M_G)	1027
Growth Potential (M_{GP})	1343
M_G/M_{GP} Ratio	0.76

Figure 3: PM2 Risk Inputs

The first input here is the Mean Time Between Failure (MTBF) requirement for the system. The second input is ultimately one of the risk parameters as it is the assumed starting point MTBF, the value that the system is assumed to be at before it begins the first phase of DT. The higher this assumed value, the higher the risk associated with the reliability growth plan. The next two inputs here define how aggressively failure modes are going to be mitigated. The Management Strategy (MS) defines how much of the overall system's failure intensity is intended to be addressed with fixes. An MS of 0.95 means that 95% of the system's failure intensity is intended to be addressed with fixes. The Fix Effectiveness Factor (FEF) defines how effective the fixes are aimed to be on average. An FEF of 0.7 means that for any given failure mode addressed with a fix, it is assumed that 70% of that particular failure mode's failure intensity is eliminated. Both MS and FEF are also a way to set risk as higher values for these tend to be more difficult to actually achieve.

The next two inputs are the formal risk metrics that are defined for a growth plan. The confidence level defines how certain you want to be that the test results indeed show that the MTBF requirement has been demonstrated during IOT. An 80% confidence level means that you are 80% certain based on the IOT results that the true system MTBF is in fact equal to or greater than the MTBF requirement. This confidence level along with the IOT length leads to the calculated maximum number of failures allowed during IOT which in turn relates to the Probability of Acceptance (PoA). The PoA is the certainty you desire that the number of failures observed during IOT will be no more than the allowable number of failures. A PoA of 70% means that you will only have a 30% chance of seeing more than the allowable number of failures.

These inputs lead to some of the calculated values in the table. The allowable number of failures during IOT is calculated based on the IOT length along with the desired confidence according to equation (1).

$$\max(k)\ such\ that\ \frac{2T_{OT}}{\chi^2_{\%conf,2k+2}} \geq MTBF_{req} \qquad (1)$$

Then the goal value for MTBF in IOT is back calculated for the specified PoA, OT length and the allowable number of failures according to equation (2).

$$PoA = \sum_{i=0}^{k} \frac{\left(\frac{T_{OT}}{IOT\ MTBF_G}\right)^i e^{-\left(\frac{T_{OT}}{IOT\ MTBF_G}\right)}}{k!} \qquad (2)$$

Following this, the goal value for MTBF at the conclusion of DT is simply calculated using the IOT MTBF goal and the degradation factor as shown in equation (3).

$$DT\ MTBF_G = \frac{IOT\ MTBF_G}{(1-D)} \qquad (3)$$

The final two major calculated metrics from figure 3 are the MTBF growth potential and the ratio of the goal MTBF value for the end of DT to this growth potential. The growth potential itself is basically the limit for MTBF that can be achieved for the system if it is tested for infinite hours while addressing the percentage of the overall failure intensity prescribed by the MS with fixes that are as effective as intended by the assumed FEF. The calculation of this MTBF growth potential is shown in equation (4).

$$MTBF_{GP} = \frac{MTBF_I}{(1 - MS * FEF)} \qquad (4)$$

The ratio of the goal MTBF for DT to this MTBF growth potential is used as a metric for evaluating the realism and effectiveness of a growth plan. Typically, ratios of below 0.6 are discouraged as they do not adequately grow the system's MTBF whereas ratios above 0.8 are discouraged as they require growing the system's MTBF to very close to its growth potential which often requires prohibitive amounts of testing.

PM2 Outputs

Once the numerical inputs are assigned and the other metrics are calculated, PM2 develops numerous visual outputs for the reliability growth plan. The first of these is the reliability growth curve, shown in figure 4.

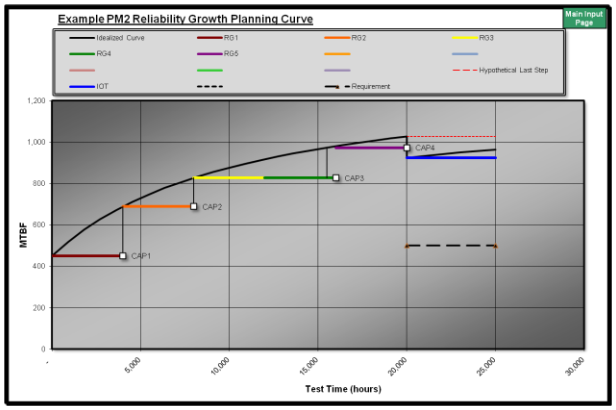

Figure 4: Example PM2 Reliability Growth Curve

This graph basically shows how the reliability is expected to grow throughout the testing phases. The jumps in MTBF are apparent at the different CAPs and there is an apparent drop going from DT to IOT associated with the degradation factor. The other three visual outputs from PM2 are all associated with the surfacing of B-modes which are the failure modes that are intended to be addressed with corrective actions. These three outputs are shown below in figures 5, 6 and 7.

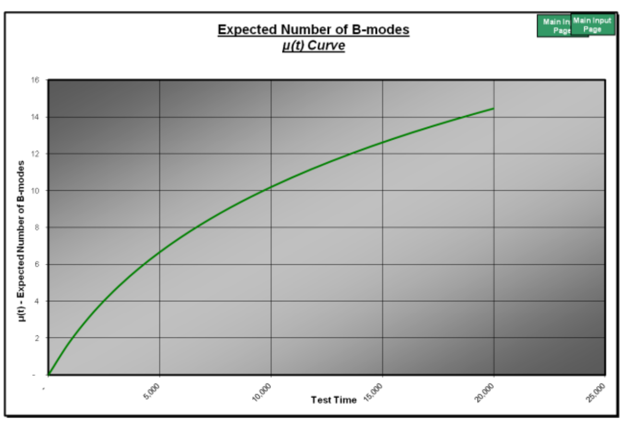

Figure 5: Expected Number of B-modes

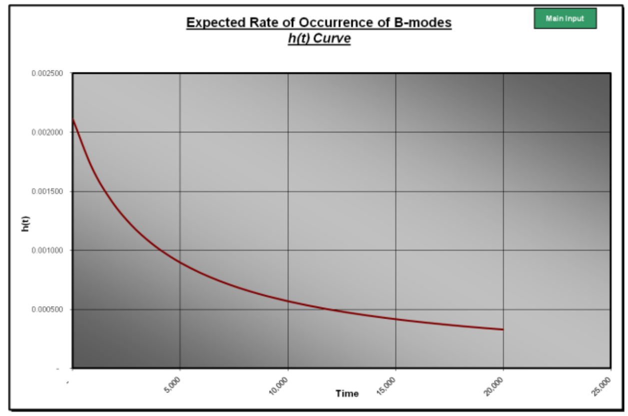

Figure 6: Occurrence Rate of New B-modes

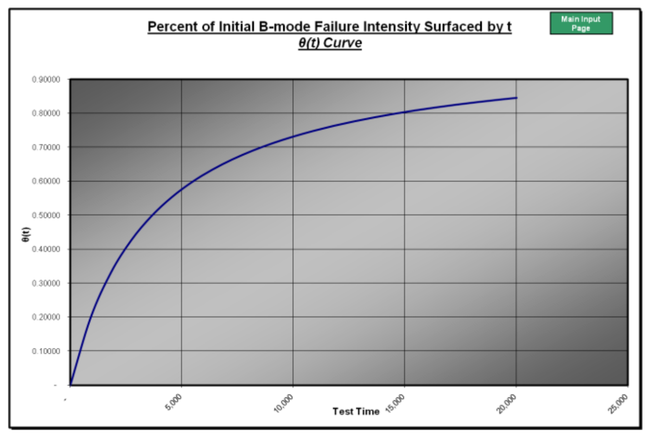

Figure 7: Percentage of B-mode Intensity Surfaced

These all take different looks at B-mode surfacing. Figure 5 details the expected number of B-modes surfaced at any time during testing. Figure 6 shows the occurrence rate for new B-modes, so as expected this is a decreasing function as there are fewer and fewer new B-modes to discover as testing progresses. Figure 7 shows the expected percentage of the full system B-mode failure intensity that has been surfaced at any point during testing and as can be seen, this is an increasing curve asymptotically approaching one. Some of these graphs will be revisited in the next section as these are crucial to showing some of the major issues that are prevalent with PM2.

PM2 Issues

The first major issue with PM2 is that the use of this model leads to incredibly high inflation of reliability goals beyond the system requirement itself. This is a substantial issue for all programs, even ones with long IOTs. This is apparent in the example shown in figure 4 which involves a 5,000 hour

IOT. The MTBF requirement is only 500 hours but as the growth curve shows, an MTBF of over 1,000 hours needs to be reached by the end of DT in order to satisfy all the specified risk metrics. This leads to having to pay for over double the reliability that is actually needed by the user and in many cases drives the goal MTBF to technically infeasible levels.

This issue gets even worse if dealing with a system that only has a short IOT planned. Figure 8 shows this scenario where the IOT length is cut in half. In this case, the MTBF goal for the end of DT is inflated all the way up to 1,451 hours, almost three times the user requirement.

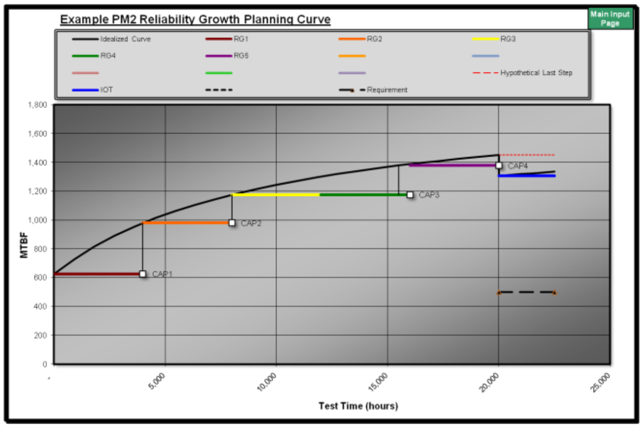

Figure 8: Example PM2 Curve with 50% IOT Length

The second major issue with PM2 is that it leads to highly inefficient testing. As discussed in the PM2 Inputs section, the reliability requirement is assessed using only IOT data. This means that all of the data gathered during DT is just thrown out when assessing the system's reliability and directly ties back into the first issue with the unrealistic reliability goals. If this data were used, as will be seen in the discussion on BCPM, the reliability goals would be lowered and the testing efficiency would be greatly enhanced.

The third major issue with PM2 is that the reliability growth curve is fitted to what is necessary, not what is likely or even feasible. This is caused by the fact that the curve itself is calculated solely to connect the specified initial MTBF with the calculated goal value for MTBF at the end of DT as shown by equation (5) where β essentially defines how steep the reliability growth curve is.

$$\beta = \left(\frac{1}{T}\right)\left(\frac{1-\frac{MTBF_I}{DTMTBF_G}}{MS * FEF - \left(1-\frac{MTBF_I}{DTMTBF_G}\right)}\right) \quad (5)$$

This leads to illogical results from PM2 when analyzing different scenarios. For example, shortening the length of DT by 50% (to 10,000 hours from the initial 20,000) yields a reliability growth curve that shows the same level of risk in terms of the ratio of the DT goal MTBF to the growth potential MTBF. Basically, keeping all the inputs the same except for the DT length, PM2 says that the two reliability growth curves are equally as risky. This is obviously not the case since many more B-modes can be surfaced and fixed in a 20,000 hour DT as opposed to a 10,000 hour DT.

The logical inconsistency within PM2 is further confounded when you analyze some of the other outputs. For the 10,000 hour DT, PM2 shows the expected number of B-modes surfaced by the end of DT as being 7.2. It also shows that these 7.2 B-modes are expected to account for 85% of the system's overall B-mode failure intensity. For the full length 20,000 hour DT however, PM2 shows an expected 10 B-modes surfaced by the 10,000 hour point in testing. It also shows that these 10 expected B-modes account for 73% of the system's overall B-mode failure intensity. For both of these runs of PM2, the only thing being changed is the length of DT. The results change in such a dramatic and illogical way however. For the same system, after 10,000 hours of DT, the shorter length DT shows fewer B-modes surfaced yet a higher percentage of the initial B-mode intensity surfaced which is completely unreasonable.

AMSAA's BCPM Model

As these significant issues with PM2 show, something better is needed to allow for more realistic reliability growth planning within the Army. This is what led AMSAA to begin work on BCPM. As of the writing of this paper, BCPM has not been formally signed off on and is still in the works by Mr. Martin Wayne.

BCPM Inputs

BCPM was structured to have an interface largely similar to PM2 so that Army reliability engineers who were familiar with PM2 would also be able to easily use BCPM. Figure 9 shows the input setup for the test profile for BCPM which is essentially identical to that for PM2. All of the options still exist to specify DT phases along with their lengths, whether or not CAPs are done at the end of a phase and also any CAP lag time as necessary.

Input the Estimated Test Schedule						
Estimated Developmental Test 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
Phase 1	RG1	4000	4000	Yes		4000
Phase 2	RG2	4000	8000	Yes		8000
Phase 3	RG3	4000	12000	No		12000
Phase 4	RG4	4000	16000	Yes	500	15500
Phase 5	RG5	4000	20000	Yes		20000
Phase 6						
Phase 7						
Phase 8						
Phase 9						
Phase 10						
	Final Demonstration Test					
	Test Name:			IOT		
	Estimated Test Duration			5000		

Figure 9: BCPM Test Profile Inputs

The second set of inputs for defining the levels of risk is shown below in figure 10.

Input the Planning Parameters	
MTBF Requirement (MR)	500
Management Strategy (MS)	0.95
Average Fix Effectiveness Factor (μ_d)	0.70
Initial MTBF (MI)	450
Planned DT to OT Degradation	0.10
Consumer Risk for Final Demonstration Test	0.20
Producer Risk for Final Demonstration Test	0.30

Figure 10: BCPM Risk Inputs

These inputs are all largely similar to PM2 as well. The only difference here is that instead of confidence level and PoA, there is consumer and producer risk. These are analogous however, as consumer risk is the same as one minus the confidence and producer risk is the same as one minus the PoA. The calculated metrics are also displayed as shown in Figure 11. Here is the goal MTBF for by the end of DT along with the different ratios of goal to growth potential and goal to initial MTBFs.

Output Metrics	
Total Test Time	25000
MTBF DT Goal (MG)	670.3
MTBF Growth Potential (MGP)	1343.3
M_G / M_{GP} Ratio	0.50
M_G / M_I Ratio	1.5
IOT MTBF Point Estimate	580.2
IOT MTBF Lower Bound	512.7
True Consumer Risk	0.16
True Producer Risk	0.13
β	0.00005
θ(TL)	0.49418

Figure 11: BCPM Calculated Metrics

BCPM Outputs

The outputs are almost identical between PM2 and BCPM. The results shown on the outputs are different however for the same inputs. For example, the reliability growth curve from BCPM shows that the MTBF goal for DT only needs to be 670 hours MTBF as opposed to 1027 hours MTBF for the same inputs in PM2. This output is shown below in figure 12. As this makes apparent, the BCPM model allows for a much more conservative reliability growth planning curve to be followed.

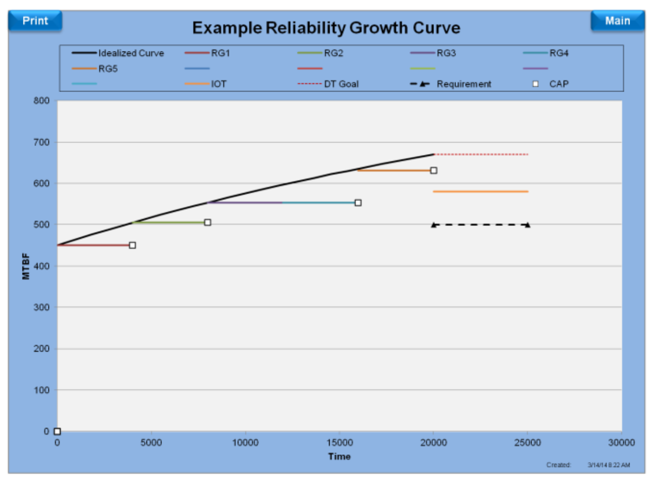

Figure 12: Example BCPM Reliability Growth Curve

The B-mode related outputs for BCPM are also the same as for PM2, just with differing results as to be expected from the different reliability growth planning curve.

PM2 vs BCPM Case Study

As mentioned earlier in this paper, BCPM has not been fully approved and as such there are still some Army related issues with using it. For a recent program however, the need for more achievable reliability goals led to BCPM being used. This case study goes over that process of going from a PM2 model to a BCPM model and back again when the BCPM reliability growth planning curve was rejected. The implications of this process are analyzed to capture the significance of the model being used for reliability growth planning.

The initial reliability growth curve was developed for this program using PM2 and is the same reliability growth curve as shown above in figure 4. The problem with this curve however was that the goal MTBF of 1027 hours was deemed incredibly high risk, bordering on completely unrealistic. As such, the program office discussed this with AMSAA and decided to employ BCPM for the program to help enhance testing efficiency and bring the MTBF goal down to a more realistic number. The parameters and metrics for this new reliability growth planning curve are shown in figure 13 below and the reliability growth curve associated with these values is shown in figure 14.

Input the Planning Parameters	
MTBF Requirement (MR)	500
Management Strategy (MS)	0.95
Average Fix Effectiveness Factor (μ_d)	0.70
Initial MTBF (MI)	300
Planned DT to OT Degradation	0.10
Consumer Risk for Final Demonstration Test	0.20
Producer Risk for Final Demonstration Test	0.30

Output Metrics	
Total Test Time	25000
MTBF DT Goal (MG)	658.3
MTBF Growth Potential (MGP)	895.5
M_G / M_{GP} Ratio	0.74
M_G / M_I Ratio	2.2
IOT MTBF Point Estimate	570.4
IOT MTBF Lower Bound	502.7
True Consumer Risk	0.20
True Producer Risk	0.15
β	0.00023
θ(TL)	0.81849

Figure 13: Parameters and Metrics for BCPM Option

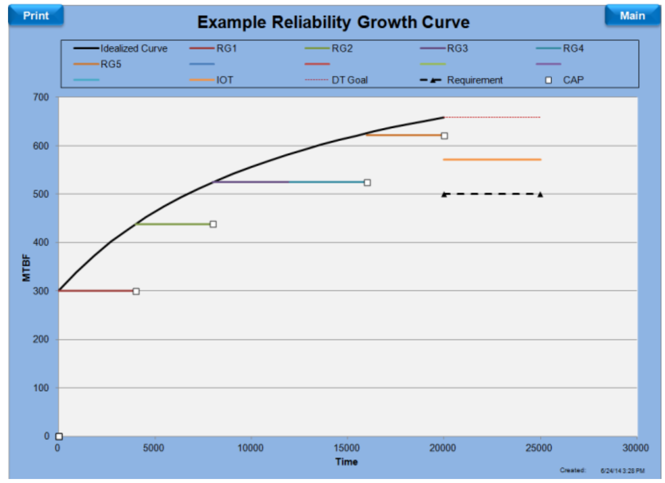

Figure 14: Reliability Growth Curve for BCPM Option

In figure 13, numerous parameters and metrics are circled to show the impacts associated with going from PM2 to BCPM. First of all, going to BCPM allowed the initial MTBF assumption to be lowered from 450 to 300, thus lowering the risk of starting DT at an MTBF value below the curve. This was while maintaining the risk parameters for confidence level and PoA. These parameters just had to be changed over to their equivalent for BCPM. The 80% confidence level became the 20% consumer's risk and the 70% PoA became the 30% producer's risk.

The next area where changes were observed was in the area of the MTBF goal and MTBF growth potential. The DT MTBF goal value dropped from 1027 hours with PM2 to 658 hours for BCPM. Having the DT MTBF goal value drop so much lowers the risk for the reliability growth curve substantially more. This ties directly in to the MTBF growth potential as well. Now this shows that the growth potential MTBF only needs to be 895 hours. With this ceiling lowered, the risk that the ceiling was overestimated initially also decreases. In addition to these changes, the ratio of the goal MTBF to the growth potential MTBF also drops from 0.76 to 0.74, meaning the program no longer has to get as close to the MTBF ceiling for the system.

So basically, going from PM2 to BCPM allowed for many different risks to be significantly mitigated. Unfortunately, within the Army, there are many layers of approval for reliability growth plans and not everyone was onboard with using the BCPM. As such, the program was forced to go back to a PM2 model that they had to tailor to make realistic. The parameters and metrics for this model are shown below in figure 15 and the corresponding reliability growth curve is shown in figure 16.

Requirement MTBF (M_R)	500
Initial MTBF (M_I)	350
Management Strategy (MS)	0.95
Average FEF (μ_d)	0.70
Confidence Level for IOT LCB	0.80
Prob. of Accept. in IOT using LCB	0.60
Prob. of Accept. In IOT using Pt. Est.	0.96
Goal MTBF in IOT (M_R^+)	828
Goal MTBF in DT (M_G)	828
Growth Potential (M_{GP})	1045
M_G/M_{GP} Ratio	0.79

Figure 15: Parameters and Metrics for Final PM2

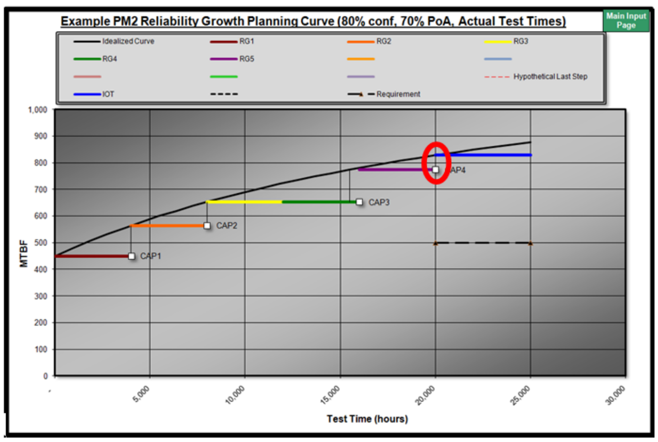

Figure 16: Reliability Growth Curve for Final PM2

As these two figures make apparent, there are significant changes that need to be made to the assumptions in order to get the DT MTBF goal value down to a realistic level. The initial MTBF had to be raised up from 300 to 350 hours. The PoA had to be lowered by 10% from 70% to 60%. The MTBF growth potential, DT MTBF goal and the ratio of the goal to growth potential also increased. In addition to these changes, the 10% degradation factor for MTBF in going from DT to IOT had to be changed to 0%. All of these changes increased different risk areas yet were necessary to keep the DT MTBF goal value at realistically achievable levels. So ultimately, going back to PM2 caused substantial increases in risk for the program because of these modified assumptions and also caused potential cost increases due to the now higher DT MTBF goal.

Why the Differences?

Looking at the inputs and outputs for the two models, it is apparent that while the same information goes in for both, what comes out is incredibly different. The main reasoning behind this is due to the fact that BCPM utilizes test data from DT along with the IOT data in order to assess the system against its reliability requirement. Therefore, since much more data is being used, the confidence bounds become much narrower and the high confidence estimation of the system's MTBF can be brought down to more reasonable levels.

Figure 17 shows how the assumptions work for PM2. Basically, when it gets time for IOT, it is assumed that nothing is known about the reliability of the system going into test. This is in spite of the fact that much DT has already occurred and much about the system has been learned. This is what the blue line shows. The "prior" IOT failure rate distribution is nothing more than the standard know-nothing distribution, an equally distributed pdf from zero to infinite. Using this "prior" with the IOT data, the result is a widely distributed Chi-Squared distribution for the possible failure rate. The 80% confidence level for this distribution is far away from the median, thus the inflated reliability goals.

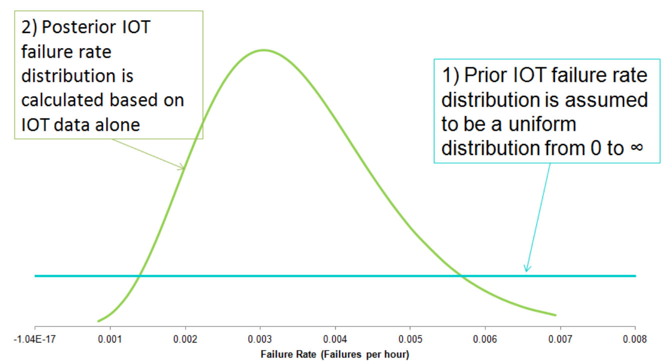

Figure 17: Effect of PM2 Assumptions

Figure 18 shows how the assumptions work for BCPM. The assumptions here work significantly differently than they do for PM2. First, based on all of the likely DT data, a DT posterior distribution is generated to show where the reliability of the system is likely to be at the conclusion of DT. To be turned into an IOT prior distribution however, it needs to be adjusted slightly. The DT posterior is shifted to account for the degradation factor and expanded as well to account for uncertainty in the degradation factor. This modified DT posterior distribution is now treated as the IOT prior distribution. Now, going into IOT, there is existing knowledge in the form of this distribution that is refined based on the results of the IOT. It is no longer assumed that nothing is known when going into IOT. As a result of this, the IOT posterior distribution is much tighter than the corresponding distribution for PM2. This ends up providing an 80% confidence level much closer to the mean and therefore much less inflated reliability goals.

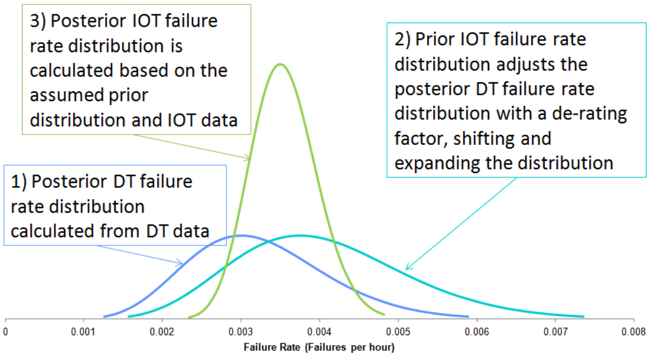

Figure 18: Effect of BCPM Assumptions

PM2 Issues that Remain within BCPM

So, while BCPM incorporates into it a much more realistic set of assumptions that allow minimizing the inflation of reliability goals and maximizing testing efficiency, some of the issues with PM2 still remain. The reliability growth curve is still calculated based on what is necessary as opposed to what is actually likely. This leads to the same set of illogical results observed from PM2. By following the same procedure and comparing B-modes for a 10,000 hour DT to those for 10,000 hours into a 20,000 hour DT, this becomes apparent. At the end of a 10,000 hour DT, BCPM shows that 14 B-modes have been surfaced accounting for 52% of the system's overall B-mode failure intensity. At 10,000 hours of the 20,000 hour DT however, BCPM shows that 17 B-modes have been surfaced, accounting for only 33% of the system's B-mode failure intensity. These similar results with fewer modes being shown to account for a greater percentage of the system's overall failure intensity demonstrate the same logical inconsistency that was present with PM2.

TARDEC Reliability Growth Planning Model

This remaining issue is one of the factors that led TARDEC to begin looking at better ways of addressing reliability growth planning in as realistic of a manner as possible. It became clear that developing a calculated reliability growth curve would not work because the curve needs to define reality, not conform itself based on a set of boundary conditions. The concept that is being pursued is a simulation-based reliability growth planning model that maximizes customizability so it can provide realistic reliability growth planning curves for any type of system being considered.

Simulation-Based Structure

The basis for this reliability growth planning model's structure is to make it similar to PM2 and BCPM from a user perspective while allowing more heavily customizable assumptions to be built into it. Figure 19 shows the input interface for the model. Similarly to PM2 and BCPM, there are places to enter information for all of the different test phases as well as the MS, FEF and initial MTBF. In addition to this, there is also a way to define the system that is to undergo reliability growth testing. This can be done in a couple of ways, the simplest being to define the number of failure modes that the system is expected to have along with a drop off value. This drop off essentially tells you the relative intensity of the different failure modes. A drop off of .94 means the failure intensity of the second most significant failure mode will be 94% as much as the failure intensity of the most significant failure mode and so on.

# of Modes	Drop Off	MS	Initial MTBF	FEF
1000	0.94	0.95	450	0.7

Test Phase	Test Decription	Length	CAP
1	RG1	4000	Y
2	RG2	4000	Y
3	RG3	4000	N
4	RG4	4000	Y
5	RG5	4000	Y
6	IOT	5000	N

Figure 19: Inputs for Simulation-Based Model

There is also a way to enter in any formula to define the shape of the distribution of failure mode intensities in case a more customized distribution is desired. The third and most customizable way for assigning the distribution of failure mode intensities is to specify failure intensity for each failure mode individually. This could be time consuming in some cases but in others, fault tree analyses or reliability predictions are available at a very detailed level from the contractors. These data sources could be directly imported into the model to allow for maximum customization of the system for which the reliability growth plan is being developed. This would greatly enhance the realism of the reliability growth planning activities as each reliability growth plan could be custom tailored to the complexity of the system and the shape of its distribution of failure mode intensities.

This leads up to the overall structure of the simulation-based reliability growth planning model which is shown in figure 20. The first step is defining the fault profile, test profile and growth strategy through the process described above. Once these are all defined, the individual test phases are simulated out to determine which failure modes are surfaced and addressed with fixes in each phase of testing. This process goes through all of the phases to simulate out the entire test plan and track all relevant metrics throughout.

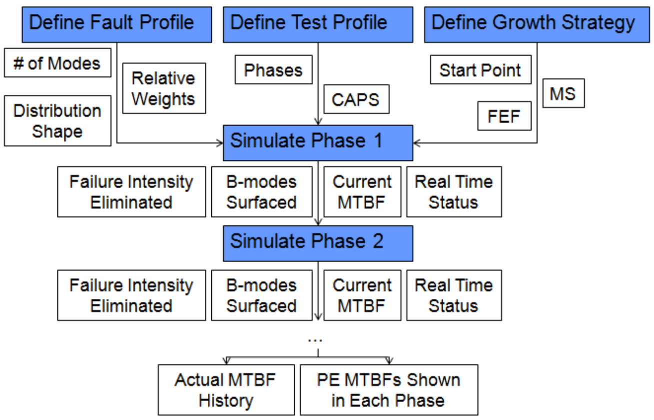

Figure 20: Simulation-Based Structure

This results in similar output graphs to both PM2 and BCPM. Figures 21 through 24 show the output plots for this simulation-based model that have counterparts within PM2 and BCPM.

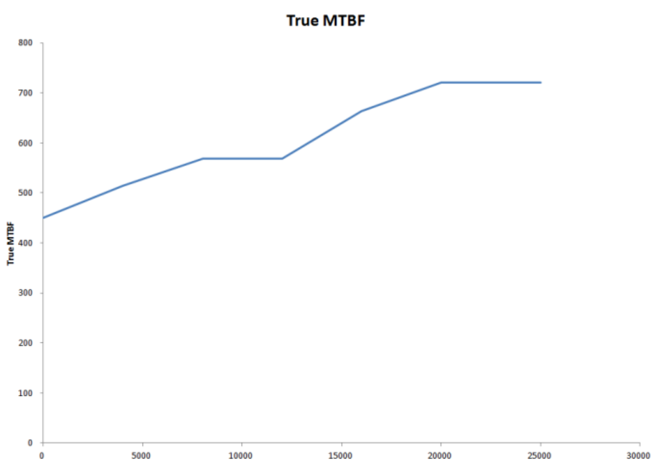

Figure 21: Simulation-Based Reliability Growth Curve

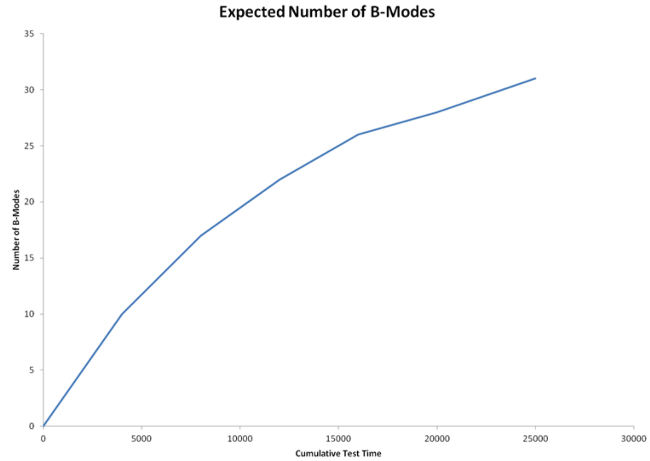

Figure 22: Expected Number of B-Modes

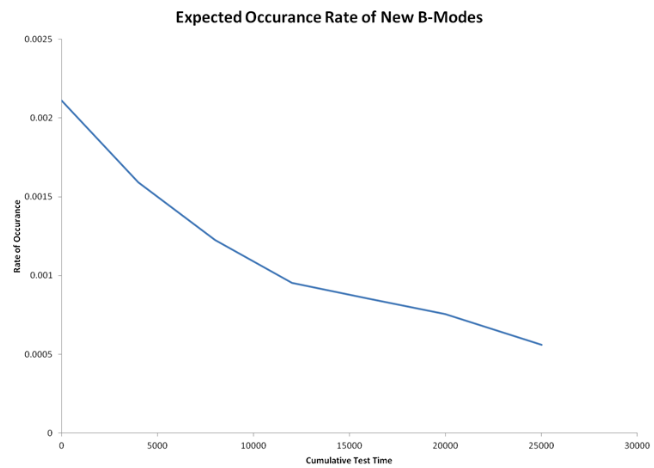

Figure 23: Occurrence Rate of New B-modes

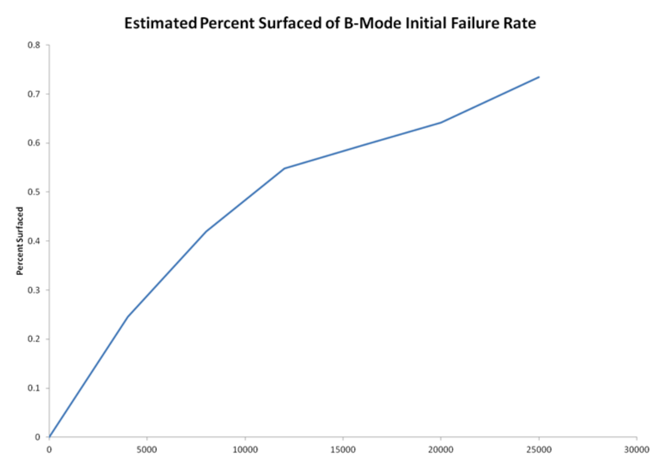

Figure 24: Percentage of B-mode Intensity Surfaced

Advantages over PM2 and BCPM

The advantages of this simulation-based reliability growth planning structure over PM2 and BCPM are numerous. The first advantage is that it gives an accurate measure of what sort of MTBF can be achieved in a given amount of reliability growth testing based on an assumed initial MTBF and failure profile. This is shown clearly by figure 25 which shows two scenarios, one with 10,000 hours of DT and the other with 20,000 hours of DT. These two lines are based on the median of 100 runs of the simulation model. As this clearly shows, the longer the reliability growth test, the more growth that can be expected. This is a substantial difference from PM2 and BCPM in that this level of growth is not based on some end point that needs to be achieved but is actually based on the knowledge of the system undergoing test tied into the amount of DT. This adds much more credibility to the reliability growth planning curve.

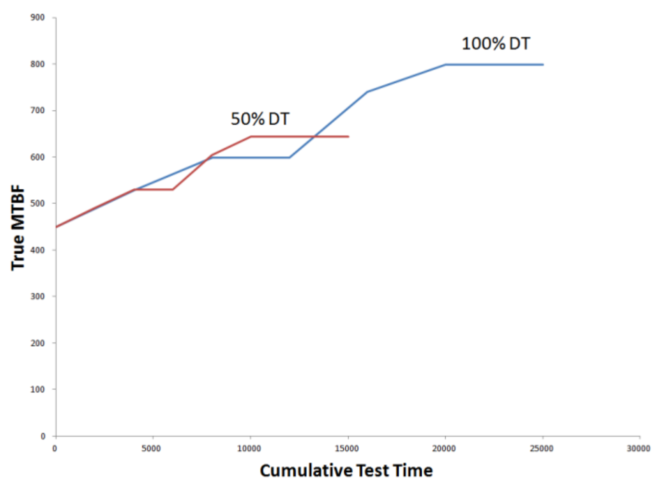

Figure 25: Realistic MTBF Growth Planning

The second major advantage of this simulation-based reliability growth planning model ties into the first advantage. The level of reliability growth that is achievable for a highly complex whole vehicle will be much different than it would be for a specific subsystem over the same length of testing. With many more failure modes for the whole vehicle, the rate of reliability growth would be much slower than it would be for the specific subsystem undergoing reliability growth testing. This is because each failure mode is much more significant when considering a specific subsystem so each fix made grows the reliability more. Figure 26 captures this point by showing reliability growth for different theoretical systems over the same testing profile. Each of the systems has a different number of failure modes so in this example, the 1,000 mode system would be most analogous to a complex full vehicle and the 10 mode system would be most analogous to a relatively simplistic subsystem. As this figure shows, the subsystem's reliability grows at a much faster rate to the point where it is over 1,200 hours MTBF by the end of DT as opposed to the full vehicle which is only at slightly under 800 hours MTBF. Allowing for this type of customization by system complexity is absolutely necessary when reliability growth plans are similarly required for full vehicles as well as subsystem upgrades such as the purchase of a new anti-tank weapon system for an existing vehicle.

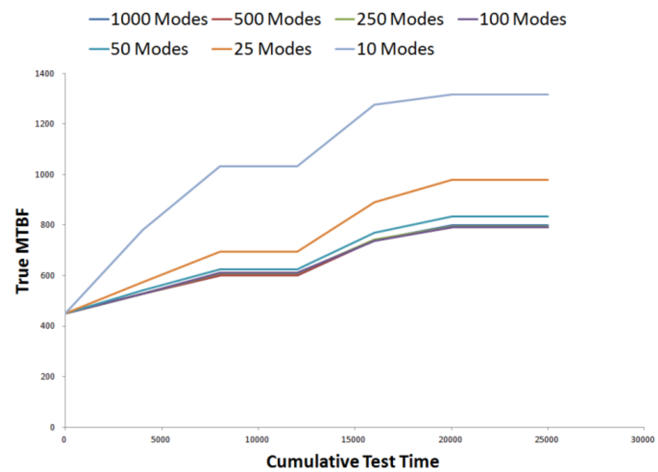

Figure 26: Accounting for System Complexity

The third advantage this simulation-based methodology holds over PM2 and BCPM is that it also allows for showing how reliability growth depends on the shape of the failure mode intensity distribution. For a system with a lot of equally likely failure modes, the same testing profile would yield much less reliability growth than for a system with a few dominant failure modes and a bunch of relatively insignificant ones. This is because each fix for a system with a bunch of equally significant modes only eliminates a small portion of the system's overall failure intensity. For the system with a few dominant modes, these modes are more likely to be surfaced during testing and the fixes will effect a much larger portion of the system's overall failure intensity. This is clearly shown in figure 27 below which shows essentially no reliability growth when each failure mode is equally likely and very rapid reliability growth when there is a 50% drop off in terms of failure rate from the highest failure rate mode to the second highest and so on.

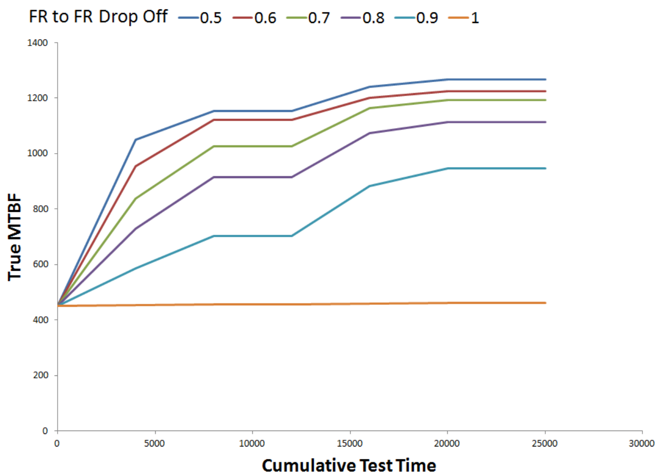

Figure 27: Failure Mode Distribution Shape Dependence

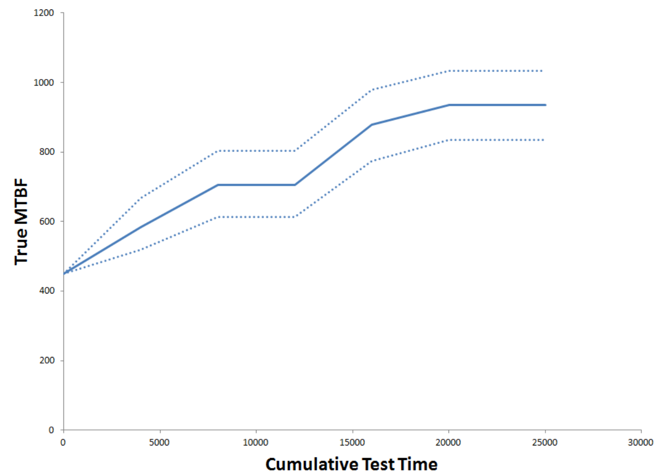

Figure 28: Reliability Growth Curve with Confidence

The last advantage that will be discussed for this model is that it allows for capturing the stochastic nature of reliability growth testing. If run many times, the same reliability growth test, for the same system, might show different levels of reliability growth each time. This is because the failures that are observed in any test are largely stochastic in nature. As such, different failure modes would be surfaced each time and therefore different amounts of the overall failure intensity of the system would be addressed with fixes each time. Running the simulation-based model, this caveat can be examined so confidence bounds can be presented for the different visual outputs. Figure 28 shows this for the reliability growth curve itself. This figure is based off of 1,000 runs of the simulation model and shows the median reliability growth curve along with the 80% confidence bounds for reliability growth associated with this testing profile. Being able to capture this for the growth curve as well as the B-mode plots allows for the model to also be used for tracking. The results during actual testing will never 100% match the plan so incorporating these confidence bounds will help allow for better realizing when the results are from statistical noise or are in fact showing significant deviation from the reliability growth curve.

Future for TARDEC Model

The simulation-based model is still in its early stages and much work remains to be done. Some of this work is minor and of a more limited scope, such as incorporating all of the good aspects of PM2 and BCPM where as some of the work is major yet would provide substantial additional capabilities. The minor items include allowing degradation factors to be included for going from DT to IOT, allowing for CAP lag times to be included and building in customizable variability to treat many of the inputs (MS, FEF, degradation factor …) as random variables as opposed to defined quantities.

One of the two major items that still needs to be incorporated is a BCPM-like way of combining DT and IOT data together. The simulation framework provides an ideal environment for showing how much reliability can grow over a given testing profile based on an assumed initial MTBF and failure mode intensity profile. It does not yet incorporate the BCPM-like methodology for combining DT and IOT data together to determine whether that realistic level of growth sufficiently demonstrates the MTBF requirement with the desired consumer and producer risks. This is a critical aspect to work on developing in order to finalize this model so that it can both explain what levels of reliability growth are possible and whether these levels are indeed sufficient.

The second major item that needs to be developed is a way for allowing accelerated DT. Reliability growth only occurs during testing when failures are exposed and mitigated. As such, more rapidly surfacing these failure modes would be ideal as the government would then get more reliability growth for their testing dollar. Many current systems have significant portions of their mission profiles dedicated to low intensity operations such as idling. Testing to the actual mission profile and thus performing all of this idling testing accomplishes little in the area of reliability growth. It would be far more beneficial to accumulate additional cross country mileage instead. In order for this to be possible however, a framework needs to be in place to translate the data from this higher intensity DT into MTBF numbers associated with the defined mission profile. This can be done by treating the reliability for a system as a combination of random variables instead of a single one. There would be one for cross country, one for secondary roads, one for primary roads, one for idling and additional random variables as necessary for other parts of the mission. These individual random variables could be combined together in different ratios to project the MTBF metric onto any number of different mission profiles and would allow for projecting the accelerated data out to the actual mission profile for which the system was designed. The concept for this is in place but the formulation of this within the simulation-based model still needs to be established.

CONCLUSIONS

Overall, it is incredibly clear that PM2 lacks the customization and realism that is necessary for the Army in a reliability growth planning tool going forward. BCPM addresses some of these issues well but leaves some of them unfixed. Despite this, a methodology similar to BCPM's for combining DT and IOT data will be necessary for any reliability growth planning model going into the future in order to maximize testing efficiency and prevent inflation of reliability requirements. The simulation-based reliability planning model being developed by TARDEC is the ideal place to do this. Combining the simulation environment with realistic assumptions and a way of combining DT and IOT data together would allow for development of reliability growth plans that are truly meaningful. They would be able to provide insight into how much DT is necessary, allow for incorporating system complexity into reliability growth curves and will also capture the stochastic nature of reliability growth testing. This would be a huge step forward that would help minimize risk for Army programs in the future.

REFERENCES

[1] "Report of the Defense Science Board Task Force on Developmental Test & Evaluation", Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., 2008.

[2] "Directive-Type Memorandum 11-003 – Reliability Analysis, Planning, Tracking, and Reporting", Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., 2011.

[3] "Planning Model Based on Projection Methodology (PM2)", U.S. Army Materiel Systems Analysis Activity, Aberdeen, Maryland, 2006.

[4] Wayne, M., "Methodology for Assessing Reliability Growth Using Multiple Information Sources", University of Maryland, College Park, Maryland, 2013.

[5] Kosinski, D., "Reliability Growth Planning for the Army: Models, Issues and Lessons Learned", Applied Reliability Symposium, Indianapolis, Indiana, 2014.