Reliability Growth Planning and Analysis of a Combat System

Using Duane Model and Crow Extended Reliability Growth Model

ABSTRACT

A combat system underwent three phases of operational testing in which faults found were fixed either immediately or at the end of each phase. The phases include test-find-test, test-fix-test, and test-fix-find-test. This paper focuses on the application of the Duane Model in developing the reliability growth test plan, phase-by-phase analysis of the reliability growth using the new Crow Extended Reliability Growth Model, and discusses the important lessons learned. The Extended Model is a flexible reliability growth model that allows the assessment of most common test strategies and provides extensive metrics for decision-making during the reliability growth programme. This is a useful case study for programme managers who are contemplating the use of reliability growth methods for development testing.

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INTRODUCTION

Modern and state-of-the-art military systems are becoming increasingly complex and reliability problems may invariably surface due to design deficiencies, systems integration, or immature technology. An effective solution is to apply reliability growth testing (RGT) to these complex design and developmental (D&D) systems early in the development phase in an attempt to identify and eliminate these deficiencies early in the system's life cycle. The key advantage of conducting RGT early is that design modifications are most cost-effective if made early in the system's life cycle. A successful reliability growth programme depends on a good reliability test programme during front-end planning and the ability to make realistic and valid assessment of the system's reliability during testing. Planning and assessment of reliability growth requires the use of mathematical models.

A widely used mathematical model in reliability growth planning is the power law model known as the Duane model. Deterministic in nature, the Duane model is suitable for reliability growth planning. A new mathematical model currently being used in the industry and US Department of Defense (DoD) for analysis of reliability growth is the Non-Homogeneous-Poisson-Process model known as the Crow Extended Reliability Growth Model. Traditional growth models address reliability growth based on fixes incorporated during the test or at the end of the test. These approaches are known as test-fix-test and test-find-test respectively. However, in today's environment, with a compressed test schedule and limited available resources for testing, a more common test strategy is the test-fix-find-test (Crow, 2004). This paper illustrates the application of the Duane Model and Crow Extended Reliability Growth Model using the reliability growth programme of a combat system as a case study. The important lessons learned will also be discussed in this paper.

DEVELOPMENT OF THE IDEALISED GROWTH CURVE OF THE COMBAT SYSTEM

The first step in the reliability growth process is reliability growth planning. It involves the development of an idealised growth curve with the Duane Model. The major role of the idealised reliability growth curve is to quantify the overall development efforts so that the growth pattern can be evaluated relative to the basic objectives and resources. It also serves as a useful tool for the programme manager to monitor the reliability growth of the combat system during its development. The formula for developing the idealised growth curve is based on the Duane model (US Department of Defense [DoD], 1981).

$$M(t) = \begin{cases} M_I & 0 < t < T_i \\ M_I \left(\frac{t}{t_I}\right)^{\alpha} (1-\alpha)^{-1} & t > T_i \end{cases}$$

Where

M_F = Target MTBF value at T

t = Cumulative test time

t_I = Cumulative test time at starting point

M_I = Initial average MTBF of the system at the beginning

α = System reliability growth rate between 0 and 1.0

For the combat system, the unit of measure for reliability was expressed in terms of rounds. A mission reliability of 200 rounds Mean-Rounds-Between-Failure (MRBF) was the target set to be achieved at the end of the reliability growth test. This target was set higher than the user's requirement as experience has shown that field reliability is typically lower compared to development testing as test conditions in developmental testing will tend to reduce certain operational potential failure modes from occurring (U.S DoD, 2005).

The total number of rounds available for the RGT programme was limited to a maximum of 2,300 due to resource constraints. This is statistically representative as it is approximately

10 times the target MRBF (Criscimagna, 1999). In addition, the high cost of the combat system has limited the test quantity to only one prototype.

Average initial MRBF, (M_I). The initial MRBF of the prototype was estimated by conducting a pre-developmental trial. The trial resulted in four failures in 280 rounds of testing. The MRBF was assumed constant during this phase since no significant design changes were incorporated during the test. As such the MRBF was estimated as:

$$\text{Initial MRBF} = \frac{280}{4} = 70 \text{ rounds} \quad (1)$$

Growth rate, (α). Since M_I, t_I, M_F and T are known, the desired growth rate can be approximated as follows:

$$\alpha = -\ln\left(\frac{t}{t_i}\right) - 1 + \left[\left(1+\ln\left(\frac{t}{t_i}\right)\right)^2 + 2\ln\left(\frac{M_F}{M_I}\right)\right]^{1/2} \quad (2)$$

The growth rate, α, was found to be 0.32 from equation (2). An α value of 0.32 indicates a moderately aggressive development program (US DoD, 1981). This growth rate is reasonable for a major development programme that would require emphasis on analysis and fixing of failure modes. It has been shown in Table 1 that the total test time is sensitive to α. A comparison was made with a similar class of systems and it has been concluded that by selecting a value of α greater than 0.32 would result in a very aggressive reliability growth programme that might not be practical to achieve. On the other hand, selecting a value of α below 0.32 would exceed the resource constraints.

The plan assumed that the MRBF of the combat system would grow from its initial level to the required 200 rounds MRBF in accordance with the following form of Duane expression for reliability growth:

$$M(t)\begin{cases} 70 & 0 < t < 280 \\ 70\left(\frac{t}{280}\right)^{0.32}(1-0.32)^{-1} & t > 280 \end{cases} \quad (3)$$

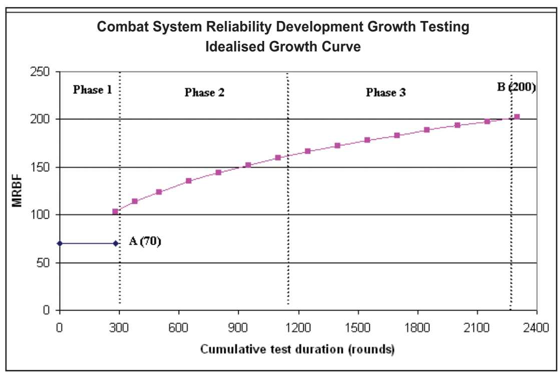

Figure 1. Idealised growth curve of the combat system

The idealised growth curve is shown in Figure 1. The reliability growth test of the combat system was divided into three test phases. Phase 1 was a pre-development phase to run-in the system and also to estimate its initial reliability. Phases 2 and 3 represent the actual reliability growth process to achieve the target. The last two phases consist of 820 rounds and 1,200 rounds of testing respectively. The strategy was to plan for more rounds to be tested in the last phase in order to allow for more time to ascertain the effectiveness of previous fixes.

M_I	70					
T_I	280					
α	0.3	0.32	0.34	0.36	0.38	0.4
T (rounds)	2880	2280	1780	1500	1280	1080

Table 1. Sensitivity analysis of α on total test time

RELIABILITY GROWTH MODELS

The choice of a reliability growth model for analysis is dictated by the type of failure management approach employed in each test phase:

Phase 1 : Crow Test-Fix-Test Extended Model

Phase 2 : Crow Test-Find-Test Extended Model

Phase 3 : Crow Test-Fix-Find-Test Extended Model

The traditional Crow Model addresses reliability growth based on the test-fix-test strategy where corrective actions for observed failures are incorporated into the system. In reality, corrective actions may be delayed until the end of test (test-find-test), or some may be incorporated during the test while others are delayed until the end of the test (test-fix-find-test). The Crow Extended Model was developed by Crow to address this practical strategy often employed during testing where some fixes are incorporated during the test and some fixes are delayed until the end of the test. The test-fix-test and test-find-test scenarios are special cases of the Crow Extended Model (Crow, 2004).

The Extended Model helps to define the failure management strategy by using failure mode designation. By doing so, useful metrics can be generated for decision-making and engineering purposes. The failure management strategy classifies failure modes into two categories, A and B. Type A failure modes are those that will not receive a corrective action. These account for failures that the management has determined as not cost-effective or otherwise justified to be corrected. Type B failure modes are further divided into two types, namely BC and BD in order to provide an assessment and management metric structure for corrective actions during and after the test (Crow, 2004). Type BC modes refer to failure modes that are corrected during the test. Type BD modes are those that are delayed to the end of the test. Type A and BD failure modes do not contribute to reliability growth during the test. Type BC failure modes once corrected will affect an increase in system reliability during the test. The system reliability will increase further after the incorporation of fixes for Type BD failure modes at the end of the test. Estimating this jump in reliability is the objective of the Extended Model. The Extended Model assigns effectiveness factor (EF) for each failure mode to adjust the failure intensity of their respective failure modes to obtain the projected reliability of the updated configuration (Crow, 2004).

ReliaSoft's RGA 6 PRO software (ReliaSoft, n.d.) is used for analysing the collected failure data and generating reliability growth plots.

PHASE 1 RESULTS AND ANALYSIS

In Phase 1, the prototype was subjected to 280 rounds of testing according to the test plan. Since this test phase was short, fixes were not incorporated into the system during the test. Three failures were identified during the test but all corrective actions were delayed till the end of the test. This management strategy is known as test-find-test. The Crow Test-Find-Test Extended Model was selected to analyse the reliability of the system after the incorporation of delayed fixes. All failure modes identified during the test received a delayed corrective action and they were classified as Type BD as shown in Table 2.

Table 3 shows the frequency and the assigned effectiveness factor (EF) for each Type BD failure mode. The EF is an engineering estimate based on the probability that the fix is effective in mitigating or reducing the probability of

j	Time to Event Xj	Classification	Mode	Failure Category
1	21	BD	1	Faulty component
2	132	BD	2	Design
3	215	BD	3	Design

Table 2. Test-find-test data for Phase 1

BD Mode	Number of Failures, N_j	Time to First Occurrence	EF, d_j
1	1	21	0.65
2	1	132	0.7
3	1	215	0.7

Table 3: Test-find-test Type B failure mode data and EF for Phase 1

occurrence for the particular failure mode. An EF of 1.0 is not practical in most cases since a fix will be unlikely to eliminate a failure mode completely. Studies have shown that an average EF of 0.7 is reasonable for a typical reliability growth programme (Crow, 2004).

Since the test data consists of only Type BD failure modes, the achieved system failure intensity is estimated as shown in Metric 1.

Metric 1: Type BD failure intensity

$$\hat{\lambda}_s = \hat{\lambda}_{BD} = \frac{N_B}{T} = \frac{3}{280} = 0.0107 \qquad (4)$$

The estimated achieved MRBF at T=280 rounds before the jump in reliability is the inverse of the achieved system failure intensity.

$$\hat{M}_s = \frac{1}{\hat{\lambda}_s} = 93.3\ rounds \qquad (5)$$

Next, the projected failure intensity due to the delayed fixes is calculated as shown below.

$$\hat{\lambda}_p = \hat{\lambda}_A + \sum_{j=1}^{M}(1-d_j)\frac{N_j}{T} + \bar{d}\hat{h}(T) \qquad (6)$$

The average EF of the delayed fixes is estimated as follows.

$$\bar{d} = \text{Average EF} = \frac{\sum_{j=1}^{M} d_j}{M} = \frac{0.65+0.7+0.7}{3} = 0.683 \qquad (7)$$

Metric 2: Intensity for Type BD failure modes that have not been seen in the testing.

$$\hat{h}(T/BD) = \hat{\lambda}\hat{\beta}T^{\beta-1} \qquad (8)$$

The term $\hat{h}(T/BD) = \hat{\lambda}\hat{\beta}T^{\beta-1}$ is a function of $\hat{\beta}$ the shape parameter and $\hat{\lambda}$ the scale parameter. These two parameters are estimated using the Maximum Likelihood Estimate (MLE) with first occurrence failure data from Table 3.

With all the above parameters defined, the projected failure intensity can be calculated.

$$\hat{\lambda}_p = \hat{\lambda}_A + \sum_{j=1}^{M}(1-d_j)\frac{N_j}{T} + \bar{d}\hat{h}(T/BD) = 0.0064 \qquad (9)$$

The projected MRBF due to the jump in reliability is the inverse of the projected failure intensity in equation (9).

$$\hat{M}_p = \frac{1}{\hat{\lambda}_p} = 156\ rounds \qquad (10)$$

Figure 2 shows that the MLE method does not produce a good curve fit for a small sample of data points. The estimate of the failure intensity in this case will be slightly lower than the actual data.

Figure 3 shows the plot of MRBF versus time during the test. The MRBF is constant *(β =1)* during the test because no fixes were

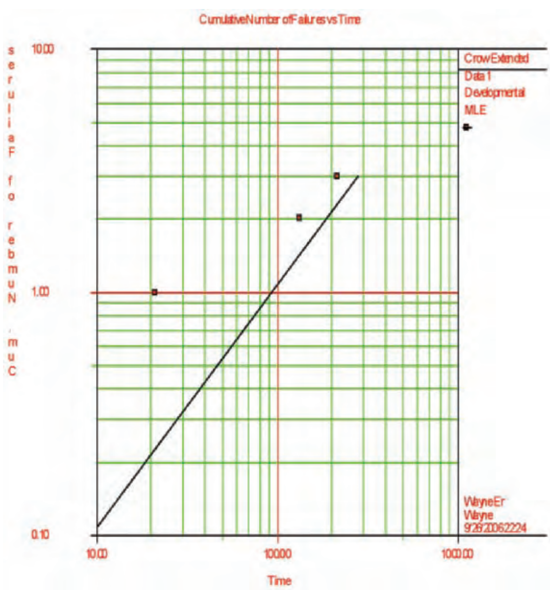

Figure 2. Cumulative failures vs time plot

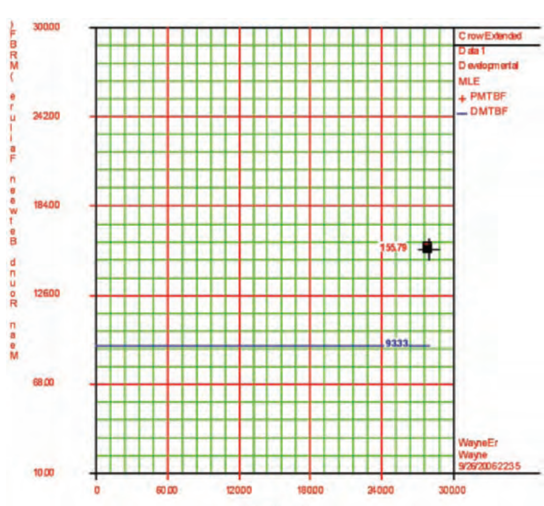

Figure 3. Test-Find-Test MRBF projection

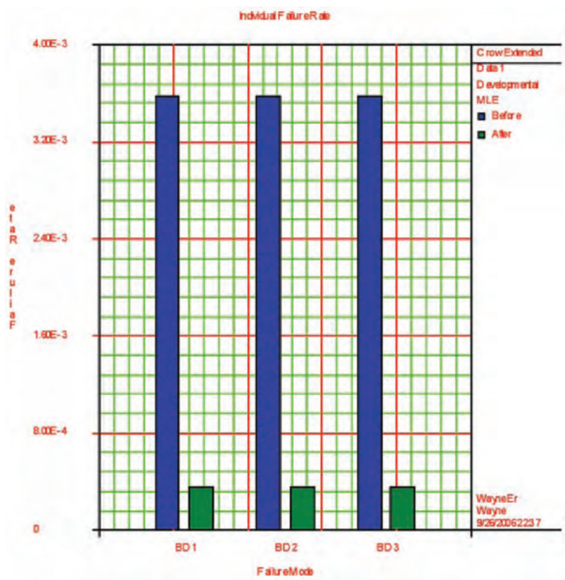

Figure 4. System's failure rate breakdown

implemented in the system and thus the system failure rate remains constant during the test. There is a jump in reliability at the end of the test due to fixes being incorporated into the system. The projection model estimates that the system MRBF jumps to a value of 156 rounds due to three distinct corrective actions with the corresponding EF stated in Table 3.

Figure 4 displays the failure rate for each Type BD failure modes before and after implementing the fixes. Failure mode BD1 has the highest failure rate and it was the main contributor to the current system's failure rate. The ability to designate failure modes has certainly provided clearer management and engineering insights in the prioritisation of failure management under constraints of time and resources.

PHASE 2 RESULTS AND ANALYSIS

The failure management approach adopted in Phase 2 was test-fix-test, in which fixes for all failure modes discovered were incorporated during the test. The system was tested for 820 rounds in this phase. In applying the Extended Model, all failures were designated as Type BC as shown in Table 4.

Fitting the Crow Test-Fix-Test Model, we have Metrics 3 to 6. The Extended Model provides additional metrics, Metrics 7 to 9.

j	Time to Event, Xj	Classification	Mode	Failure Category
1	27	BC	1	Faulty component
2	72	BC	2	Design
3	122	BC	2	Design
4	265	BC	3	Software
5	317	BC	4	Design
6	394	BC	5	Design
7	455	BC	2	Design
8	719	BC	6	Faulty component

Table 4. Test-fix-test data for Phase 2

BC Mode	Number of Failures, N_j	Time to First Occurence
1	1	27
2	3	72
3	2	275
4	1	317
5	1	394
6	1	719

Table 5. Unique first-time occurrence BC failure mode for Phase 2

Metric 3: Shape Parameter

$$\hat{\beta} = \left(\frac{N-1}{N}\right)\frac{N}{N\ln T - \sum_{1}^{N}\ln X_i} = 0.6203 \qquad (11)$$

The calculated value of $\hat{\beta}$ of 0.7089 ($\hat{\beta}$ <1) implies positive and improved reliability growth in this phase. The relationship between the growth rate and the shape parameter is given below.

Metric 4: Growth rate

$$\alpha = 1 - \hat{\beta} = 0.37 \qquad (12)$$

The scale parameter is estimated as:

$$\hat{\lambda} = \frac{N}{T^{\hat{\beta}}} = 0.124 \qquad (13)$$

Metric 5: Achieved failure intensity

$$\hat{\lambda}_{CA} = \hat{\lambda}\hat{\beta}T^{-1} = 0.00605 \qquad (14)$$

The demonstrated instantaneous MRBF at the end of Phase 2 after 820 rounds of testing is the reciprocal of equation (14).

Metric 6: Demonstrated MRBF

$$\hat{M}_{CA} = \frac{1}{\hat{\lambda}_{CA}} = 165 \text{ rounds} \qquad (15)$$

Due to six distinct fixes, the reliability of the system grew to 165 rounds at the end of 820 rounds of testing.

Figure 5 indicates that reliability increases with time due to effective application of the test-fix-test strategy in surfacing and fixing failure modes. According to the idealised growth curve, the expected MRBF at the end of Phase 2 should approach 159 rounds. The demonstrated MRBF of 145 rounds is approaching the expected target.

Metric 7: Failure Intensity $\hat{h}(T/BC)$ for Type BC failure modes at the end of 820 rounds of test. Apply Equation (14) to the data in Table 5. This gives

$$\hat{h}(T/BC) = 0.0041 \qquad (16)$$

This is the rate at which new distinct problem BC failure modes are occurring at the end of 820 rounds of testing.

Metric 8: Instantaneous MRBF to Next New Type BC Failure Mode.

$$\hat{M} = \hat{h}(T/BC)^{-1} = 240\ rounds \qquad (17)$$

The above results indicated that at T=820 rounds, new, distinct Type BC failure modes were occurring every 240 rounds. This metric allows the programme manager to anticipate the next BC failure so that pre-emptive corrective actions can be taken.

The failure mode strategy plot in Figure 6 is a pie chart of failure modes with categories to represent the steps taken to address the modes. It shows that 22.1% (Type BC-seen) of the system initial system's failure intensity was removed from the system and 77.9 % are future Type "C" modes that will be observed if testing continues (Type BC-unseen).

It may also be of interest from both the engineering and management perspective to quantify the level of effectiveness of the fixes for the six Type BC failure modes.

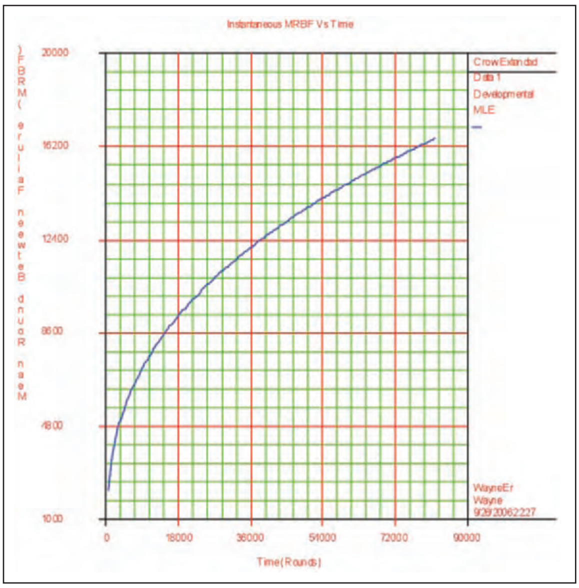

Figure 5. MRBF growth plot for test-fix-test

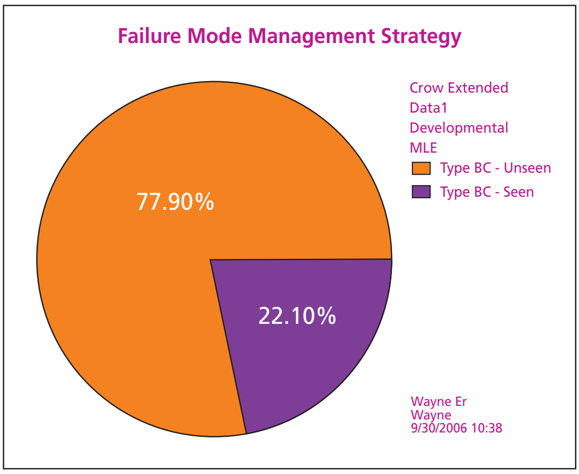

Figure 6. Failure mode strategy

Metric 9: Average effectiveness factor for Type BC Failure Modes.

$$\hat{d}_{BC} = \frac{\hat{\lambda}_I - \hat{\lambda}_{CA}}{\hat{\lambda}_{I(BC)} - \hat{h}(T/BC)} = 86\% \qquad (18)$$

The above computation implies that the six corrective actions removed an average of 86% of the failure rate from the six unique Type BC failure modes. An average of 14% remained in the six Type BC failure modes.

PHASE 3 RESULTS AND ANALYSIS

In Phase 3, some fixes were incorporated into the system during the test while others were delayed until the end of the test. The delayed fixes were due to unavailability of spares and limited time available for troubleshooting during test. A total of nine failures were observed in 1200 rounds of testing. Failures that received a correction action during the test were classified as BC while those that were delayed were being classified as BD. The failure summary is presented in Table 6.

j	Time to Event, Xj	Classification	Mode	Failure Category
1	55	BD	1	Faulty component
2	101	BC	1	Design
3	212	BC	1	Software
4	317	BC	2	Faulty component
5	379	BC	3	Software
6	465	BC	4	Design
7	520	BD	2	Faulty component
8	579	BD	3	Quality
9	900	BC	5	Workmanship

Table 6. Test-fix-find-test data for Phase 3

BD Mode	Number of Failures, N_j	Time to First Occurrence	EF, d_j
1	1	55	0.6
2	1	520	0.6
3	1	579	0.6

Table 7. Test-find-test Type BD failure model data and EF for Phase 3

The first part of the analysis aims to estimate the demonstrated reliability based on both Type BC and Type BD failure modes that surfaced during the test.

The shape parameter $\hat{\beta}$ is calculated using the MLE based on the data in Table 6.

$$\hat{\beta} = \left(\frac{N-1}{N}\right)\frac{N}{N\ln T - \sum_{i=1}^{N}\ln X_i} = 0.636 \quad (19)$$

The calculated $\hat{\beta}$ value of 0.715 ($\hat{\beta}<1$) implies positive reliability growth in this phase. The growth rate is given by:

$$\alpha = 1 - \hat{\beta} = 0.36 \quad (20)$$

The calculated growth rate of 0.36 is consistent with that of Phase 2.

The achieved failure intensity before the incorporation of the delayed fixes at a cumulative time of 1200 rounds is:

$$\hat{\lambda}_{CA} = \hat{\lambda}\hat{\beta}T^{-1} = 0.0047 \quad (21)$$

The achieved MRBF is the inverse of the failure intensity given by:

$$\hat{M}_{CA} = [\lambda_{CA}]^{1} = 210\ rounds \quad (22)$$

Figure 7 shows an improved MLE fit as compared to Figure 2 as a result of an increased number of data points.

The demonstrated MRBF of 210 rounds at the end of Phase 3 prior to the incorporation of fixes was slightly above the target of 200 as shown in Figure 8. The next step is to estimate the jump in reliability as a result of delayed fixes.

Metric 9: Intensity for Type BD failure modes that have not been seen during the testing, and also the rate at which new distinct Type BD modes are occurring at the end of the test. Apply Equation (21) to the data in Table 7.

$$\hat{h}(T/BD) = 0.0025 \quad (23)$$

The inverse of equation (23) gives 400 rounds, which is the instantaneous MRBF of the next unique BD modes. This is a quantum improvement over Phase 1. At the same time it allows the programme manager to anticipate the next BD failure and allow pre-emptive corrective actions to be taken.

Metric 10: Projected Failure Intensity, $\hat{\lambda}_{EM}$, due to delayed fixes into the system.

$$\hat{\lambda}_{EM} = \hat{\lambda}_{CA} - \hat{\lambda}_{BD} + \sum_{j=1}^{M}(1-d_j)\frac{N_j}{T} + \bar{d}h(T/BD)$$
$$= 0.0039 \quad (24)$$

Metric 11: Projected MRBF due to incorporation of delayed fixes is the inverse of the project failure intensity in Metric 10.

$$\hat{M}_{CA} = \frac{1}{\lambda_{CA}} = 255 \; rounds \qquad (25)$$

The Extended Model estimates that the MRBF grew to 210 rounds as a result of three corrective actions for BC failure modes during the test. It then jumps to 255 rounds as a result of the delayed corrective actions for Type BD failure modes. The combat system is estimated to meet the reliability requirements after taking into account the effect of delayed fixes. Lastly, it is also of interest to the management to assess the growth potential or maximum achievable MRBF of the combat system based on the current failure management strategy.

Metric 12: Growth Potential failure intensity with both BC and BD failure modes

$$\hat{\lambda}_{GP} = \hat{\lambda}_A + \left(1 - \hat{d}_{BC}\right)\hat{\lambda}_{BC} + \sum_{j=1}^{M}\left(1 - d_j\right)\frac{N_j}{T} = 0.0032 \qquad (26)$$

Metric 13: Growth Potential MRBF with both BC and BD failure modes

$$\hat{M}_{GP} = 305 \; rounds \qquad (27)$$

The current management strategy of fixing all failure modes can increase the system MRBF to a maximum of 305 rounds as shown in Figure 9.

In conclusion, the combat system grows from an initial MRBF of 93 rounds in Phase 1 to 255 rounds in Phase 3 and it has the potential to reach a maximum MRBF of 305 rounds using the current management strategy of fixing all surfaced failure modes. The combat system is estimated to meet the reliability requirements at the end of the RGT.

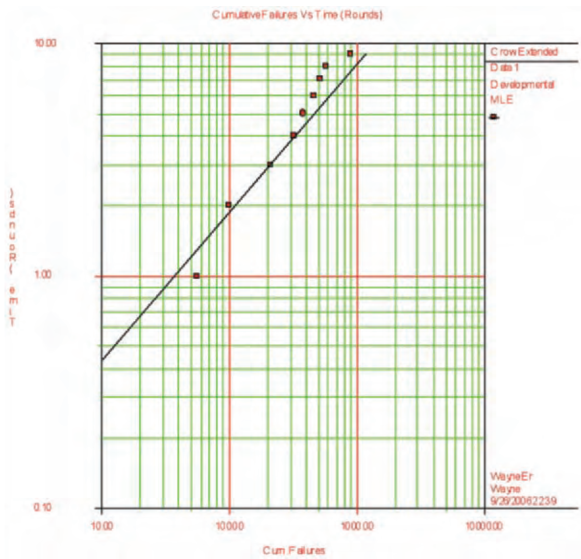

Figure 7. Cumulative failures vs Time

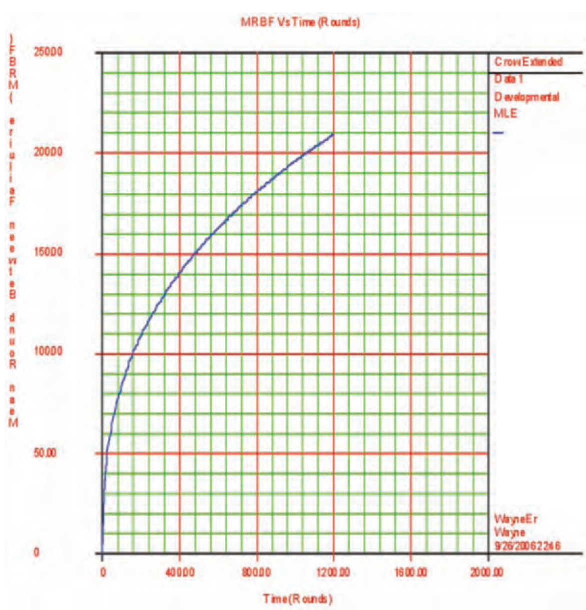

Figure 8. MRBF vs Time before delayed fixes

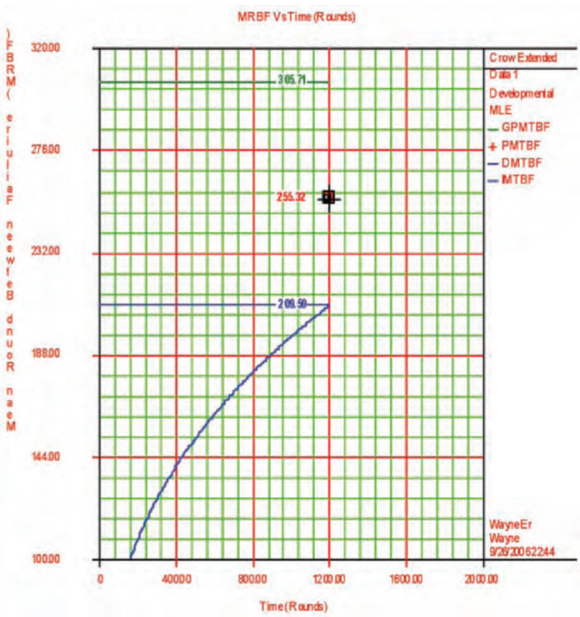

Figure 9. MRBF Growth potential plot

LESSONS LEARNED AND CONCLUSION

This paper has demonstrated the detailed application of the Duane Model and Crow Extended Model using a combat system as a case study. Some of the important lessons learned are summarised below.

In reliability growth planning, the total test time required for the RGT programme is sensitive to the following parameters: 1) the system's initial reliability, 2) the initial test time and 3) the growth rate. In most practical cases, the total test time is usually a constraint due to limited time and resources available in the development programme. The most precise way to estimate the initial system's reliability is to subject the system to pre-development testing and the initial test time must be long enough for at least the first failure to surface. This paper concludes that the highest achieved growth rate is 0.37, which agrees with historical data that the typical growth rate for a combat system of similar complexity should not exceed 0.4.

The Crow Extended Model is a more flexible growth model compared to the traditional reliability growth model. It can address the reliability growth of most test scenarios. It allows estimation of the increase in the system's reliability due to correcting delayed failure modes. This is particularly useful for decision-making when the demonstrated reliability of the system is below the growth target and no further testing is possible due to time or resource constraints. It is therefore necessary to assess if the reliability requirements can be met after incorporating the delayed fixes.

The use of failure mode designation in the Crow Extended Model allows generation of many useful metrics for making technical and management decision. Examples of these metrics are: 1) the initial system reliability at the beginning of the test, 2) the average effectiveness factor of remedying failure modes, 3) the reliability growth potential, and 4) the system-failure-rate breakdown for individual failure modes, etc.

It was observed that the MLE method of data analysis tends to produce slightly biased results for a small sample size of failure data. In reality, any statistical model requires a reasonably large sample size to obtain a good fit. Under such circumstances, engineering assessment becomes critical when statistical assessment cannot provide unbiased reliability assessment.

Lastly, the Extended Model and its extensive metrics are applicable for new complex systems undergoing evolutionary development in which new capabilities will be added sequentially and fielded in various blocks. Consequently the reliability growth in each block will typically follow the test-fix-find-test development testing, and therefore the Extended Model applies.

REFERENCES

Criscimagna, N. H. (1999) Reliability Growth. START Sheet, 6(3). Retrieved Jan 2006, from RIAC Web site: http://www.quanterion.com/RIAC/Publications/STARTSheets/PDFFiles/rgh.pdf.

Crow, L. H. (2004) An Extended Reliability Growth Model for Managing And Assessing Corrective Actions. Annual Reliability & Maintainability Symposium. Los Angeles, California: Institute of Electrical & Electronic Engineers (IEEE), Inc.

Er, K. H. (2005) Analysis of the Reliability Disparity and Reliability Growth Testing Of A Combat System Using AMSAA Extended Reliability Growth Models. Monterey, California: Naval Postgraduate School.

ReliaSoft. (n.d.) ReliaSoft's Reliability Growth Reference On-Line Help. Retrieved June 2006, from ReliaSoft Corporation Web site: http://www.weibull.com/RelGrowthWeb/reliability_growth.htm

US Department of Defense. (2005) DoD Guide for Achieving Reliability, Availability, and Maintainability. Washington, D.C.: Department of Defense.

US Department of Defense. (1981) Military Handbook (MIL-HDBK-189): Reliability Growth Management. Washington, D.C.: Department of Defense.

BIOGRAPHY

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