Planning a Reliability Growth Program Utilizing Historical Data

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Key Words: Historical Reliability Data, Growth Rate, Fix Effectiveness Factor, Discovery Rate, Planned Growth Curves

SUMMARY & CONCLUSIONS

From historical data this paper will note the significant patterns and key parameters that provide the basis for general guidelines that are very useful in establishing a realistic reliability growth testing program. These guidelines also address concerns raised by the 2008 Defense Science Board Task Force addressing reliability. As noted by this Task Force two major risks areas are the initial MTBF and the Growth Potential MTBF. In particular, the Defense Board Task Force report, Ref. 10, found that the "low initial MTBF and low Growth Potential are the most significant reasons that systems are failing to meet their operational suitability requirements." This paper will address data and experiences on these two key parameters and provide practical information on how they are managed. The information on these two key parameters and additional information on other parameters, such as growth rates, are very useful in reducing the risks and cost of a reliability growth program. In addition to the data, guidelines will be given regarding the use of these parameters to address the concerns of the Defense Science Board Task Force.

1. INTRODUCTION

For many years prior to the Department of Defense (DoD) Acquisition Reform in 1998, reliability growth testing was common and implemented on many developmental programs. During this time there were various papers, reports, and studies on data, key parameters, and experiences that were based on actual reliability growth testing programs. This historical information is very useful because as part of the new DoD direction regarding reliability, a reliability growth plan must be developed along with the corresponding reliability growth planned curve. The purpose of the planned curve is to set realistic interim reliability goals to be attained during the testing that indicate that sufficient progress is being made in order to reached the final goal or requirement. If the reliability growth interim goals are not realistic and set too high, for example, then assessments of the progress may incorrectly indicate that the program will not be successful, or if the interim goals are set too low then problems and issues may not be uncovered in a timely manner.

Clearly, planning models should use historical data as much as possible, particularly regarding parameters that significantly determined the shape and the ending reliability at the completion of test. This paper provides information on major key parameters affecting reliability growth planning that can be used as inputs for planning models, and will illustrate their application with numerical examples. New data and historical information on a very important planning parameter, the discovery rate, is given in this paper. The user can use this information in planning a growth test program and also to evaluate the realism of a proposed reliability growth test program. These applications are discussed in the examples.

NOTATION

α	Duane/Crow (AMSAA) Growth Rate
FEF	Fix Effectiveness Factor
d	Average Fix Effectiveness Factor
GPDM	Growth Potential Design Margin
MS	Management Strategy
β_D	Discovery Rate Parameter

2 BACKGROUND ON PLANNING PARAMETERS AND MODELS

This paper will explore and discuss several important parameters affecting reliability growth. In order to understand the significance and applications of these parameters for reliability growth planning we will first give some background and historical information. In publish tables on historical experiences regarding reliability growth testing there are two important parameters estimated from the data, the growth rate, and average effectiveness factor. We will next discuss these two parameters and how they are calculated and used. We will then introduce and discuss additional key parameters of particular interest in reliability growth planning. These key parameters and concepts are relevant regardless of the planning model. The specific application of these input parameters to several models is discussed in this section.

2.1 *Duane Postulate and Growth Rate*

In 1962 J. T. Duane of General Electric published a paper, Ref.1, in which he plotted data from several systems undergoing reliability growth testing at General Electric. For each system Duane plotted the cumulative or average failure rate (intensity) at various time points during the testing. If N(t) is the cumulative number of failures up to time t during the testing Duane calculated the cumulative failure rate given by

$$C(t) = \frac{N(t)}{t} \tag{1}$$

Duane then plotted $\ln(C(t))$ versus $\ln(t)$. See Figure 1. As observed by Duane, Figure 1, the plots are close to being linear when plotted on $\ln-\ln$ scale. From this relationship Duane noted the parameter "Growth Rate" in his paper.

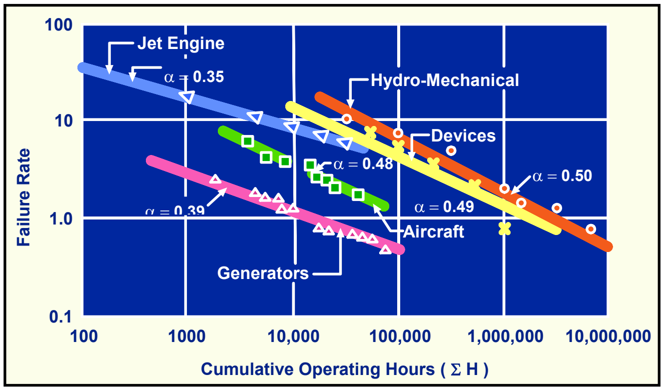

Figure 1. Original Duane Data

Duane called the negative of the slope of the straight lines, α , in Figure 1, the "growth rate."

2.1.1. Learning Curve Growth Rate Property

The linear pattern on $\ln-\ln$ scale plotted by Duane is the most common pattern empirically observed during reliability growth testing. This pattern reflects a learning curve characteristic which typically should be expected during reliability growth. Specifically, reliability growth takes place as the instantaneous failure intensity becomes less than the average failure intensity. As noted above, the cumulative failure intensity is

$$C(t) = \lambda t^{-\alpha} \tag{2}$$

and the instantaneous failure intensity (Ref. 1), is

$$r(t) = \lambda\left(1-\alpha\right)t^{-\alpha}. \tag{3}$$

The difference is $D(t) = \lambda t^{-\alpha} - \lambda\left(1-\alpha\right)t^{-\alpha} = \lambda t^{-\alpha}\alpha$ and

$$\ln(D(t)) = \text{Constant} + \alpha \ln(t)\,. \tag{4}$$

Therefore, the Growth Rate α is the rate on $\ln-\ln$ scale in which the instantaneous failure intensity is less than the cumulative failure intensity.

2.1.2 Crow (AMSAA) Model Growth Rate Estimation

In 1972 Crow, see Ref. 2 and Ref. 3 addressed the issue of establishing a statistical framework for reliability growth data that has the empirical properties noted in the Duane Postulate. Crow showed that the reliability growth failures times followed a non-homogeneous Poisson Process (NHPP) with failure intensity given by

$$r(t) = \lambda\beta t^{\beta-1}, \tag{5}$$

thus allowing for statistical procedures based on this process for reliability growth analyses.

Under the Crow (AMSAA) (CA) model, the achieved or demonstrated failure intensity at time T, the end of the test, is given by r(T). Based on the Crow (AMSAA) model the maximum likelihood estimates (MLEs) for λ and β are estimated based on actual failure times or grouped data. Now, T is the end of test. At time T the estimate of the failure intensity $r(T)$ (estimates λ, β) is

$$\hat{r}(T) = \hat{\lambda}\hat{\beta}T^{\hat{\beta}-1} = \left(\frac{N}{T^{\hat{\beta}}}\right)\hat{\beta}T^{\hat{\beta}-1} = \frac{N}{T}\hat{\beta}\,. \tag{6}$$

Using the Crow (AMSAA) model the growth rate (GR) estimate is

$$\hat{\alpha} = 1 - \hat{\beta}\,. \tag{7}$$

The Crow (AMSAA) model has the learning curve Growth Rate Property given by (4) with growth rate α.

2.2. Fix Effectiveness Factors

The application of Fix Effectiveness Factors in the context of a reliability projection model was introduced by Crow (1983), Ref. 5. When a corrective action is incorporated into a system to address a problem failure mode, the failure mode is rarely eliminated because of the corrective action. Instead the rate in which we will see that failure mode reoccur is reduced. The fraction decrease in the failure mode's failure rate is called the Fix Effectiveness Factor (FEF). Knowledge of historical FEFs is very important for reliability growth projections and as inputs to reliability growth planning models. Historical experiences on Fix Effectiveness Factors will be given in this paper.

2.3. Discovery Function, Discovery Parameter and Management Strategy Parameter

In order to have reliability growth during test it is clear that we must first see a problem failure mode. In 1982 Crow, Ref. 5, made the important observation that the total failure rate for all the problem failure modes not yet seen, $\lambda_{B(UNSEEN)}$, is exactly equal to the instantaneous rate at time T, h(T), in which we are discovery new, distinct problem, or Type B, modes. Crow used this observation to developed the projection model Ref. 5, (using average effectiveness factor)

$$\lambda_{\text{New}} = \lambda_A + (1-d)\lambda_B + d\cdot h(T) \tag{8}$$

that estimates the jump in the failure rate, λ_{NEW} , after corrective actions, where λ_A is the failure rate for all failure modes that will not be corrected if seen, λ_B is the failure rate for all failure modes that will be corrected if seen, and d is the average fix effectiveness factor (FEF). See also Crow, Ref.11. The discovery function h(t) can be viewed as a special case of the reliability growth instantaneous failure intensity r(t) when there are no Type A modes, the effectiveness factors are equal to 1, and corrective actions are incorporated so there are no repeat failure modes. Therefore, given that reliability growth data follows the Duane Postulate and Crow (AMSAA) model pattern, this would imply that the discovery rate has the form

$$h(t) = \lambda_D\beta_D t^{\beta_D-1}. \tag{9}$$

The failure modes in the discovery function are determined by the Type A and Type B modes management strategy. The Management Strategy, MS, is defined as the ratio

$$MS = \frac{\lambda_B}{\lambda_A + \lambda_B}. \tag{10}$$

Generally, it can be expected that the larger the MS is the quicker the reliability growth. The MS will be discussed below for a reliability growth program. From historical experiences, a MS of at least 0.95 should be expected for most reliability growth programs, and this is the value generally recommended for planning purposes. This means that failure modes that make up 95% of the initial failure rate will be addressed by corrective action if seen during test.

2.4. Growth Potential MTBF, Initial MTBF and Growth Potential Design Margin

The growth potential MTBF is the maximum reliability that can be attained with the design, FEFs, and the management strategy, MS. This is achieved when there are no further Type B modes to be seen and corrected, that is, when h(t) =0. From above, using an average FEF d, (See Crow, Ref. 6 and Crow and Gibson, Ref. 8) the growth potential failure intensity is

$$\lambda_{GP} = \lambda_A + (1-d)\lambda_B. \quad (11)$$

The growth potential MTBF is

$$M_{GP} = 1/\lambda_{GP}. \quad (12)$$

and the initial MTBF is

$$M_I = 1/\lambda_I = 1/(\lambda_A + \lambda_B). \quad (13)$$

It is typically very difficult, and rarely happens that a system will reach its reliability growth potential during a reliability growth test. The reliability growth generally becomes slower, and more expensive, after approximately the point when the system MTBF is 2/3 of the growth potential MTBF. Although we would expect a comprehensive historical reliability growth program to have matured the system reliability MTBF to 2/3 or greater of the growth potential MTBF, the growth would typically be much slower after 2/3 of the growth potential MTBF M_{GP} is attained.

The Growth Potential Design Margin is defined as

$$GPDM = \frac{M_{GP}}{M_F} \quad (14)$$

where M_F is the final MTBF. From historical experiences we should expect that $GPDM \le 1.5$. For growth planning the GPDM should be relative to the required MTBF M_{Req} ($M_F = M_{Req}$) so that a general guideline is

$$M_{Req}(1.5) \square M_{GP} \quad (15)$$

if we want to economically attain the requirement.

2.5. Relationship of Key Reliability Growth Parameters

Several of the reliability growth parameters discussed in this section are actually dependent on each other. For the initial failure intensity λ_I, the growth potential failure intensity λ_{GP}, the average fix effectiveness factor d, and the management strategy MS, Crow, Ref.7, has shown that

$$\lambda_I = \left[\frac{1}{1-d\square MSP}\right]\lambda_{GP} \quad (16)$$

This is a key equation used in reliability growth planning.

In addition, the mean time to the very first Type B mode discovered is equal to $1/\lambda_B$, which is determined by MS and λ_I. Therefore, the h(t) function and β_D are also related to the parameters in (16). Specifically, the λ_D in (9) has the relationship

$$\lambda_D^{1/\beta_D} = \lambda_B \cdot \Gamma\left(1 + \frac{1}{\beta_D}\right). \quad (17)$$

These relationships are used in providing additional information on historical data and experiences and in the Extended Planning Model example.

2.6. Applications of Historical Data for Planning

The planning model given in the original Mil Hdbk 189, Ref 4 (see also Ref. 12) is the Crow (AMSAA) /Duane Postulate Planning Model with several key input parameters. Following Crow, see Ref. 7 and Ref. 12, these input parameters include (1) the average MTBF $M_{Average}$ over the initial test phase (2) the management strategy MS (3) the growth rate α (4) the total test time T. With these inputs the output is the final MTBF M_F at time T and the corresponding planned growth curve. Another model used for planning is the PM2 Model, Ref. 12. As noted in Ref. 12 the input parameters for the PM2 model include (1) The total test time T (2) the requirement MTBF M_R (3) the management strategy MS (4) the average FEF d, and (5) the initial MTBF or the GPDM. The PM2 model has a discovery function of the form

$$h_{PM2}(t) = \frac{\lambda_B}{(1 + \beta_{PM2} \cdot t)} \quad (18)$$

with parameter β_{PM2}. If the requirement (or goal) MTBF is given, then the PM2 model solves for this parameter such that the required MTBF M_F is met at time T, that is, $M_F = M_R$. In this case the parameter β_{PM2} is solved, (Ref. 12 equation 5.5-35) and would not be a user input. The output is a planned growth curve that meets the requirement MTBF at time T.

The Extended Planning Model, discussed below, has input parameters which include (1) the total test time T (2) the requirement MTBF M_R (3) the management strategy MS (4) the GPDM (5) the average FEF d, and (6) the discovery β_D parameter in the h(t) function $h_{EM}(t) = \lambda_D \beta_D (t)^{\beta_D - 1}$, equation (9). With these inputs the output is the final MTBF M_F at time T with the corresponding planned growth curve. This is the MTBF that can be attained at time T, or T can be adjusted as the test time required to attain the required MTBF M_R. In additional, the β_D that is necessary to meet the requirement over a test period T can be evaluated to asses the risk associated with the plan, based on historical experiences and data. The parameter

$$\alpha_{EPM} = 1 - \beta_D \quad (19)$$

can be viewed as the growth rate for the Extended Planning model.

3 HISTORICAL RELIABILITY GROWTH DATA AND EXPERIENCES

In 1990 P. Ellner and B. Trapnell, Ref. 9, published average growth rates and fix effectiveness factors for a number of Army systems that had been subjected to reliability growth testing. One of these systems was a helicopter. In addition to this report other information is available on the helicopter which allowed the calculation of all of the parameters discussed above. For the helicopter we have the actual historical data given in Table 1.

CA β	GR α	MS	FEF	GPDM	β_D	λ_D
0.60	0.40	0.952	0.75	1.33	0.73	1.12

Table 1. Actual Reliability Growth Parameters for Helicopter

Based on data for other complex military and commercial systems the actual discovery rates, as calculated by the Crow (AMSAA) model, are given in Table 2.

System Type	B_D
Military Complex Mechanical/Electronic Heavy	0.75
Military Complex Discrete (One Shot) System	0.61
Commercial Complex Mechanical/Electronic	0.66
Commercial Complex Mechanical/Electronic	0.77
Average	0.70

Table 2. Actual Discovery Rates for Complex Systems

For the systems discussed in P. Ellner and B. Trapnell, Ref. 9, the β_D 's are not given. However, sufficient data and information are provided to calculate an upper bound on the discovery parameter β_D under certain reasonable assumptions. In the helicopter example the MTBF was matured to 3/4 of the GP MTBF (GPDM = 1.33). For the systems in the report if we assume that the MTBF is matured to only 2/3 of the GP (GPDM = 1.5), and a minimum MS of 0.95, we can calculate the corresponding system β_D which may be used as a conservative discovery rate for planning purposes. For these calculations we use an assumed GPDM of 1.5, MS = 0.95, use the Extended Projection Planning model, discussed below, with discovery function h(t) given by (9), use the relationships given by equation (16) and with the actual data in Ellner and Trapnell solve for the corresponding β_D for each system. These results are given in Table 3.

System Type	Discovery Rate β_D
Navigation System	0.73
Ground Radio	0.70
Airborne Radio	0.69
Missile Electronic Sys	0.68
Missile 1	0.60
Missile 2	0.79
Missile 3	0.76
Missile 4	0.83
Missile 5	0.70
Average	0.72

Table 3. Derived Discovery Rates for Military Systems

The actual historical data discussed in Tables 1 and 2 have an overall average β_D of approximately 0.70, and the derived β_D in Table 3 have an average β_D of 0.72. For general planning purposes an average β_D of 0.70 or greater is suggested, based on this data. An average for complex, heavy mechanical/electronic systems should perhaps be 0.73 or greater, based on the data.

System Type	Growth Rate alpha
Helicopter	0.40
Navigation System	0.26
Navigation System	0.53
Navigation System	0.24
Ground Radio	0.40
Airborne Radio	0.32
Missile Electronic Sys	0.32
Missile 1	0.46
Missile 2	0.49
Missile 3	0.27
Missile 4	0.64
Missile 5	0.32
Missile 6	0.60
Average	0.40

Table 4: Actual Growth Rates for Military Systems

The historic growth rates in Table 4 were published in the 1990 Army study where the growth rates were calculated using the Crow (AMSAA) model applied to the data.

In Crow, Ref. 7, actual fix effectiveness factors for a complex commercial electronic system being developed at Bell Laboratories were given. For the Bell Laboratories system the average FEF was 0.80. Also, for a very complex large medical device the average FEF was .70. In 1990 P. Ellner and B. Trapnell published average fix effectiveness factors for a number of Army systems that had been subjected to reliability growth testing. These are given in Table 5 with an overall average of 0.69.

Heavy Ground Vehicles	FEF		Light Ground Vehicles	FEF
System 1	0.79		System 4	0.71
System 2	0.71		System 5	0.65
System 3	0.75		System 6	0.85
Avg. HGE	0.75		Avg. LGE	0.74
Missiles	FEF		Missiles	FEF
System 7	0.81		System 10	0.55
System 8	0.56		System 11	0.78
System 9	0.55			
			Avg. Missiles	0.65
Launchers	FEF		Misc.	FEF
System 12	0.60		System 14	0.75
System 13	0.66		System 15	0.61
			System 16	0.78
Avg. Launchers			Avg. Misc.	0.71

Table 5. Actual FEF for Military systems

Regardless of the planning model an equivalent average β_D can be considered. Also, to address the concerns of the Defense Science Board Task Force a planning GPDM of at least 1.5 times the requirement and an MS of at least 0.95 are reasonable reliability growth planning objectives for these parameters. Based on historical experiences a FEF of 0.70 is typical for reliability growth planning.

These historical data and guidelines are presented for general reference and information and more specific historical data regarding particular system applications would always be desirable and should be considered if appropriate.

4. EXTENDED RELIABILITY GROWTH PLANNING MODEL

An Idealized Reliability Growth Planning Curve is the reliability at time t if all Type B modes that have been seen at time t are fixed. This is what the 1982, Ref. (5), projection Model estimates. The application of the 1982 Projection model as an Idealized Growth Curve concept was first proposed by Crow in 1984, Ref. 6. Also, in 1989 Gibson and Crow, Ref. 8, showed that under reasonable conditions we can use an average Fix Effectiveness Factor d and write the 1982 projection model as

$$\lambda_{\text{Projection}} = \lambda_A + (1-d)\lambda_B + d \cdot \lambda_D \beta_D t^{\beta_D - 1}. \quad (20)$$

The 1982 Projection model is a special case of the Extended Projection Model, Ref. 11.

For projections the parameters in the projection model are estimated and the effectiveness factor is an input based on historical experiences. For planning all of the parameters are inputs. This is the Extended Reliability Growth Planning Model as defined in terms of failure intensity as

$$\lambda(t)_{\text{Extended-Planning}} = \lambda_A + (1-d)\lambda_B + d \cdot \lambda_D \beta_D t^{\beta_D - 1} \quad (21)$$

and in terms of MTBF as

$$M(t)_{\text{Extended-Planning}} = \left[\lambda_A + (1-d)\lambda_B + d \cdot \lambda_D \beta_D t^{\beta_D - 1}\right]^{-1}. \quad (22)$$

Now note the relationship of the terms in the Extended Planning model as given by equations (16) and (17).

The Extended Reliability Growth Planning Model has the Learning Curve Property, equation (4), so that $\alpha_D = 1 - \beta_D$ may be viewed as the growth rate for the idealized planning curve. Equation (22) gives the Idealized Reliability Growth Planning Curve. The Idealized Curve is the attained MTBF if all of the Type B failure modes discovered by time t are fixed by time t. This is the starting point for planning. The actual growth curve modifies the Idealized Curve to account for delays or lag in the time a problem is first seen to the time it is actually fixed or corrected.

5 NUMERICAL EXAMPLES

In this section we illustrate the use of several of the parameters using the Extended Reliability Growth Planning Model. This model utilizes most of the key input parameters.

Example 1.

To illustrated the application of several of the parameters discussed in the paper for growth planning, suppose we have an MTBF requirement of 100 hrs. for a mechanical/electronic system that will be undergoing a reliability growth test. What is the minimum Initial MTBF at the start of the growth test, and how many test hours should we plan for in the growth test? Suppose we plan to manage the design and corrective actions such that GPDM is 1.5, and the MS = 0.95. Also, suppose we assume an FEF, based on the data in this paper, of d = 0.70 and suppose we also would like to have user input regarding the discovery function h(t).

In this example, we input $\beta_D = 0.70$. With these inputs all of the terms in the Extended Planning Model, equation (22), can be individually determined. Solving, the Initial MTBF is $MTBF_I = (\lambda_A + \lambda_B)^{-1} = 50.25$. Using an initial MTBF of 50.25, d = 0.70, and $\beta_D = 0.70$ we see that the Extended Planning Model Idealized Growth Curve attains the requirement of 100 hours at T = 2767 hours. This is called the Nominal Idealized Growth Curve. For the Actual Idealized Planned Growth we need to account for any delay or lag in incorporating corrective actions. Suppose, on average, 500 hours of test time elapses before a corrective action is implemented for a problem, after it is first seen or discovered. Then, instead of T = 2767 hours we will need to have the actual test time T = 3267 hours of testing in order to attain a 100 hr MTBF during the reliability growth test. This Actual Idealized Planned Growth, with lag = 500 hrs, is illustrated in Figure 2.

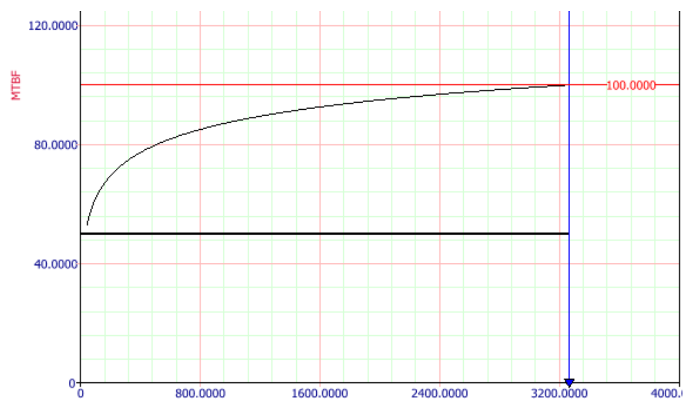

Figure 2: Extended Reliability Growth Model Planned Curve

Example 2.

Suppose a reliability growth plan has been developed for a program based on the following assumptions and conditions. The total test time is T = 5000 hrs. The requirement MTBF is $M_F = 1200$ hrs., the design margin is GPDM =1.4, the average FEF = 0.8, and the management strategy is MS = 0.95. Suppose we want to evaluate this plan in terms of risk. The GPDM is less than 1.5 which may indicate that the reliability growth test program will be costly if the requirement is met. In addition, the average FEF of 0.8 may indicate an assumed FEF that is too high, based on an historical data average closer to 0.7. The discovery rate β_D is a key indictor of the risk associated with a reliability growth plan. Applying the Extended Planning Model to the data in the example gives the equivalent β_D that is necessary to attain the requirement of 1200 in 5000 hrs of testing. This equivalent discovery beta is

$\beta_D = 0.3554$. See Figure 3. This value of β_D is outside (extremely low) the range of the historical data given in this paper, and experiences, in general. Therefore, there is strong evidence that this program may not attain its requirement of 1200 hrs. in the allocated test time of T = 5000 hrs., and that the input parameters and assumptions are not realistic. This may be viewed as a high risk reliability growth plan.

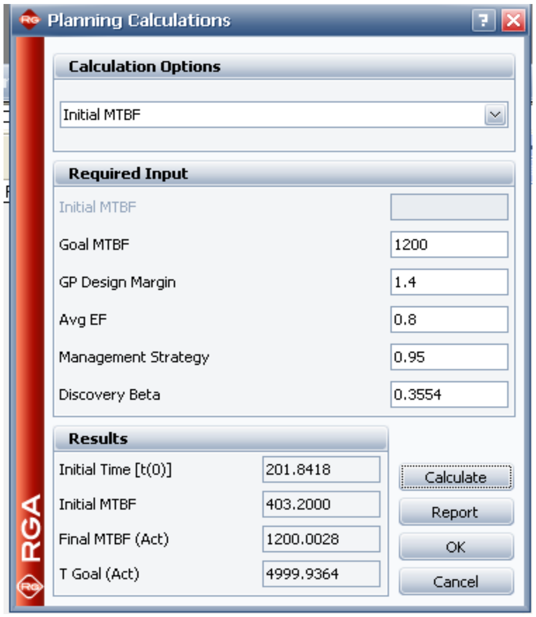

Figure 3: Extended Reliability Growth Model Parameters

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BIOGRAPHY

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