# STAGE-GATING ACCELERATED RELIABILITY GROWTH IN AN INDUSTRIAL ENVIRONMENT

*Dana Crowe and Alec Feinberg*

**ABSTRACT**

In this paper, an Accelerated Reliability Growth (ARG) Stage-Gate (SG) process is described that is used for product development of assemblies, hybrids, and discrete components. Traditionally, reliability growth science is applied at the assembly level. This is because of the greater risk in the development of complex products compared to the component level. However, the approach here applies accelerated reliability growth Test-Analyze-And-Fix (TAAF) strategies to all platforms types whether they be assemblies or simple components. What makes this possible is integrating the concepts of ARG methods with a SG approach. Using a SG approach, product reliability growth occurs as it passes through each developmental SG, similar to a test phase in traditional TAAF reliability growth. Thus, each developmental SG becomes the test phase, and reliability growth occurs as the product matures and passes through each gate. This concept is illustrated using a SG accelerated growth curve. Here five basic SGs are presented for ARG program planning of smooth fast reliability transitions to achieve and assure reliability across each platforms.

**INTRODUCTION**

Through the years, the IES has provided a platform for authors to present numerous accelerated testing methods. Papers have been presented on accelerated testing, Highly Accelerated Life Testing (HALT), Step-Stress, Highly Accelerated Stress Screening (HASS), Environmental Stress Screening (ESS), failure-free accelerated testing, reliability growth, accelerated reliability growth, and so forth. Some examples of these are listed in References 1-13 and definitions of these tests are provided in Tables 1 and 2. These practices are all important as each has been used today in both commercial and industrial applications for ensuring product reliability. The methods have not been without controversy and confusion.

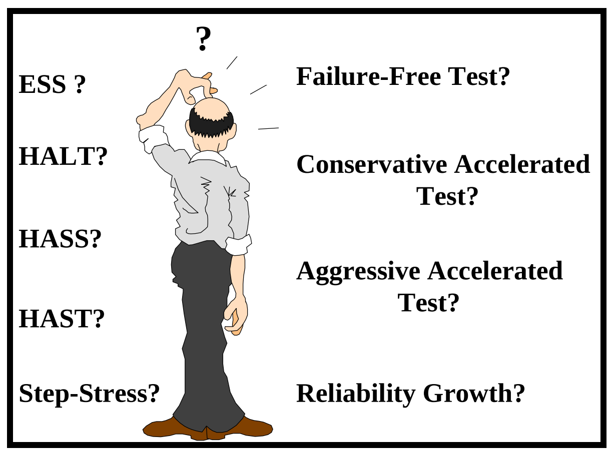


**Figure 1** What is the best accelerated testing program?

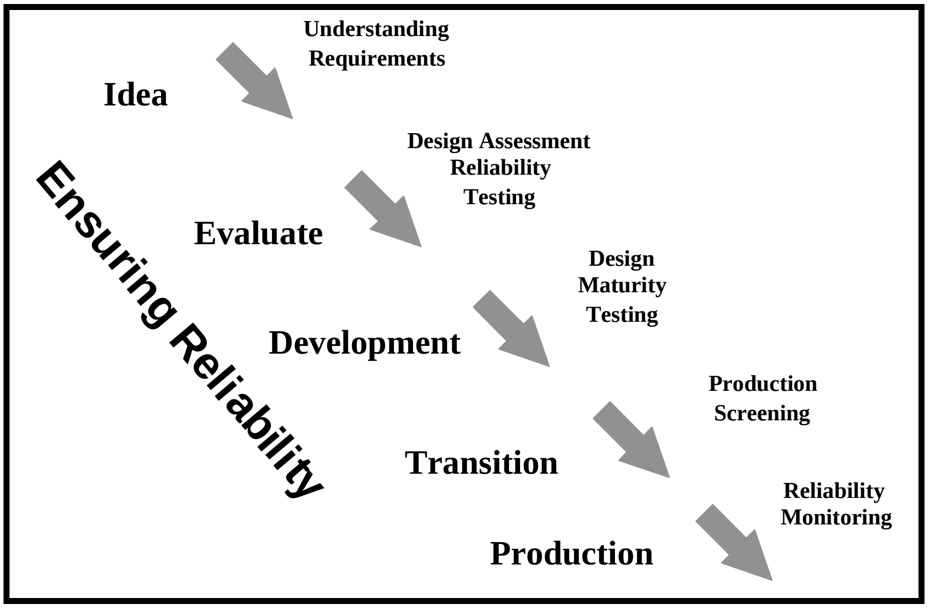


**Figure 2** Reliability Stage-Gate approach

The conservative approach has tended towards moderate accelerated testing while unconsevative methods utilize highly accelerated test techniques. Confusion exists on when a particular test method should be used and the reliability growth that can be achieved with any one method. In this paper an approach to integrating and implementing these test techniques throughout the product development cycle is presented. This is referred to as an Accelerated Reliability Growth (ARG) Stage-Gate (SG) plan or process. This process for product development of assemblies, hybrids, and discrete components is in use in industry.

## THE ACCELERATED RELIABILITY GROWTH STAGE-GATE APPROACH

The term "Stage-Gate" is not uncommon for usage with product development in industry. The term simply implies that for a product to pass into its next development stage, it should successfully pass through a test gate. A traditional Stage-Gate includes gates for the idea, evaluate, develop, transition and production phases. An illustration of this type of Stage-Gate is shown in Figure 2 with the traditional phases shown under each arrow (representing the gate).

**Table 1** Stage-Gate Accelerated Reliability Growth Phases

| PHASE | STAGE-GATE | TASK | DESCRIPTION |
|---|---|---|---|
| 1 | Idea | Understanding Customer Requirements | Concurrent engineering, FMEA, competitive benchmarking, and reliability modeling |
| 2 | Evaluate | Design Assessment Reliability Testing | Used for risk mitigation. Concentrate on finding and fixing failure modes as fast as possible. Perform highly accelerated reliability growth risk studies, method such as HALT with TAAF, process reliability risk studies, step-stress, etc. |
| 3 | Develop | Design Maturity Testing | Demonstrate that a design is reliability and has good quality. Perform statistically significant accelerated test, usually failure-free tests. |
| 4 | Transition | Screening | Ensure early production units are robust. Check for infant mortality problems. |
| 5 | Production | Monitoring | Ensure continual product reliability and quality. |

**Table 2** Common definitions and uses of a number of accelerated tests

| ACCELERATED TEST/METHOD | STAGE GATE | DEFINITIONS AND USES |
|---|---|---|
| Accelerated Reliability Growth | 1-5 | As defined in Reference 15 is the positive improvement in a reliability parameter over a period of time due to changes in product design or the manufacturing process. A reliability growth program is commonly established to help systematically plan for reliability achievement over a programs duration so that resources and reliability risks can be managed. In this paper, the manner in which it is applied is through a stage-gate program combined with accelerated test methods. |
| (UCR) Understanding Customer Requirements | 1 | UCR is a common sense topic that is often overlooked. It can be a simple exercise or include a full approach. In a full approach tools such as FMEA, competitive benchmarking, and reliability predictive modeling are used to assure the smartest approach in product maturation program. |
| HALT (Highly Accelerated Life Test) | 2 | A type of step-stress test that often combines two stress such as temperature and vibration. This highly accelerated stress test is used for finding failure modes as fast as possible and assessing product risks. Frequently it exceeds the equipment specified limits. |
| Step-Stress Test | 2 | Exposing small samples of product to a series of successively higher "steps" of a stress like temperature, with a measurement of failures after each step. This test is used to find failures in a short period of time and performing risk studies. |
| HAST (Highly-Accelerated Temperature and Humidity Stress Test) | 3 | This test is performed in a sealed chamber such as an autoclave enabling higher than atmospheric pressures to occur. This allows a humid environment with temperatures above 100$^o$C. As a results, shorter test times can be achieved. For example a 1000 hour 85$^o$C/85%RH test can be replaced by a 80 hour 130$^o$C/85%RH HAST test at 33.5 psi . |
| Failure-Free Test | 3 | Also termed zero failure testing. This is a statistically significant reliability test that demonstrates that if a product passes a test with no observed failures, it will meet a particular reliability objective at a certain level of confidence. For example, the reliability objective may be 1000 FITs (1 million hour MTTF) at the 90% confidence level. |
| HASS (Highly Accelerated Stress Screen) | 4,5 | This is a screen test or tests used in production to weed out infant mortality failures. This is an aggressive screen since it implements stresses that are higher than common ESS screens. When aggressive levels are used, the screening should be established in HALT testing. |
| ESS (Environmental Stress Screening) | 4,5 | This is an environmental screening test or tests used in production to weed out latent and infant mortality failures. |

In terms of ensuring reliability, terms above the arrows describe the Stage-Gage reliability design appropriate for the gate. Table 1 provides a description of these terms with common test definitions in Table 2. The SGs are described in more detail below.

This Stage-Gate method is then an accelerating product reliability growth plan that is practical for industry applications. The associated accelerated reliability growth curve for this plan is shown in Figure 3. In this view, the reliability growth curve is directly linked to Stage-Gate levels (or phases). Mathematically linking maturation levels to a reliability growth curve in this way has previously been described (Ref. 11). An example is given in the Appendix. Figure 3 illustrates how product reliability growth is viewed and planned for over the Stage-Gate phases or levels. As the figure shows, it is necessary for reliability to engage early in the design cycle with an early understanding of customer requirements, especially to ensure the successful reliable designs required in today's technically demanding marketplace. To determine the type of reliability effort associated with product development, the risk for each project is accessed. If the product is new technology and revolutionary in nature, an extensive Stage-Gate effort is performed. Since technology risk is linked to financial risk, this is also factored into the assessment.

**THREE ACTIVITIES SUPPORTING STAGE-GATE**

Reliability today is an expected part of doing business. As markets have changed and developed, it has become necessary for manufacturers to find ways to meet the ever-growing demands of customers. Through the process of self-assessment and gap analysis, companies have recognized a need for a fundamental shift in the way it does business. To meet today's challenges and supports all business units, three major reliability assurance activities shown in Figure 4 were identified and required to support this Stage-Gate process.

In the first activity, ***Design for Reliability (DfR),*** concurrent engineering starts the design process. The goal is to design products that are reliable. Thus, DfR may be defined as a reliability process that is used to effect the design for a positive improvement in reliability. The second building block, ***Reliability demonstration,*** a product's reliability is assessed.

Reliability demonstration takes place in two main elements: Process Reliability and Design Maturity Testing. Process reliability focuses on development of a fundamental understanding of a platform's inherent reliability design while in design maturity testing a product's failure rate objective is demonstrated over its life hazard conditions. The third activity, ***Reliability Analysis,*** obtains physics-of-failure knowledge about the product's design and its testing capabilities. Each activity and how it is viewed to support the Stage-Gate process is described below.

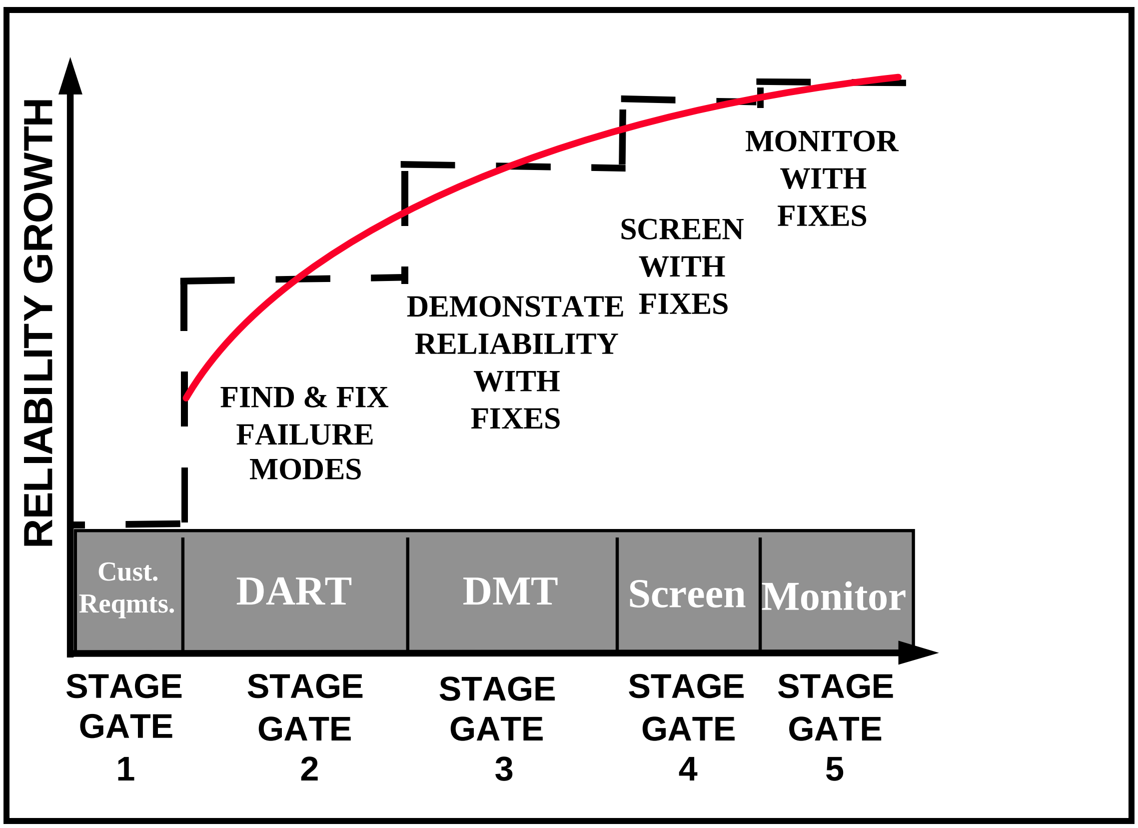


**Figure 3** Stage-Gate Accelerated Reliability Growth Model

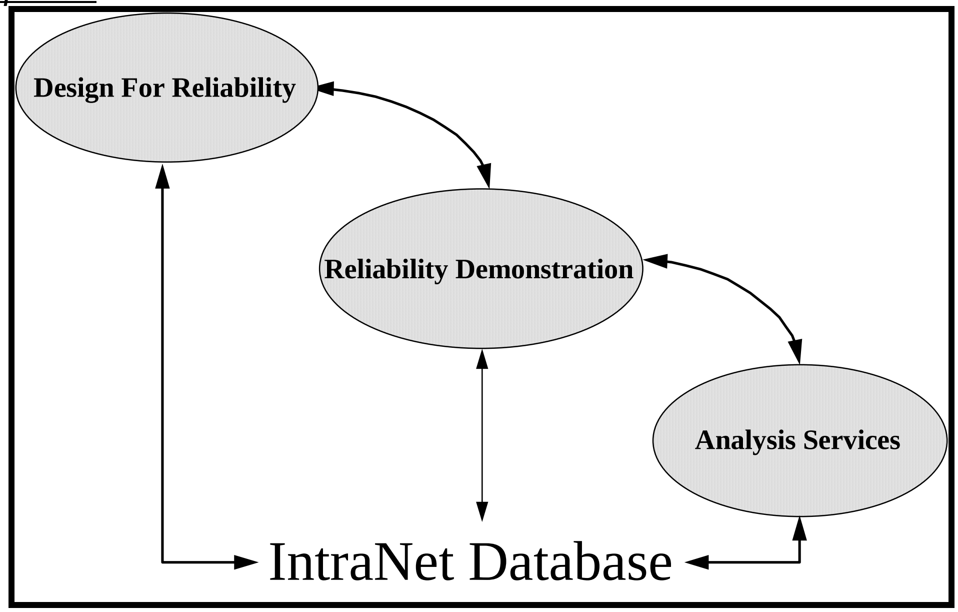


**Figure 4** Modern Approach to Reliability

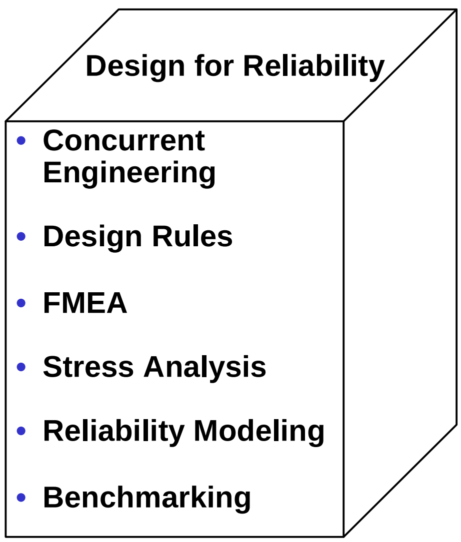


**Figure 5** Design for Reliability (DfR) Activities

**DESIGN FOR RELIABILITY ACTIVITIES SUPPORTING STAGE-GATE**

In ***Stage-Gate 1, Design for Reliability (DfR)*** activities related to understanding customer requirements occur (see Fig. 5). These activities include the key DfR tools: concurrent engineering, Failure Modes and Effects Analysis (FMEA), competitive benchmarking, and reliability predictive modeling. This process actually starts in this stage and can continues through the full product development cycle.

These tools are deployed to reduce the risks that could affect first pass success of the project's deployment.

Concurrent engineering means being active in the product design phase. One of the most important tool to ensuring that reliability is integrated with product design is FMEA. The FMEA tool can also identify those specified or unspecified customer requirements of the design and how failure may occur, the severity of such failure, and the probability of the failure occurring. With these factors identified, the design process can be focused on the major issues of the product and its potential use environment. Concurrent engineering also ensures that proper design rules are followed such as derating designs and incorporating lessons learned in process reliability studies and failure analysis.

Competitive Benchmarking is also important in assisting the DfR process. Such benchmarking in the design process ensures that all important design aspects have been incorporated. Assessment of competition is important as they may similarly be assessing you. Leveraging all possible inputs available in today's challenging marketplace is part of best commercial practices to ensure state-of-the-art product performance, materials, packaging, mechanical and electrical integrity, and to identify cost issues.

Reliability predictive modeling is used to make initial product Mean-Time-Between-Failure (MTBF) estimates. MTBF estimates are important in assessing feasibility of reliability goals. Predictive modeling activities can continue through all Stage-Gates to refine MTBF estimates and ensure the product's reliability will meets its target.

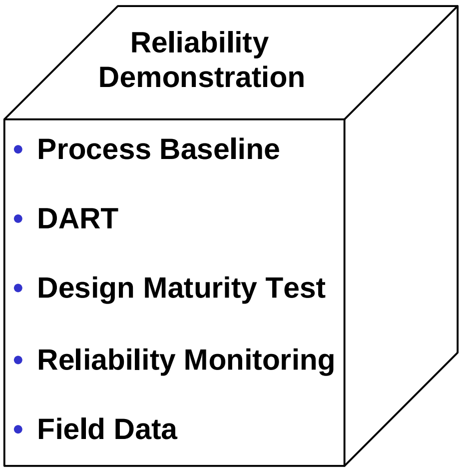


**Figure 6** Reliability Demonstration Building Block

**RELIABILITY DEMONSTRATION ACTIVITIES SUPPORTING STAGE-GATE**

***Reliability demonstration*** activities are on-going in ***Stage-Gates 2 through 5 (see Fig. 6).*** Once the design has finished the idea phase, it is ready for demonstration.

Process reliability effort is considered a strong part of the demonstration activity by helping to identify design capabilities and product requirements. It identifies failure mechanisms and their activation energy which also is used in DMT planning. This provides a baseline for the process. It also provides assessment for the platform selections in order to meet the product's expected life hazard conditions and safety needs.

In the ***second Stage-Gate evaluation***, two major efforts are undertaken. The first is risk mitigation. Design Assessment Reliability Testing (DART) on the product is used to evaluate any potential problems identified by the team that could affect first-pass success.

The second activity in this stage is reliability growth. A traditional Test Analyze and Fix (TAAF) approach combined with a highly accelerated reliability growth tests such as HALT is used. This activity is capable of maturing a product's reliability growth by as much as 65% and does so in a timely manner so that a customer's schedule can be met. Most of the reliability growth occurs in this phase, as indicated in Figure 3.

When the end of this phase is reached, the product is ready for the ***Design Maturity Test, Stage-Gate 3***. In gate 3, little reliability growth takes place compared with the previous gate (see Figure 3). In this stage, demonstrating that a product's reliability objectives will be met, is the main interest. This is accomplished by performing statistically significant failure-free accelerated testing. Failure-free accelerated environmental tests usually includes vibration, temperature-humidity-bias (such as HAST or equivalent), temperature-cycle, and high temperature operating bias testing. These tests are based on reliability science, historical information, process physics-of-failure studies (such as activation energy investigations), environmental product limits, and product environmental objectives. Typically, a statistically significant test ensures that the product will meet its reliability objective at the 90% confidence level. Tests results are then presented to customers detailing each tests and its results.

In the next stage, transition ***Stage-Gate 4*** is implemented. This Stage-Gate consists of ***product screening*** and is used on products for which infant mortality may be an issue and/or to ensure that early production units are robust. The screening test plans are based on information identified in the earlier stages of the development cycle. For example, information from HALT testing may be used to set up an aggressive HASS or a moderate ESS. Screening is implemented with a TAAF program to ensure that any necessary corrective actions are implemented. Screens are removed as soon as product robustness is verified.

At this point, the product moves into ***Monitoring, Stage-Gate 5.*** This full-scale production phase ensures continual product reliability and quality. If a design fails to meet its required objective in the monitoring cycle, the necessary corrective action is taken to ensure product integrity.

**RELIABILITY ANALYSIS**

The third major reliability activity that support the Stage-Gate program is reliability analysis (see Fig. 7). This activity in integral to ensuring a successful TAAF program. As products have increased in their sophistication, it has become necessary to be able to analyze the complex microelectronics materials, process effects, and units' dynamic performance.

Reliability analysis includes product and process analysis, construction and reverse engineering, materials and physical analysis, and failure mode investigative studies, including thermal and electrostatic discharge probing. Reliability analysis allows one to build upon past experience and historical information. Having the right information at the right time enables a company to make the correct decision for a product.

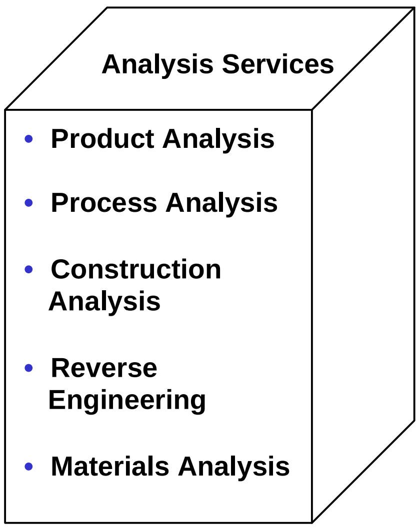


**Figure 7** Analysis services building block

This ever-growing historical analysis information database is shared with the engineering community by linking each analysis tool to one common database that is connected to the company intranet. Thus, data and reports are available anywhere within the intranet.

## SUMMARY

In this paper, an overview of how to systematically grow product reliability has been presented. An accelerated reliability growth Stage-Gate program has been devised. Companies currently use this five Stage-Gates process to ensure for a full reliability effort. The bottom-line results have been dramatically low PPM return rates, designs that are initially correct and on time, and customer satisfaction. These results are directly linked to the accelerated reliability growth Stage-Gate program.

## REFERENCES

1. G.K. Hobbs, "Highly Accelerated Life Tests - HALT," Proc. of the Institute of Environmental Sciences, 1992, pp. 377-381.
2. A.M. Hopf, "Highly Accelerated Life Test for Design and Process Improvement," Proc. of the Institute of Environmental Sciences, 1993, pp. 147-155.
3. H. McLean, "Highly Accelerated Stressing of products with Very Low Failure Rates," Proc. of the Institute of Environmental Sciences, 1992, pp. 443-450.
4. Z. Sherf, P. Hopstone, "Tailoring and Highly accelerated Life Testing, Two Contradictory or Two Complementary Testing Philosophies? ," Proc. of the Institute of Environmental Sciences, 1993, pp. 87-93.
5. G.K. Hobbs, "Highly Accelerated Stress Screen - HASS," Proc. of the Institute of Environmental Sciences, 1992, pp. 451-457.
6. E.L. Kyser, "HALT and ESS for Quick-to-Market Scenarios," Proc. of the Institute of Environmental Sciences, 1996, pp. 140-148.
7. H. Caruso, "Environmental Stress Screening of Spares and Repairs," Proc. of the Institute of Environmental Sciences, 1992, pp. 446-481.
8. J.E. Bridgers, "Combining 217 & ESS Technology," Proc. of the Institute of Environmental Sciences, 1992, pp. 22-53.
9. A.A. Feinberg and G.J. Gibson, "Accelerated Reliability Growth," Proc. of the Institute of Environmental Sciences, 1993, pp. 102-109.
10. A.A. Feinberg "Accelerated Reliability Growth Models," Journal of the Institute of Environmental Sciences, 1994, pp. 17-23.
11. A.A. Feinberg, G.J. Gibson, and R.H. Shupe, "Connecting Technology Performance Maturation Levels to Reliability Growth," Proc. of the Institute of Environmental Sciences, 1992, pp. 415-421.
12. H. Caruso, "A Check List for Developing Accelerated Reliability Tests," Proc. of the Institute of Environmental Sciences, 1996, pp. 42-49.
13. J.Jordan and M. Pecht, "How Burn-In Can Reduce Quality and Reliability," Proc. of the Institute of Environmental Sciences, 1996, pp. 16-19.
14. L.H. Crow, "Reliability Growth Projections with Applications to Integrated Testing," Proc. of the Institute of Environmental Sciences, 1995, pp. 94-103.
15. MIL-HDBK-189, Reliability growth Management (13 Febuary 1981).

**APPENDIX: ACCELERATED RELIABILITY GROWTH STAGE-GATE MODEL**

Accelerated reliability growth has been previously described in References 9 and 10. In this view, it is possible to link the reliability growth curve directly to Stage-Gate levels (or phases). Mathematically linking maturation levels to a reliability growth curve in this way has previously been described (Ref. 11). In this appendix an example of this procedure for the interested reader is provided. This exercise may appear somewhat academic, as traditional reliability growth is difficult to apply over phases with unknown acceleration factors and different tests. However, even in traditional reliability growth, it is often customary to assign growth goals to developmental stages in a program (Ref. 15). Thus, in reality a qualitative growth model can be planned and mapped in a traditional sense to development levels. One advantage of attempting to estimating growth, is in assessing a projects risk. If conservative growth estimates indicate that achieving a reliability goal would be unlikely, than a high risk can be assigned which will most likely effect the management of the project. As an example, the traditional reliability growth example cited in MIL-HDBK-189 (Ref. 15, page 46) is used. This example has also been described in the accelerated reliability growth case in Reference 10. The results are shown in Figure 8 (reproduced from Figure 2, Ref. 10 for convenience). The model for the accelerated growth curve is

$$M(t) = M_I \qquad t \le t_1$$

$$M(t,A) = \frac{M_I}{1-\alpha}\left(\frac{t}{t_1}\right)^{\alpha} A^{\alpha} \qquad t \ge t_1$$

where the parameters are defined in Ref. 10. The growth parameters for this example are $\alpha$=0.23, $M_1$=50, $t_1$=1000, with an overall acceleration factor of A=20.36. Note there are five test phases which makes it a good example for mapping to a 5 phase Stage-Gate process. Also, in the figure, the MTBF has been put in units of 1000 hours for a more typical expected commercial case. The test time phase are T2=2,500, T3=5,000, T4=7,000, and T5=10,000. These test phase are not unreasonable for a Stage **Gate process.**

For example, phase 3 is actually 2,500 hours in length (=5000-2,500 hours). This could easily be the length of a design maturity test. Here an estimate may be refined of the growth potential over a particular Stage-Gate in which growth factors can be more accurately assessed.

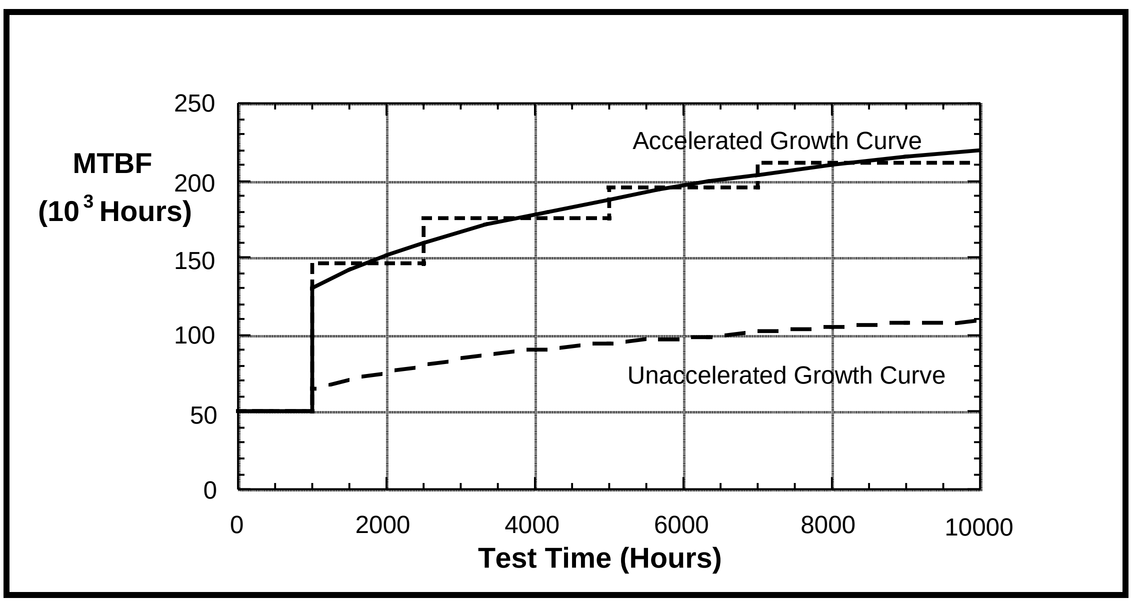


**Figure 9** Accelerated and Unaccelerated Reliability Growth Curve (Reproduced from Ref. 10).

To map this planned growth to a five stage gate process a simple mapping theory described in Reference 11 is used. In this reference, reliability growth is mapped to a program's development levels L as

$M(t) = M_I \qquad L \le L_1$

$$M(t, A) = \left(\frac{L_i}{L_1}\right)^{\gamma+1} M_1 \qquad L \ge L_1$$

To find gamma (as shown in Reference 11), one simply equates

$$\frac{M(t)}{M_1} = \left(\frac{L_i}{L_1}\right)^{\gamma+1}$$

We wish to map the growth curve in Figure 8. The curve actually starts at a value of about 130 and increase to 221 hours (See Table 1, Ref. 10). Since a 5 level Stage Gate process is used, with Level $L_1$=1 and the ith top level of 5, then

$$\frac{221}{130} = \left(\frac{5}{1}\right)^{\gamma+1}$$

Solving give $\gamma$+1=0.33. Then the curve is mapped to the 5 Stage-Gate Process as

$M(t) = 50 \qquad L_i \le 1$

$$M(t, A) = \left(\frac{L_i}{1}\right)^{0.33} 130 \qquad Li \ge 1$$

The result is shown in Figure 9. As envisioned in this model, most of the growth is expected to occur Stage-Gate 2.

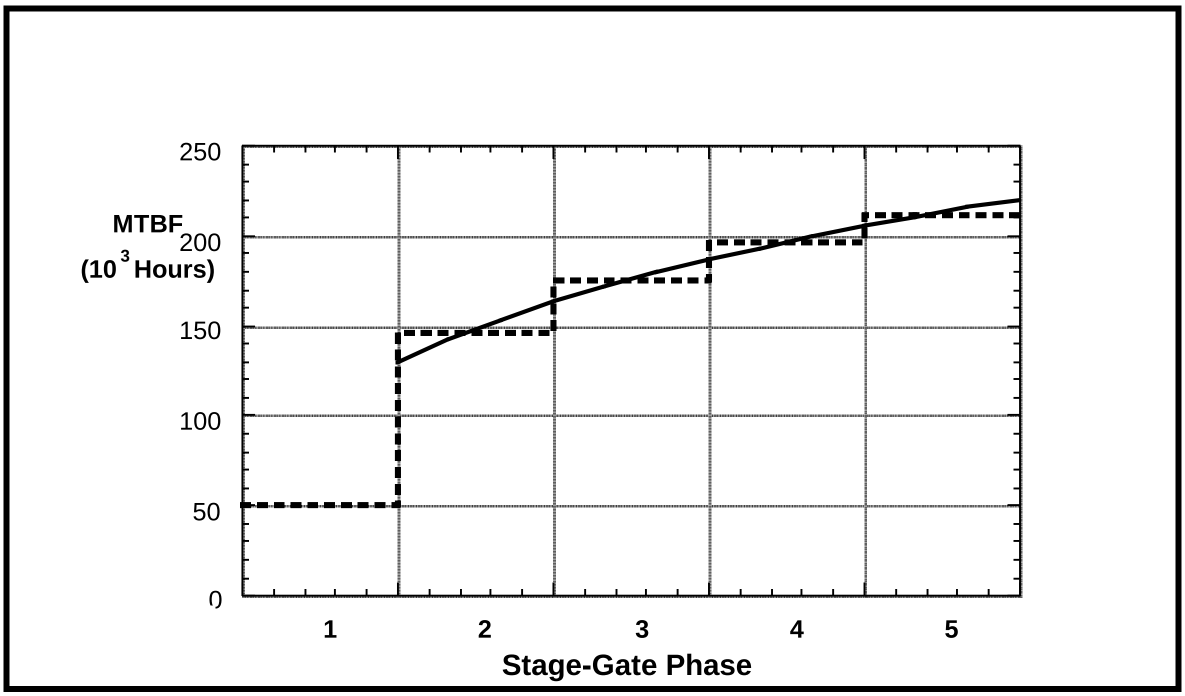


**Figure 9** Mapped Stage-Gate Accelerated Reliability Growth Curve of Figure 8