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Hi-Tech Equipment Reliability A Practical Guide for Engineers and the Engineering Manager

By Dr. Vallabh H. Dhudshia
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High-Tech Equipment Reliability Series

WWK recently received permission to reprint sections from Dr. Vallabh H. Dhudshia's book, *Hi-Tech Equipment Reliability: A Practical Guide for Engineers and the Engineering Manager*. This book, first published in 1995, is now out of print (second edition to be published later in 2007) but still provides useful guidance to the equipment engineering community as they strive to improve cost of ownership (COO).

Dr. Dhudshia has been an equipment reliability specialist with Texas Instruments and with Xerox Corporation. He served as a Texas Instruments assignee at SEMATECH for three years. Dr. Dhudshia received a Ph.D. in IE/OR from New York University. He is an ASQ fellow and a senior member of ASME. He has developed and taught courses in equipment reliability overview and design practices. He is an affiliate of WWK, specializing in reliability consulting.

In this issue of Applied Cost Modeling we are reprinting Chapter 2. We hope that you find the information in this series useful.

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Calendar of Events

July 2007

17-19 **SEMICON West (WWK booth #2716)**
Moscone Hall South
San Francisco, CA

19 **Understanding & Using Cost of Ownership**
Marriott Hotel
San Francisco, CA

September 2007

4-5 **SEAJ/SEMI Industry Strategy and Technology Forum (ISTF)**
Yokohama, Japan

October 2007

9-11 **SEMICON Europa**
Stuttgart, Germany

23-25 **International Test Conference (ITC)**
Santa Clara, CA

November 2007

4-5 **International Trade Partners Conference**
Maui, HI

December 2007

5-7 **SEMICON Japan**
Makuhari Messe, Japan

Basics of Reliability Discipline

2.1 Objectives

The objective of this chapter is to present a simple definition for reliability and for the following five basic elements of reliability discipline:

1. Reliability function
2. Failure rate function
3. Population and samples
4. Failure and its categories
5. Component and system - non-repairable and repairable

Other prime objectives of this chapter are to show relationships between reliability functions, failure rate function, and the two most popular statistical functions, cumulative density function (CDF) and probability density function (PDF).

2.2 Formal Definition of Reliability

Reliability is the probability of performing intended functions for a specified time under the stated operational conditions.

Mathematically, it is written as:

$$R(t) = Pr[\ T > t\ ] \qquad (2.1)$$

WHERE:
t = Specific time of interest
T = Random variable
R(t) = Reliability at time t
Pr[ ] = Probability of

EXAMPLE:

$$R(1000\ Hr) = Pr\ [\ T > 1000\ Hr] = 0.95$$

In this example, 95% of the equipment[2] units should survive past 1000 hours.

Three key points of the above formal definition require further explanation.

Intended Functions: All equipment has its intended functions, whether they are formally documented or not. However, a given reliability level applies to a given set of the functions that the equipment was designed to accomplish. If the equipment is used for functions other than its intended design, the same reliability level may not apply to these new functions. It is the manufacturer's responsibility to see that equipment users understand equipment's intended functions.

Specified Time: The reliability level changes as the equipment ages. It is necessary to include equipment age in establishing a reliability level. Without inclusion of such time element, any reliability level is ambiguous and can mislead a user about the specific reliability level.

Stated Operational Conditions: Factors such as operating environment, operating stress level, operating speed, operator skill level, and maintenance procedures and policies can affect the reliability of any equipment. If the value of any factor varies from assumed operational conditions, the reliability level may differ.

EXAMPLE:

The reliability of a blower in a card cage operating in its ambient environment at 60%

[2] In this book, equipment, product, and system, mean more or less the same thing. For uniformity, equipment is typically used. There may be a few places where product or systems are used to enhance readability. However, they all refer to one thing.

of its rated power will be 0.85 at 2 years after installation.

2.3 Reliability Function

Reliability function is defined as:

$$R(t) = Ns(t) / N \quad (2.2)$$

WHERE:

N = Number of identical product units put on a life test
Ns(t) = Number of units survived after time t
t = Specific time of interest

For the illustration purpose, time is used as a measure of life in this chapter. There are many other measures of life used in industry, as listed below

- Number of cycles performed
- Number of wafer processed
- Distance traveled
- Number of prints made
- Number of transactions made

The above Equation (2.2) leads to a simple methodology to develop the reliability function for any real life situation.

1. Put N identical product units on a life test under identical operating stresses and operating environments. For illustration, run a life test for 100 identical light bulbs.

2. Start the life test, and keep a record of the failure time (life length) of each unit as shown in Table 2.1.

3. Sort the failure time data collected in Step 2 from the smallest to the largest, as also shown in Table 2.1.

4. Select at least ten equal-length intervals within the range and then determine the number of units that survived time t.

5. Calculate R(t) for each selected t.

6. Prepare a table of t and R(t) similar to Table 2.2, and also draw graphs of t vs. R(t) and t vs. 1 - R(t), similar to those shown in Figure 2.1

Table 2.1 Light Bulb Life Test Data: Observed and Sorted

Observed Times to Failure, Hour									
487	256	104	757	86	637	137	54	29	30
333	86	14	542	29	140	190	48	79	65
1	553	54	2	18	84	80	79	125	301
433	39	113	426	166	78	512	591	117	497
58	255	23	179	359	146	499	153	695	100
125	45	460	33	454	33	13	137	261	374
297	357	5	316	222	551	174	3	139	33
20	60	62	244	95	359	267	748	222	162
22	69	108	90	199	12	79	208	21	72
32	29	287	13	661	198	94	128	14	241

Sorted Time to Failure, Hour									
1	20	33	65	86	125	174	255	359	512
2	21	33	69	90	128	179	256	359	542
3	22	39	72	94	137	190	261	374	551
5	23	45	78	95	137	198	267	426	553
12	29	48	79	100	139	199	287	433	591
13	29	54	79	104	140	208	297	454	637
13	29	54	79	108	146	222	301	460	661
14	30	58	80	113	153	222	316	487	695
14	32	60	84	117	162	241	333	497	748
18	33	62	86	125	166	244	357	499	757

For all practical purposes, the t vs. R(t) graph is a powerful tool for non-reliability

Table 2.2 Reliability Function For Light Bulbs

Light Bulb Age t, Hour	Reliability Function R(t) at Age t
0	1.00
20	0.89
40	0.77
60	0.71
80	0.62
100	0.55
120	0.51
140	0.44
160	0.42
180	0.38
200	0.35
220	0.34
240	0.32
260	0.28
280	0.26
300	0.24
320	0.22
340	0.21
360	0.18
380	0.17
400	0.17

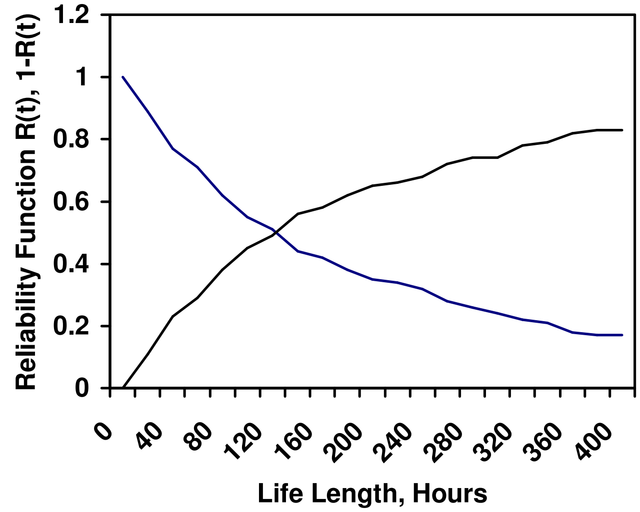
engineering personnel. This graph can be used to interpolate reliability at any time of interest without going into reliability mathematics. For example, the reliability of the light bulb is 0.35 at 200 hours.

2.4 Failure Rate Function

The second most important function in reliability is the failure rate function, $\lambda(t)$, which relates the age t of a product unit and the number of failures per unit time at that age. Mathematically, it is given as:

$\lambda(t)$ = (Number of units failed between $t - \Delta t/2$ and $t + \Delta t/2$)/(Number of units at the beginning of the age interval x Δt) (2.3)

Figure 2.1 Graph of Reliability Function R(t) and 1-R(t)



WHERE:

$\lambda(t)$ = Value of the failure rate function at time t
Δt = Age interval increment

Figure 2.2 shows the $\lambda(t)$ vs. t graphs for the light bulbs life test data, which appears to be a straight line.

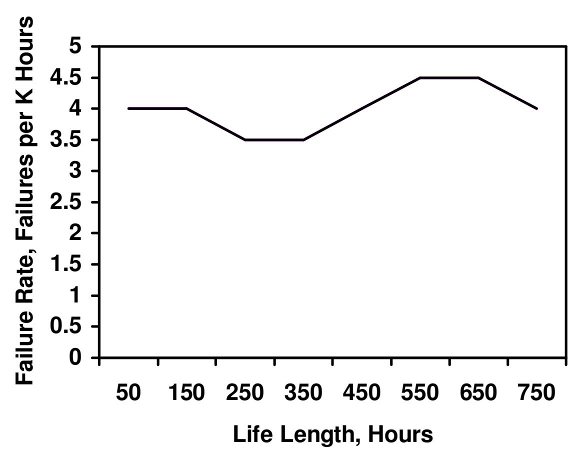


Figure 2.2 Failure Rate Graph

2.5 Relationship Between Reliability Function and Other Probability Functions

Two widely used probability functions are cumulative density function (CDF) and probability density function (PDF). See Reference 1 for a detail statistical definition.

CDF is usually noted as F(t) and it refers to cumulative failure percentage at time t. Reliability Function refers to surviving percentage at time t. Therefore, both functions are related with the following relationship:

$$1 - R(t) = F(t) \qquad (2.4)$$

As mentioned earlier, Figure 2.1 contains a graph of F(t) for our bulbs.

PDF is usually noted as f(t) and it refers to failure probability density at time t. In layman's language, it shows percentage failed in a unit of time at time t. Both CDF and PDF are very closely related, as follows:

$$f(t) = d[F(t)] / dt \text{ or } F[t] = \int_0^t f(t)\, dt \qquad (2.5)$$

WHERE:

F(t) = CDF at time t
f(t) = PDF at time t

From relationships of Equations (2.4) and (2.5), it is obvious that all three functions (reliability function, CDF, and PDF) are mathematically related. We need to know only one of them to calculate the other two.

For example, the most popular, simple, and widely used PDF in reliability discipline has exponential relationship between f(t) and t. It is known as Exponential PDF and is given as follows:

$$f(t) = (1/\theta)\, e^{-(t/\theta)} = \lambda\ e^{-\lambda t} \qquad (2.6)$$

WHERE:

θ = Mean life
λ = Failure rate = 1/(mean life)

Note that the failure rate is constant for exponential PDF. Also, we need to know only mean life to characterize the entire distribution.

Using Equation (2.5)

$$F(t) = 1 - e^{-(t/\theta)} = 1 - e^{-\lambda t} \qquad (2.7)$$

And using Equation (2.4)

$$R(t) = e^{-(t/\theta)} = e^{-\lambda t} \qquad (2.8)$$

Figure 2.3 shows a graph of the PDF and Figure 2.4 shows graphs of CDF and Reliability Function for an exponential distribution for MTBF=100 hours. Similar graphs are available for other PDFs in any statistical textbook. Figure 2.5 shows such graphs for some of the popular PDFs.

Figure 2.3 Exponential PDF for MTBF = 100 Hours

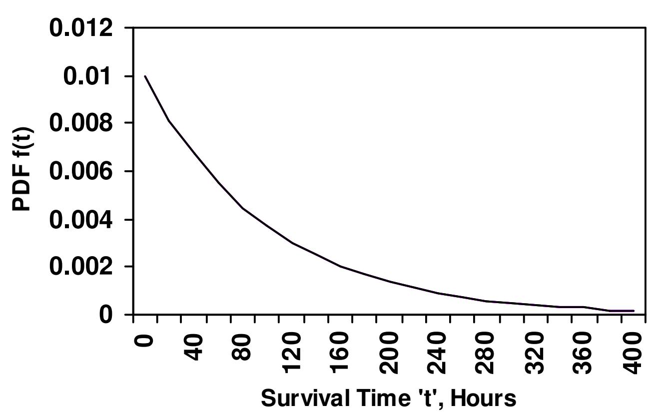
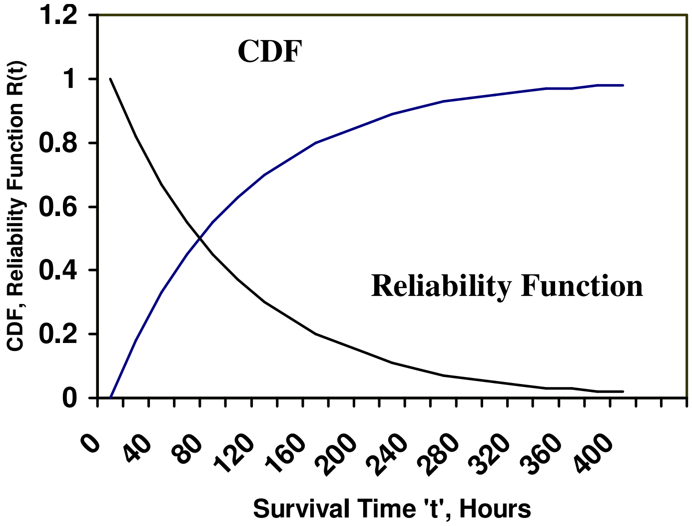


Figure 2.4 Exponential CDF and Reliability Function for MTBF = 100



2.6 Population and Samples

It is important that we understand the difference between a population and a sample and the statistical relationship between them. A population represents all the similar units performing the similar functions. For example, all the units belonging to an entire equipment line represent an equipment population. Generally, the population is large and it is impractical to measure the value of a population metric of interest. Therefore, we randomly select a limited number of units from the population, called samples, to measure value of interest. Since the samples are limited in number, the measurements are practical. The sample metric values are estimates of the respective population metric. In statistical terminology, the values of the population metrics are inferred from the value of the corresponding sample metrics. Statistical techniques (see Reference 2) are used to determine confidence in the inferences. The larger the sample size, the more confidence we have in the estimates for the respective population metric. Figure 2.6 depicts relationship between population and sample.

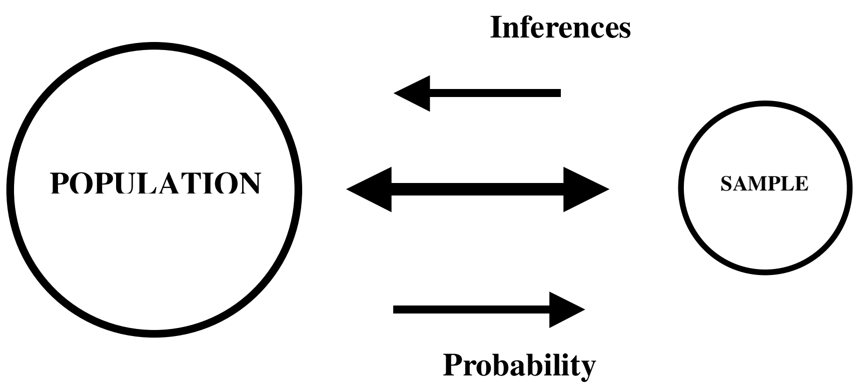


Figure 2.6 Population and Sample Relationship

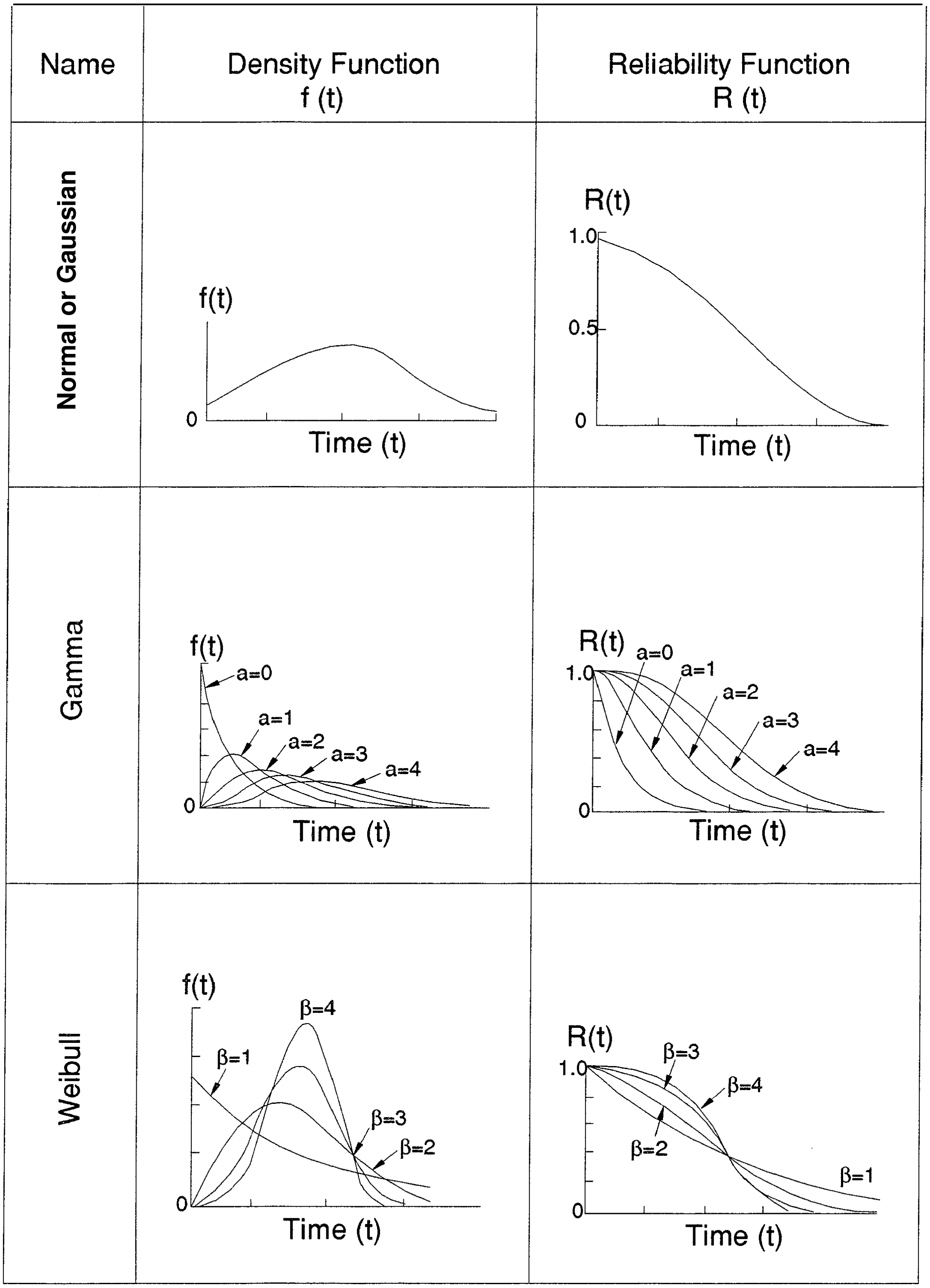


Figure 2.5 Well Known PDF's and Their Reliability Functions

2.7 Definition and Categories of Failures

Two main elements of the reliability discipline are failure and time (or other measures of life) to failure. Failure is defined as an event or state in which any equipment or part of the equipment does not or would not perform as intended. Some subjectivity may be required in the phrase "does not perform as intended" if the intended functions are not defined thoroughly.

Any part failure, software or process recipe problem, facility or utility supply malfunction, or human error could cause an equipment failure.

Failures can be categorized many different ways. Five of the most widely used failure categorizations are:

2.7.1 Catastrophic, Degradation, and Intermittent Failures

Catastrophic failures are sudden, unexpected, and nonreversible (e.g., broken part, short circuit, open resister, etc.)

Degradation failures occur when the output degrades slowly below the expected level and it is not reversible (e.g., bearing wear out, corrosion of surface, fatigue, etc.)

Intermittent failures are those events in which the equipment performance keeps flip-flopping below and within the expected level at unknown times and for unknown reasons (e.g., intermittent circuit board failures).

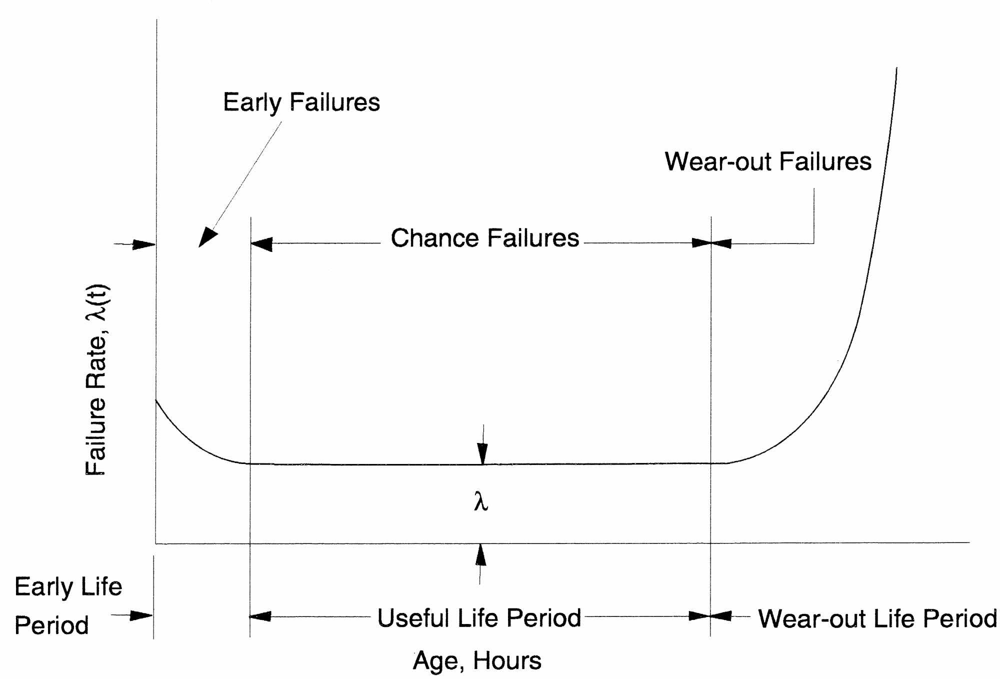
2.7.2 Early, Chance, and Wear-out Failures

Figure 2.7 shows a graph of t vs. failure rate λ (t) for typical equipment. Since this graph looks like a cross section of a bathtub, it is known as bathtub curve in the reliability field.

The failures that occur during the early life period when the failure rate is decreasing are called early failures. These failures are caused by poor manufacturing practices, poor quality control, insufficient burning-in or screening of parts, and improper debugging after the final assembly.

Chance failures occur during the period when the failure rate is constant (middle of the graph in Figure 2.7). These failures are caused by design errors, misapplication of parts, unexplainable causes, and improper operations.

Figure 2.7 Early, Chance, and Wear-out Failures



Wear-out failures occur during the period when the failure rate is increasing (see Figure 2.7) after staying constant at a lower level. These failures are caused by aging of parts, fatigue, creep, and corrosion, or other deterioration caused by age.

2.7.3 Critical and Non-Critical Failures

Critical failures stop the equipment from performing the intended functions while non-critical failures do not affect the equipment performance. For example a label falling off is a non-critical failure. However, if a safety label falls off and the regulations require the label be affixed properly at the proper location to operate the equipment, then it is a critical failure.

2.7.4 Independent and Dependent Failures

If something fails without the influence of other failures in the equipment or outside factors, then it is an independent failure. If something fails because of another failure, it is considered a dependent failure. For example, a card cage exhaust blower failure (an independent failure) increases temperature in the card cage, which causes a circuit board failure. In this situation, the circuit board failure is a dependent failure. Sometimes, dependent failures are discounted in reliability calculations.

2.7.5 Relevant and Nonrelevant Failures

Relevant failures are caused by failure(s) of components, modules, software, and process while performing their intended functions. Nonrelevant failures are caused by other factors that are not part of the equipment performing the intended functions. For example, power failure, facility problems, or an out-of-spec consumable can stop intended functions of the equipment. These failures are nonrelevant failures for the equipment operation. Nonrelevant failures are discounted in reliability calculations.

2.8 Component and System

It is also important that we understand the difference between a component and system.

A component is a basic part of a system that may be an individual piece or a complete assembly of individual components. It is not subjected to disassembly and, hence, it is discarded the first time it fails. For example, a heat lamp in a heater assembly is considered a component.

A system is a combination of components, parts, assemblies, modules, accessories, and software connected to perform the intended functions. At least one component in the system must fail to cause the system to fail. For example, a power supply failure in a tungsten deposition system may stop it from performing its intended function.

The systems belong to either one of two main categories - non-repairable systems and repairable systems. A non-repairable system is discarded the first time it ceases to perform its intended function(s), i.e. when it fails. A system that, after failing to perform at least one of its intended functions, can be restored to perform all of its intended functions by any method other than replacing the entire system is called a repairable system. Replacing, repairing, adjusting, cleaning the appropriate component(s), rebooting, or re-installing software can restore a repairable system.

Most large systems, such as semiconductor manufacturing equipment, are repairable systems. The distribution of failure times between two successive failures of a repairable system is discussed in Chapter 4.

There is subjectivity in the above definitions. A component for one person may be a system for another. For example, for all practical purposes, a computer monitor is a component in a large manufacturing equipment system, while it is a system for the manufacturer of the monitor. For many repairable systems, field replaceable units (FRU's) are considered components.

Three basic types of systems (series, parallel, and standby) are discussed in Chapter 4.

REFERENCES

1. Gerald J. Hahn and Samuel S. Shapiro, Statistical Models in Engineering, John Wiley & Sons, Inc., New York, NY, 2007.

2. William W. Hines and Douglas C. Montgomery, Probability and Statistics in Engineering and Management Science, John Wiley & Sons, Inc., New York, NY, 2003.

WWK offers "Equipment Reliability Overview" training based on this book's content. This training can be customized for your organization. For more information, please contact WWK at info@wwk.com.

[Look for installment 3 in the fall edition of Applied Cost Modeling]

Wright Williams & Kelly, Inc. Releases Factory Explorer® v2.9

Wright Williams & Kelly, Inc. (WWK) announced today the release of a new version of its integrated capacity, profitability, and discrete-event simulation software, Factory Explorer® v2.9. The latest additions to this powerful planning package are the result of WWK-funded research at the University of Arkansas.

The major features that have been added include a series of operator-modeling capabilities that allow for varying operator headcount by shift, alternative operator groups at the process step level, skill set descriptions allowing for cross-equipment training and productivity deltas, overtime scheduling and payroll, and real-world shift descriptions, including overlapping shifts. These enhancements are of particular interest to micro-electro-mechanical systems (MEMS) organizations that typically require more manual production and assembly operations than wafer fabs.

Additionally, Factory Explorer® v2.9 integrates data acquisition with FabTime®'s cycle time management database for automated model building and maintenance.

WWK Hosts Cost of Ownership Seminar at SEMICON West
WWK and SEMI Co-Sponsor Event for the 15th Consecutive Year

WWK announced that it will be presenting its highly acclaimed seminar, "Understanding and Using Cost of Ownership," during SEMICON West. "Understanding and Using Cost of Ownership" will be held at the San Francisco Marriott on Thursday, July 19 from 9am to 5pm. This seminar covers all aspects of Cost of Ownership (COO) and Overall Equipment Efficiency (OEE) from fundamentals to hands-on applications. Registration for this seminar can be done directly on the Semiconductor Equipment and Materials International (SEMI) web site at www.semi.org or by calling WWK directly.

There is limited seating available for this seminar, so please contact SEMI or WWK today to guarantee your place in this once-a-year event. It is expected that registration will close out shortly for this program. As an added benefit, WWK's software maintenance clients qualify for a 20% discount off the list price of the seminar if they book directly with WWK.

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BluGlass Ltd
Cost of Ownership Impacts for GaN-LED Deposition and Device Assembly

Executive Summary

To determine the potential cost savings of the RPCVD process at the epi-wafer and device assembly levels, BluGlass retained the services of Wright Williams & Kelly, Inc. (WWK), an internationally recognized expert group in cost of ownership modeling.

This report summarizes the results of WWK's cost of ownership models, comparing the RPCVD process on two-inch diameter (2") buffered-glass substrates against the more conventional MOCVD process on similar-sized sapphire substrates. The MOCVD data was collected by an independent industry expert and includes current best estimates of material and other input costs and productivity for a US-based manufacturing facility.

The following cost comparison is based on a 21 x 2" wafer capacity commercial production tool for both the MOCVD and RPCVD processes. The wafer-level analysis shows an overall cost savings of 48% for RPCVD, with the major cost driver being a 70% reduction in materials and consumables costs. The largest factors in this area are a substantial reduction in substrate cost and the complete elimination of ammonia. Over a projected seven-year useful life, the operating costs for RPCVD are almost US$8M lower than MOCVD for a single piece of equipment.

In order to determine the impact of BluGlass' epi-wafer cost advantage on final-assembled LED costs, WWK constructed a downstream-assembly cost model for a 0.35- x 0.35-mm square mesa-structure blue LED in a standard "Blue LED T1" encapsulated package with water clear lens. WWK used an outside expert to provide a backend-assembly process flow; a list of capital equipment including supplier, pricing and production capacity; a list of basic materials and consumables; and an estimate of testing costs. The integrated cost model assumed no difference in processing costs between MOCVD and RPCVD post-epi-wafer and shows that the RPCVD process generates a 10% cost advantage at the finished LED level.

The methodologies used to generate the above results are compliant with standards from Semiconductor Equipment and Materials International (SEMI) covering the areas of equipment reliability (E10), cost of ownership (E35), and overall equipment efficiency (E79).

Wright Williams & Kelly, Inc. to Exhibit at SEMICON West

Meet the World's Experts in Operational Cost Modeling and Simulation

Wright Williams & Kelly, Inc. announced it will be exhibiting once again at SEMICON West in San Francisco from July 17th through 19th. WWK will be located in Moscone Hall South (#2716). Additionally, WWK will be providing a special gift to all who visit their booth.

"This is a unique opportunity for all of our customers and visitors to meet with WWK's staff. Our U.S. technical staff as well as our overseas operations will be present at SEMICON West this year," stated David Jimenez, President of WWK. "Representatives from our Asian and European operations will be available to discuss local issues of interest during the show."

SEMICON West 2006 marked WWK's 15th Anniversary, a remarkable feat for any company in the rapidly changing landscape of high-tech manufacturing. WWK commemorated the event with a special gift to all who visited their booth at the show. The demand for the gift was so high that WWK is repeating the presentation again this year.

WWK will be holding live demonstrations of all of its products. A semi-private demonstration area will allow clients to look at software solutions for their specific needs. WWK's product line includes TWO COOL® for detailed process step level cost of ownership (COO) and overall equipment efficiency (OEE), PRO COOL® for process flow and test cell costing, Factory Commander® for full factory capacity analysis and activity based costing, and Factory Explorer® for cycle time reduction and WIP planning. Additionally, WWK offers a highly flexible product management software package that helps sales forces eliminate errors in product configuration and quotation processes.

ISMI has released the following publicly available document, "SEMI Standard S23 Application Guide: Selecting and Using Measurement Instruments to Conserve Resources."

The development of SEMI S23, "Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment," was a collaborative effort between ISMI and the semiconductor equipment supplier community. To promote the use and acceptance of SEMI S23, ISMI recently completed the S23 application guide, which may be downloaded from the following web site:

http://ismi.sematech.org/docubase/document/4783aeng.pdf

The SEMI S23 standard is available for purchase through

www.semi.org

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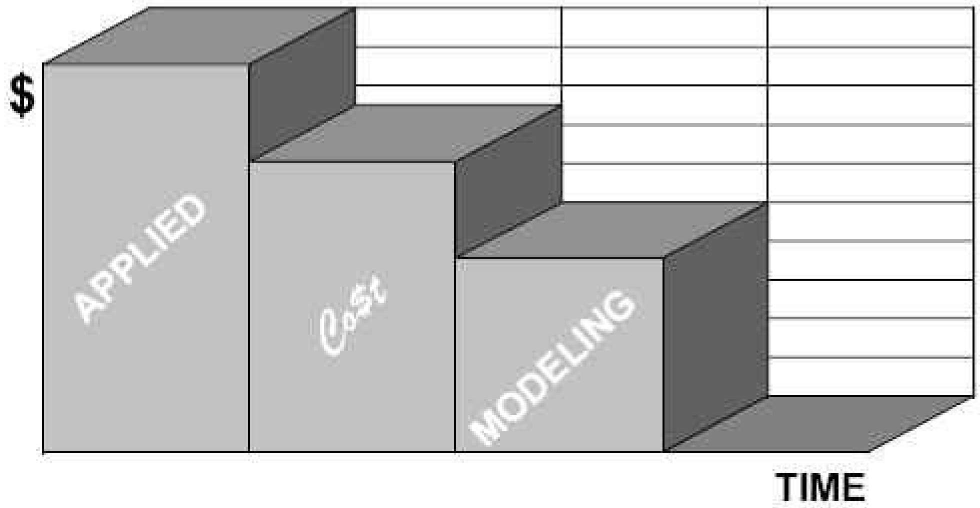
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