RELIABILITY AND MAINTAINABILITY IN INDUSTRY AND THE UNIVERSITIES

Charles Lipson, Professor
Narendra J. Sheth, Associate Research Engineer
David B. Sheldon, Research Assistant
Department of Mechanical Engineering
University of Michigan
Ann Arbor, Michigan

Abstract

Different methods of expressing Reliability and Maintainability are discussed in this paper. This involves reliability based on intuition, on customer failures and warranties, on experience with military contracts, on laboratory, field, and acceptance testing. The role of universities in advancing the state of the art of Reliability and Maintainability is included.

Introduction

Reliability and maintainability had its impetus during the later years of World War II when the military discovered that as high as 60% in the electronic equipment delivered to the fighting forces was not in operable condition. The equipment had been damaged in transit due to poor packaging or was the result of faulty manufacturing. After the war, the government initiated extensive investigations into why the material was not reliable and what should be done to make it so. After almost two decades the work of these government committees and government sponsored projects is now finding its way into consumer products.

There are two major reasons why the techniques used to assure reliable materiel have taken so long to reach individual consumer products; 1.) Most of the rioneering work was done in the field of electronics while consumer industry products are concerned largely with mechanical components, 2.) Until recently, industry, unlike the military was not interested in expensive reliability analysis.

With the advent of reliability studies electronic equipment received the principal attention. A large number of committees and advisory panels was established, the most prominent being the Advisory Group on the Reliability of Electronic Equipment founded in 1952. Each of the groups devoted almost entire attention to establishing reliability prediction techniques and reliability programs for electrical and electronic equipment. Investigation of mechanical component was shunted aside. Mechanical Systems were neglected for two reasons; 1.) Government appropriations were nst ear-marked for research in the area and 2.) Mech ical components did not readily lend themselves to reliability analysis. There is no question about the failure of a light bulb but in the case of a roller bearing or valve spring how does one determine the precise moment that the part has "failed"? Is it when the bearing seized or when the first signs of spalling occurred? Is it when the valve spring broke or when its efficiency was reduced to 75%? Our point is that while the majority of consumer products depend on mechanical components the ability to predict the reliability of these components is still in its infancy. While studies of the reliability of electronic equipment began in the 1940's, analysis of mechanical components is largely a product of the 1960's.

In past years the industrial producer could not afford a sophisticated reliability program and still remain price competitive. Within the last five years industry has seen almost a complete reversal and manufacturers are establishing reliability-maintainability programs to keep up with their competitors and maintain their percentage of the market. The future will see more and more reliability techniques being adapted to industrial production in order to assure quality merchandise and gain customer loyalty.

Methods of Expressing Reliability and Maintainability

It is interesting to note how over the years the definition of "reliability" has grown and changed in meaning. In the 1940's the term was all encompassing and a cure-all for whatever ailed the piece of equipment was, "Make it more reliable." With the passing of time the definition took on many new implications and became more quantitative. Splinter words such as "maintainability," "availability," and "product assurance," filled the voids that reliability could not cover.

Today reliability and maintainability have different meanings to different people e.g. the academician, the general consumer and the industrial producer. To the academician, reliability is "the ability for the part or assembly or system to fulfill its function under specified operating conditions for a specified period of time under specified environment without failure."[1] Maintainability might be defined as: "The probability that, when maintenance action is initiated under stated conditions, a failed system will be restored to operable conditions within a specified total time.[2]

To the average consumer reliability and maintainability are subjective terms. When a product is reliable or maintainable, the purchaser has confidence in it. Brand names usually set certain images of the product that have been established through advertisement, personal experience and a knowledge of friends' experiences. The purchasing public associates "reliability" and "failure" at opposite ends of the spectrum. When told that reliability is the ability to operate for a specified time under specified conditions <u>before failure</u>, the consumer shouts "Planned obsolesence!!" To him a part is never supposed to fail.

The consumer has mixed emotions about maintainability It is a nuisance when you have to change the oil in your car every 3,000 miles but it is a blessing when the burned coil In the toaster can be replaced in ten minutes. Maintainability is something you hope you won't need but if you do, it should be as fast as possible.

What the consumer does not realize is that replacement of short lived parts at proper intervals can slow the rise of the failure rate curve (Figure 1). This is true in automobile and aircraft engines, domestic appliances, machine tools, and other products.

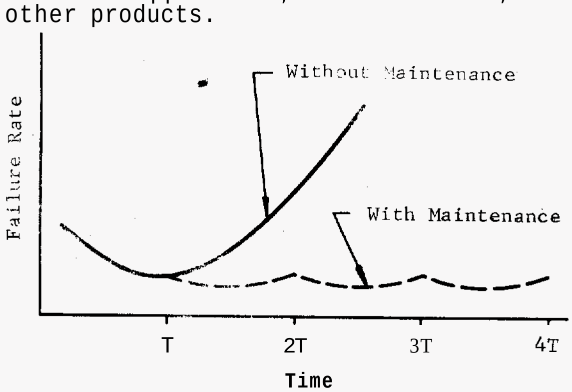


Figure 1 Effect of Preventive Maintenance.[4]

To a manufacturer reliability is not a one sentence statement - it is a company-wide program. One of the automotive companies lists the following five steps as the basis of their engineering reliability program:

"1. Define specific reliability requirements for each vehicle system and subsystem.

"2. Design components, subsystems, and systems to have the required reliability.

"3. Conduct sufficient testing to verify adequacy of the design.

"4. Specify part requirements precisely and clearly to our manufacturing activities and outside suppliers.

"5. Monitor all sources of field information to anticipate and react quickly to problems, and provide feed back to modify future designs and processes."[4]

The term "reliability" has many technical and engineering connotations. In one plant, reliability is merely an extension of the technical functions of quality control. In another plant, it is the adaptation of mathematical analysis and the use of computers to the pre-approval stage of design projects. Therefore, it is necessary to have a comprehensive definition of the term in relation to the specific industry and company at hand.

Once again turning to the automotive industry, which has been a pioneer in the field of consumer product reliability, they have taken the total concept of a "Reliability Program" and broken it down into eight aspects:

"1. Management Program - to establish effective control of the reliability effort.

"2. Design Program - to provide and preserve reliability in design.

"3. Production Program - to produce reliable products.

"4. Evaluation Program - to measure and predict reliability.

"5. Use Program - to maintain equipment reliability in the field.

"6. Research Program - to develop new methods for achieving reliability.

"7. Education and Motivation Program - to provide reliability, skill, instruction and motivation.

"8. Public Relations Program - to inform on progress in reliability."[5]

Reliability, then has different meanings to different people. To the educator it is precise and quantitative, to the consumer it is subjective, and to the manufacturer it is a company-wide program involving not only the engineering department but all phases of management.

<u>Reliability Based on Intuition</u>

One has often heard the expression, "There is no substitute for experience", and many industries today depend on this experience and skill to produce reliable products. The skill of an experienced tool and die maker, a glass blower, a casting expert, a senior design engineer; these are talents that can only be gained through experience. Very often one encounters people that "have a feel" for what is right; these people are invaluable to industry. No matter how well one understands the theory behind reliability and maintainability, if he doesn't know how to apply it he is of limited use to his company.

There are industries that use the techniques of reliability but keep no written records. Suppose that Sam Jones is operating a small job shop producing rubber grommets. Once or twice a day he goes to the production line and picks up five or six pieces and takes them back to the office where he has devised a small test stand. He tests five and only one tears apart. Since Sam knows that his test stand exerts a much greater force than will ever be encountered in actual operation, he makes the statement, "Yeh, that's good enough, keep'em rolling." Little does he know that he has just performed an accelerated test using given acceptance standards.

There are many industries that have no need for reliability programs, assurance tests, and sophisticated techniques for checking the quality of their product. To these industries a good inspection line is all that is needed to insure "highly reliable" products. A good example would be companies that produce plastic wastebaskets, or thumb tacks, or file cabinets, or brooms, or pencils, or clothing, or furniture, etc.

Reliability Based on Customer Failures and Warranties

Customer complaints on failed parts have existed ever since the first cave man "bought" an axe from his neighbor in exchange for the front quarter of a tyrannosaurus and later discovered the head *of* the axe was not flint and furthermore it was bound with immitation hide. From this-time hence manufacturers have given more and more attention to customer complaints in re-evaluating the design and manufacture *of* their product.

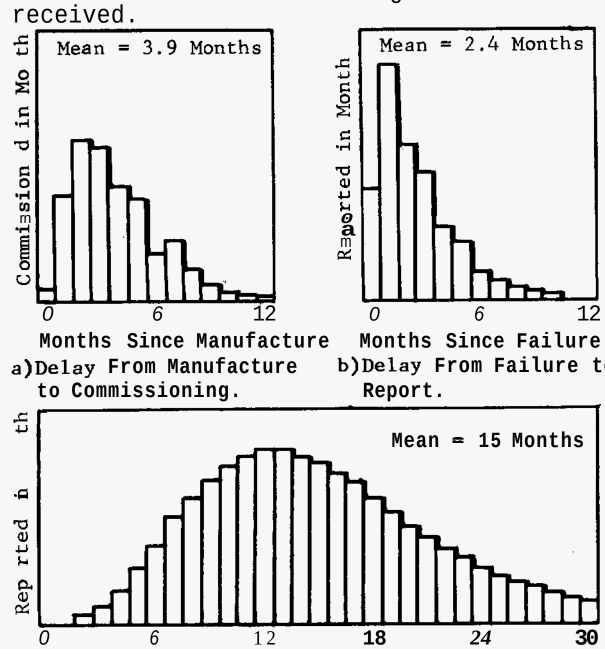
This method of increasing product reliability through evolution is well adapted to equipment that maintains a similar design over an extended period of time, The reliability and efficiency of large electrical motors and steam turbines has increased substantially over period *of* years yet the basic design has remained fairly constant. Each failure of a turbine blade provides the manufacturer with an added insight on how he can change the design of that particular part to insure that it will not fail in the future.

In the same way automotive companies use customer failures to predict the reliability of future designs. They accomplish this by calculating how reliable the present model is,based on how many autc parts have been sold, how long they have been driven, and how many parts have failed. Knowing the reliability of an existing part they then attempt to correlate the old design with the new design, considering deviations between the two.

This practice is becomi[illegible] increasingly important as [illegible]ve companies extend their warr[illegible]riods and expand the nnmber of ite[illegible]on the automobile that are warranted. This is exemplified by Chrysler 1963 inaugration of 5 year - *50,000* mile drive train warranty. Unless they were sure that their designs were adequate to operate without numerous failures, the warranty could have proven a financial mill stone. Cost figures are not available, but Chrysler claims that the cost of servicing this warranty has decreased ever since 1963. This would indicate that as faulty parts are encountered, they are redesigned for greater reliability and longer life.[6]

Ford Motor Company claims that from the warranty data analyzed after six months or less of field service, they can predict product reliability and lifetime warranty cost and repair rates as much as two and one-half years ahead. In addition, the warranty data analysis can be used to identify differences in problem rates between assembly plants, months *of* production, vendor sources, and vehicle option, and can describe the type of complaint for each part.[7]

One of the difficulties encountered in analyzing warranty data is the variable delays between failure and report of the failure. Figure 2 illustrates the delay distributions for service information. Figure 3 is an analysis of failures with reference to the production date. The lower diagram shows that a change in manufacturing standard occurred in May 1964 but this is not apparent in the current level of returns shown in the upper curve. The effect of any sudden change in failure rate due to any particular cause appears gradually and it is difficult to discover among all the data received.



a) Delay From Manufacture to Commissioning.

b) Delay From Failure to Report.

c) Total Delay From Manufacture to Report of Failures Occuring During the 12-Month Warranty Period

Figure 2 Diagrams of Delay Distributions.[8]

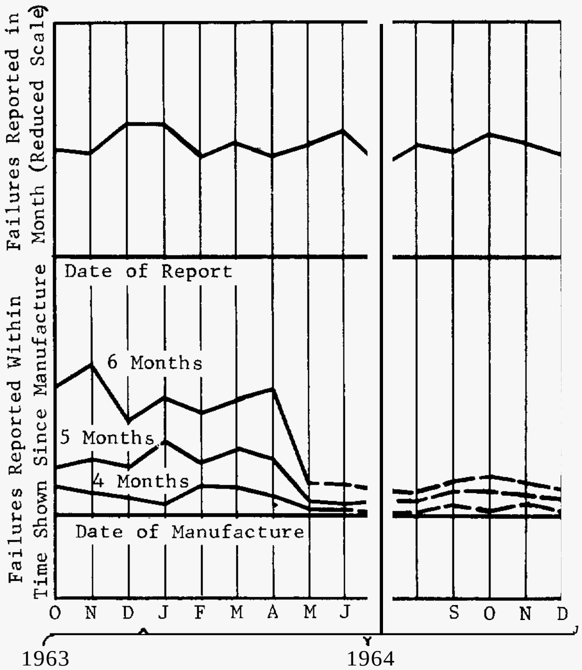


Figure 3 Analysis of Failures.[8]

A major shortcoming of many reliability programs is that they are initiated after the part is in production. Reliability prediction techniques should be used in the earliest phase of a totally new product for an effective means of assuring proper emphasis and direction of the development program. Reliability improvement steps taken in today's products will have its reflection in the products' warranty cost tomorrow. Therefore the better the reliability programs, the less cost of product warranty. For example, the total prodcct warranty cost of Westinghouse Electric Corporation, as a percent of gross sales billed for the year 1963 was 25% lower than 1962, and the 1964 figures indicate a further reduction. (Figure 4)

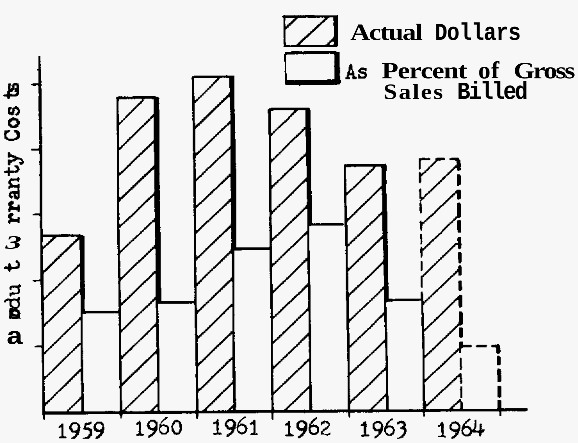


Figure 4 Product Warranty Costs[9]

There is frequently a problem in interpreting service data. All too often not enough data is taken or emphasis is placed on the wrong component. Some reliability departments are not spending sufficient time to develop optimum interpretation of failure data. Figure 5 shows considerable scatter in engine exhaust valve life. This data was obtained from fleet operation of groups of five identical engines. From these results one would tend to doubt the validity of field data, but compare Figure 5 with Figure 6 which represents the results of similar tests conducted on the dynamometer under controlled conditions. These data show about the same degree of scatter as in the fleet operation. This suggests that scatter is an inherent characteristic of a fabricated part and not a flaw in the accuracy of field data.

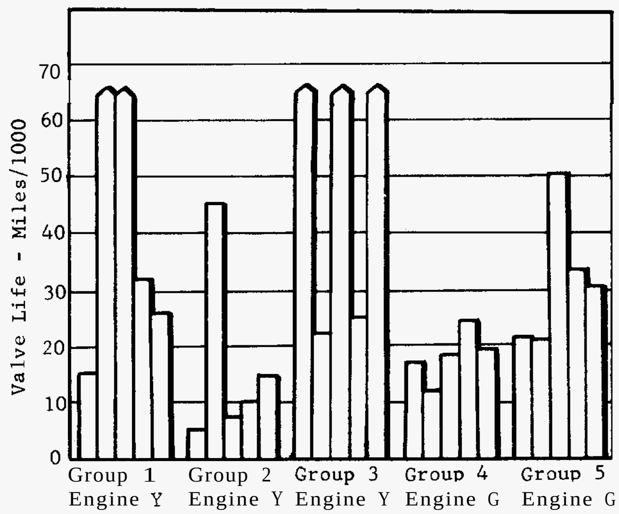


Figure 5 Engine Exhaust Valve Life, Fleet Test.[10]

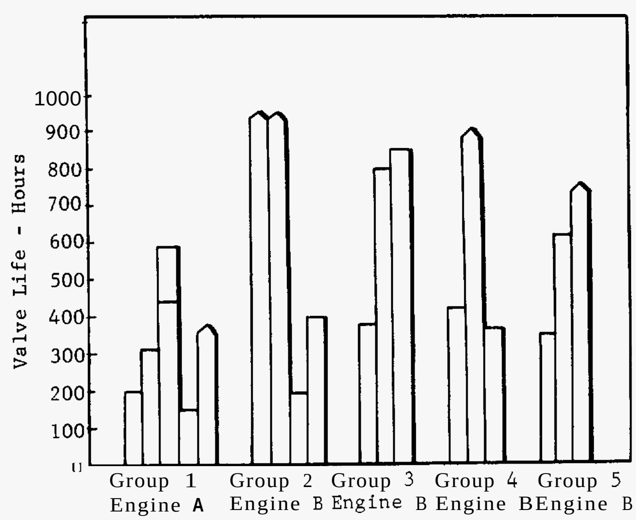


Figure 6 Engine Exhaust Valve Life, Dynamometer Test.[10]

There is an extensive collection of automotive reliability data, on Mobil Oil's Repair Center in Cherry Hill, New Jersey. Established in the early 1960's this center has tested thousands of cars against manufacturer specifications. Brakes, fuel pumps, carburetors, distributors, spark plugs, batteries and other components can thus be evaluated on a reliability basis. The relationship of part reliability to mileage is shown in Figure 7.

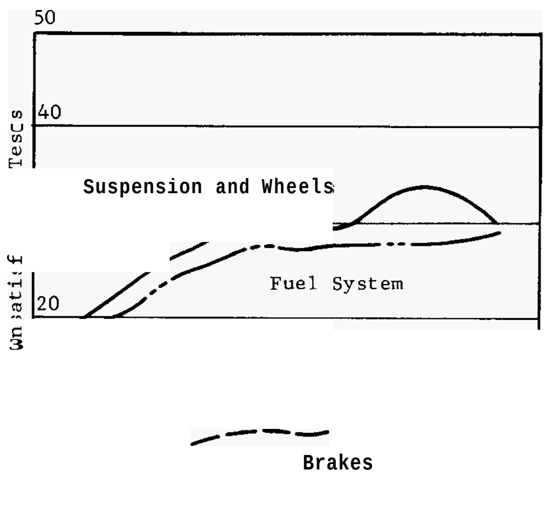


Figure 7 Automotive Reliability.[11]

Reliability Based on Experience with Military Contracts

Military standards and procedures were the first publications to include extensive reliability requirements for manufactured materiel. Many companies who have been concerned with these procedures through their government contracts are now awakening to the fact that these same techniques can be applied to their mass consumer products.

In 1961 Raytheon decided that it must reduce the warranty expenses on an infrared oven that was being marketed to restaurants, cafeterias, and institutions.[12] Among the suggestions for reducing these costs was the establishment of a reliability program, but Raytheon had no formal reliability group in the consumer products divisions. However, one of their military equipment groups had such an experienced staff. The outcome was that this staff established a reliability program which was a cut-down counterpart of their military reliability procedures. It was an ambitious project for a commercial product but the results were well worthwhile. Raytheon claims that the average annual warranty cost per equipment has been reduced 80% and within one year the investment in the program was saved six times over as compared to predicted warranty expenses without the program. Raytheon gave major emphasis to high warranty cost items in their reliability studies thereby reducing the cost of the program. (Figure 8)

Westinghouse Electric Corporation, like Raytheon, has operated military reliability programs under defense and space contracts for more than one and a half decades. They too asked themselves if a company-wide reliability program for consumer products would pay for itself. Westinghouse assuned that it would and initiated a pilot program in seven divisions. The results have been favorable and the program is now being installed in several other divisions. Figure 9 shows how the unreliability of a system can far outweigh the higher initial cost of reliable system when the defective system experiences costly maintenance and downtime. This was a strong argument presented by Westinghouse for improved reliability of consumer durables.

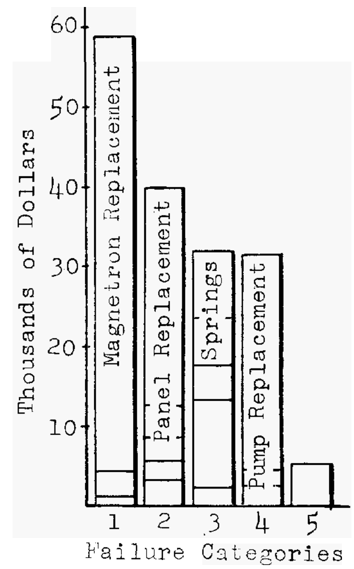


Figure 8 Ordered Distribution of Warranty Costs for Failure Categories.[12]

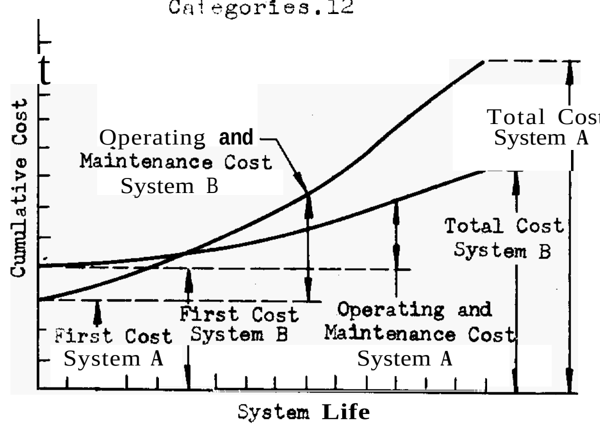


Figure 9 Effects of Reliability on Total Cost.[9]

Reliability Based on Testing

Some industries can predict and insure component reliability by simply plugging numbers into standard formulae or by using go-no-go testing. On the other hand, they may do extensive testing under different environmental conditions and insure a high degree of reliability through sophisticated statistical techniques. Many industries are increasingly involved in such testing. This is done largely to verify the predicted values of reliability, as the art of prediction is still in its infancy.

Laboratory Testing

Laboratory testing is commonly used when the components or systems can be tested in an accelerated manner in a controlled environment. In developing such tests, the applied loads are simulations of what is encountered in the actual operation.

Most of the laboratory tests should be designed to run to failure so that life characteristics and nodes of failure can be determined. To analyze the test results, the Weibull probability paper (Figure 10) is commonly used. Advantages of using the Weibull distribution are:

1. Almost any scatter data will fit the Weibull distribution as it has three parameters.
2. Graphical interpretation of data becomes very easy.
3. Weibull represents a family of different distributions, such as normal, exponential, etc.

Figure 10 shows the results of a simultaneous test of 12 components terminated after the ninth failure.

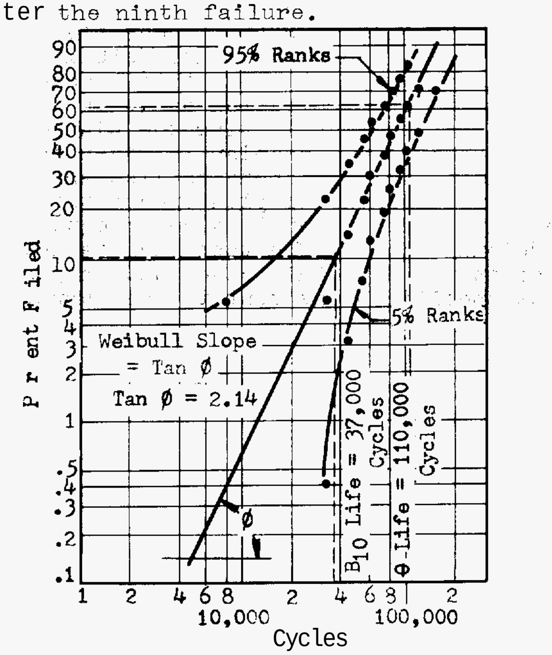


Figure 10 Weibull Plot of Laboratory Test Data.4

Field Testing

In the automotive industry field and proving ground tests are used to supplement laboratory tests to establish final reliability assurance. The primary objectives of proving ground tests are to uncover basic design defects and determine the mode of failure.

In the automotive industry the proving groand tests total many million test miles per year. A basic durability route is layed out in such a way that the vehicle, rather than being subjected to abnormally severe use, receives more frequent applications of conditions encountered in normal use. Since the tests involve small sample sizes (small nnmber of test vehicles), each experiment is designed to produce maximum amount of information at a high level of confidence.

It is also very essential to interpret and understand the test results in terms of customer experience. This is becoming an increasingly important factor in developing a reliable product. In the last few years, the automotive industry has put considerable effort into developing correlations between life of the parts in the customers' hands and the same part life on the proving grounds. Proving ground data and warranty data are then analyzed using Weibull probability paper as shown on Figure 11.

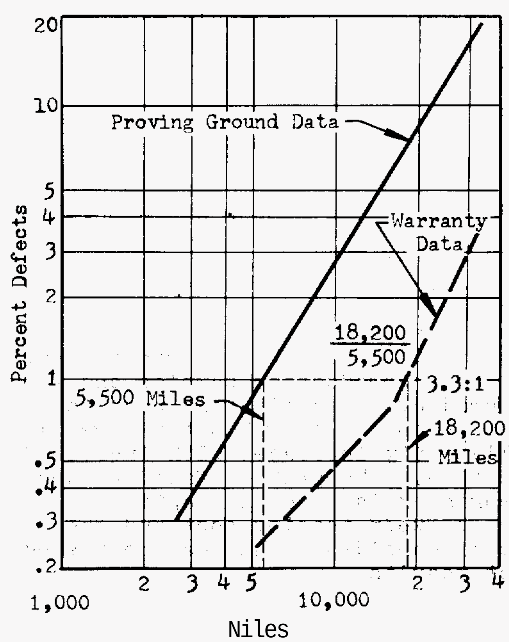


Figure 11 Proving Ground to Customer Correlation.4

This particular analysis showed a 1.0 percent defect rate at approximately 18,200 customer miles and 5,500 proving ground miles. The test severity ratio of customer miles to proving ground miles is 3.3:1 at this point. Good correlation is dependent upon having the same mode of failure in testing and in the field.

Acceptance Testing

Many of today's large companies subcontract the manufacture of certain components to their suppliers. The delivery of a quantity of parts to a purchaser may involve acceptance testing by a purchaser. This testing and inspection can be an expensive and time consuming task. For example, one of the big three auto companies has over 2,500 outside supplier companies furnishing about 77,000 different types of production parts at an annual cost of about two billion dollars.[4]

An essential step in the reliability program is developing an effective test plans for use in monitoring reliability. They must be expressed in terms which are clearly understood by the manufacturing and quality control personnel of the parent company and of the suppliers. This is particularly important as reliability usually requires the use of statistical techniques.

Group Test Plan There are two methods for acceptance testing in common use. The group test plan is applicable to small parts which can be conveniently tested in groups. In automobile this might include lightbulbs, turn signals, brake linings, bearings, small springs, locks, etc. Parts are selected at random and tested simultaneously to predetermined life levels. The decision, regarding whether the lot is satisfactory, unsatisfactory or further testing is required, will depend on the number of inoperative or failed parts at each life level. The final decision is reached with a minimum of testing. This reliability test plan can only be of use if life data on a number of representative parts exist. Automotive industry obtains representative data from preproduction samples and from prior production sample test results. Figures 12 and 13 show how the lower limit of reliability increases with increased sample size. The problem faced by any test engineer is to obtain optimum balance between testing cost and the degree of confidence that can be placed on test results.

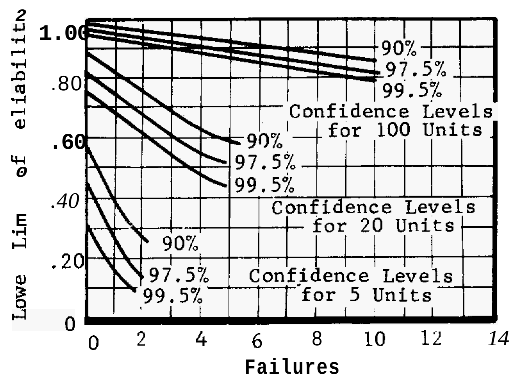


Figure 12 Reliability vs Failures for Several Confidence Levels and for Several Sample Sizes Tested[13]

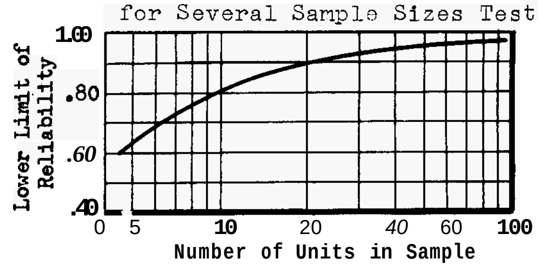


Figure 13 Reliability vs Sample Size Tested.[13]

Sequential Test Plan A sequential test plan can be applied to parts such as crankshafts, transmissions, pumps, axles, and other parts that are tested one at a time. This plan is based on exponential sequential plan developed by Wald[14] and modified by Epstein and Sobel.[15] The sequential plan that the automotive industry uses was developed by subsitution characteristics of the Weibull distribution for the mean time between failure in the exponential plan. The truncation for the plan based on the work done by Epstein[16] for the exponential plan was also transformed into Weibull terms. Another point about this truncation plan is the truncation point is selected rather than letting the plan do it. An example of the plan is given in Figure 14. The plan operates like an exponential sequential plan except that life values are raised to a power equal to the Weibull slope. The test plan tables are constructed in this case, and in part of the specifications sent to the supplier.[4]

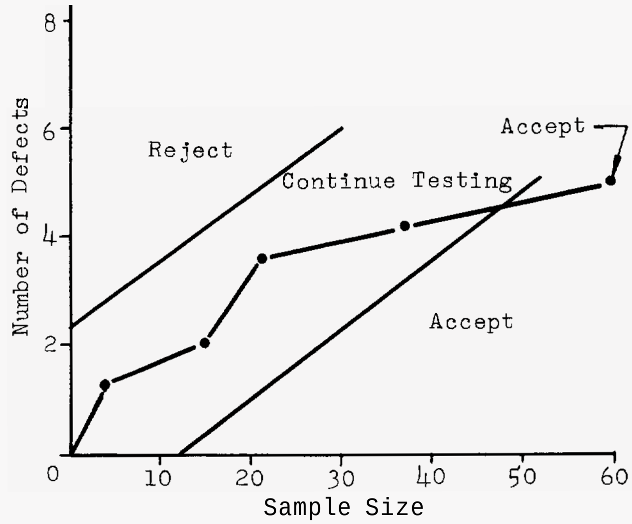


Figure 14 Application of a Reliability Specification for Part Testing One at a Time.

Role of Universities

Universities play an important role in advancing the state of the art of reliability and maintainability. An examination of the curricula of 35 universities with leading engineering departments revealed that 10 of them offer courses specifically in reliability. These are given generally in the department of industrial engineering.

The content of these courses indicates that very few of them are directed toward mechanical components. By and large they serve the needs of space technology, with heavy emphasis on advanced statistical theories rather than on practical engineering applications. Representative topics included are:

1. A study of the time variant life characteristics of components and systems.
2. Measurement of reliability parameters.
3. Principles for design and use of attribute and variables sampling plans and sampling procedures.
4. Advance statistical methods for determining reliability growth curves with associated confidence limits.

In order to advance the state of the art of reliability and maintainability there is a real need for courses and curricula in reliability of mechanical devices. Probably because of our proximity to large industrial centers we at the University of Michigan address ourselves toward the development of such courses. We find that the following specific areas seem essential to the development of reliability of mechanical components and devices.

1. The Study of Scatter and the multiplicity of factors responsible for it.
2. Statistics, with particular emphasis on the statistics of small samples. Weibull, normal, log-normal, t, F, and χ^2 distributions.
3. Failure Analysis, involving study of the modes of failure, factors influencing them, and methods for failure identification.
4. Stress and Strength Analysis, both for flexural and contact loading. This includes, cummulative damage, understressing and overstressing, and strength at low number of cycles.

4\. Design Analysis, which comprises reliability of gears, bearings and other mechanical components; reliability of systems such as engines and gear boxes; when to use statistical tolerances and when algebraic tolerances seem more appropriate.

6\. Design of Experiments, this includes number of samples necessary for the results to be significant; the meaning and limitations of accelerated tests; techniques for reducing testing, such as sudden death and sequantial approach; multivariant analysis and random factorials.

7\. Reliability in Production analysis of manufacturing quality, infant mortality, control charts.

References

1. Lipson, Charles, Jal Kerawalla and Larry Mitchell, Engineering Applications of Reliability, Engineering Summer Conferences, University of Michigan. Ann Arbor. Michigan, 1963.

2. Von Alven, William H. Editor. Reliability Engineering, ARINC Research Corporation, Prentice-Hall Inc.. Englewood Cliffs. New Jersey, 1964.

3. "A Manual of Reliability", Product Engineering, Special Report, McGraw-Hill Publishing Co. Inc., 1960.

4. Simpson, Bruce H., "Reliability and Maintainability Part 2 - Automotive: The Ford Reliability Program", Mechanical Engineering, March 1966.

5. Yost, H. C., Cirector of Reliability The Electronic Divisiono f General Motors Corp., definition appearing in the editorial of Automotive Industries, August 1960.

6. Osann, F., "Commercial Reliability- The Chrysler 5 and 50 Warranty", Proceedings of Eleventh National Symposium on Reliability and Quality Control, Miami Beach, Florida, January 1965.

7. Simpson, Bruce H., "Reliability Prediction from Warranty Data," Automobile Engineering Congress, Detroit, Michigan, January 1966.

8. Corney, C. T., "The Achievement of Design Reliability", Lucas Engineering Reveiw, Vol. 2, No. 2, June 1965.

9. Daly, T. A. and P. H. Ockerman, "Commercial Reliability - A Good Investment?", Proceedings of Eleventh National Symposium on Reliability and Quality Control, Miami Beach. P'lorida, January 1965.

10. Lipson, Charles, "Recent Developments in Testing and Design Methods", report submitted to International Harvester Company, Engineering Research Division, December 1961.

11. Oil Power, Vol. 64, No. 2 edited by Harold B. Olsen Jr., copyright 1964 by Socony Mobil Oil Co., Inc.

12. Lebre, Edward G., "Commercial Reliability", Product Engineering, April 13, 1964.

13. Wilson, R. B., "Designing Equipment for Reliability", Mechanical Engineering, December 1957.

14. Wald, Abraham, "Sequential Analysis", John Wiley & Sons Inc., New York, N. Y., 1947.

15. Epstein, Benjamin and Sobel, Milton, "Sequential Life Tests in the Exponential Case," Annals of Mathematical Statistics, Vol. 26, 1955, PP. 82-93.

16. Epstein, Benjamin, "Truncated Life Tests in the Experimental Case", Annals of Mathematica1 Statistics, Vol. 25, 1954, pp.555-564.