How To Use Reliability Engineering Principles For Business Issues

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Abstract

Failures of equipment and processes waste money on unreliability problems. Unreliability is the costly part of the economic equation. The business issue of reliability is control and prevention of failures to reduce costs and improve operations by enhancing business performance with affordable levels of reliability. Reliability numbers by themselves will not motivate improvements. Money values resulting from unreliability will cause reliability numbers to spring into life and guide actions for making cost effective changes using actual plant data for costs and failures. Reliability engineering tools and principles are discussed which assist plant improvement programs for reducing the high cost of unreliability.

Reliability Definitions

Reliability has many definitions (Barringer 1998):

- As a general sense, reliability is the ability of an item to perform a required function under stated conditions for a stated period of time.
- As a characteristic, reliability denotes the probability of success or the success ratio.
- As a measure of quality, reliability exists by design as an objective or a requirement of a product from its inception to the end of its working life.
- As a probabilistic statement, reliability is concerned with the probability of future events based on past observations.
- As a basic concept, durable and high probability of failure-free performance under stated conditions including all item life units, not just mission time and all failure with the item, not just mission-critical failures at the time level of assembly.
- As an overall concept, reliability is a special development of engineering industries for the collective measures of quality that reflect the effect of time in storage or time in use of a product. The concept is distinct from measures that show the state of the product at time of delivery.
- As a business concept, reliability is concerned with a balanced integration of strategies for procurement, installation and start-up, equipment/process operations, maintenance, and reliability which avoid failures and maintenance interventions by focusing on the long term cost of ownership in financial terms to avoid waste and optimize plant availability.

The simplest reliability definition to use is the characteristic, and the most productive reliability definition relates to the business concept.

Many people associate reliability with maintenance issues, however the root of reliability problems begins long before maintenance is required. In short, this popular concept is putting the horse before the cart. Reliability is designed into the equipment by engineering, launched on its course by best installation practices by project engineering, demonstrated by operations in careful use of the equipment, and it is only sustained by maintenance.

Maintenance is often perceived as the root of reliability issues--most true roots of reliability problems occur upstream of maintenance departments. Maintenance departments go through five distinct development phases (Leonard and Roberts 1998) as shown in Figure 1:

1) **Reactive Stage**: The maintenance goal is to restore equipment to proper condition as failures occur. It is a fix when broken strategy. Proficiency is demonstrated when repairs are accomplished in the minimum amount of time. Individuals and departments are rewarded for heroic efforts, and the key numeric is maintenance efficiency--no matter how many breakdowns occur. Nearly all problems are viewed as maintenance problems.

Reliability awareness programs commence with complaints of too many failures. The question often raised is "How do we compare to others (and we lack numbers for comparison)?" The stage is set for beginning to understand definitions of reliability.

At this awareness stage, reliability is "something" we lack but others have. Benchmarking with other businesses at the awareness stage is difficult because facts are lacking thus little or no information can be traded.

2) **Preventive Stage**: The maintenance goal is control of planned maintenance activities rather than allowing unplanned machine breakdowns. The expected outcome is reducing unanticipated expenses--the issue is planned expenses are OK but unplanned expenses are not OK.

Reliability awareness of performing preventive maintenance task at specific intervals helps realize inherent equipment reliability. At this awareness stage, much reliability work is busy work with the expectation that no machine is allowed to fail while in service by performing good maintenance as a planned event. A key metric is the ratio of planned work to unplanned work, and benchmarking for this specific characteristic becomes a holy grail by elimination of machinery break-downs by concentrating on best maintenance practices to reduce failures and improve availability by doing things in maintenance correctly to avoid failures.

3) **Predictive Stage**: The maintenance goal is elimination of machinery outages by use of technology to measure machine conditions (usually by machinery vibration monitoring), assess machinery problems, and decide on the corrective action.

Reliability techniques are used to predict equipment failures and forecast remaining equipment life. The predictive concepts allow good planning to select the proper time for restoration efforts which, in turn, reduces the mean time to make repairs.

Often the prediction/planning/timing of predicted repairs is considered as planned work. Thus two metrics result in happiness for keepers of maintenance data as the ratio of planned to unplanned ratios improve and the good planning for restoration results in smaller mean times to repair.

Reliability awareness of performing predictive maintenance task at or near the end of life achieves maximum life from the equipment and accepts the concept that equipment fails in a probabilistic manner. The reliability concepts of predictive maintenance understand that careful observations must be maintained at periodic intervals to discover impending problems.

At this reliability awareness stage, much of the reliability work is considered as wasted effort by business managers because problems are found so infrequently and thus the costs for predictive maintenance is an easy target for cost reductions. A key metric is the ratio of predicted problems found compare to the number of observations. To control costs, frequently the data gathering effort of predictive maintenance is performed by operations personnel as they make their daily surveillance rounds of equipment--furthermore operator collection of data fits into the total productive maintenance concept of teamwork to protect and extend equipment life.

4) **Proactive Stage**: The maintenance goal is application of predictive, investigative, and corrective technology to extend equipment life and eliminate reactive maintenance efforts. Proactive maintenance efforts involve technology for: root cause failure analysis, precision rebuild and installation, performance specifications for new and reworked equipment, certification and verification of rebuilt equipment, design modification of substandard equipment, and gathering and analyzing failure data. This stage results in engineering results with technology.

Reliability awareness of how engineering technology is used, by working the numbers, quickly separates availability issues from reliability issues. Unfortunately, numeric results for availability are often euphemistically called reliability.

Availability, described as a percentage number, is uptime divided by total time. For continuous processing plants, total time must equal the hours in one-year (8760 hours). In most cases, availability is fairly high--from the low to mid 80%'s for 4th quartile plants and mid to high 90%'s for 1st quartile processing plants. Reliability is often inferred by consideration of mean times to failure. Reliability is sometimes calculated using time intervals of one year or the time interval between turnarounds. For most continuous processing plants, the reliability numbers are very small, i.e., the probability for having zero failures of the system for the designated time interval is very small as shown in Figure 2 for a plant with three conditions.

5) **Reliability-Driven Stage**: The maintenance strategy is a balanced integration of the previous four stages. It emphasizes elimination of breakdowns in the system which disrupt production and cause high losses from maintenance costs and loss of gross margins from the economic enterprise. The strategy is money driven. Reliability-driven maintenance considers the total and long-term cost of ownership, which requires the elimination of waste to maximize the business results through consideration of the time value of money, net preset values, and return on assets for the investors during the life of the plant.

Reliability awareness at this stage is high and the cost of failures is clearly identified as a major opportunity for improvement by working the numbers to justify improvements. Reliability of equipment is quantified and reliability of processes is quantified. As reliability is improved, failures decline, availability improves, and operations proceed smoothly without the need for squeezing the last minute from each repair job because the failures are few.

Reaching the reliability-driven maintenance stage requires considerable teamwork, which can only be accomplished by changing the culture in the organization. The reliability emphasis must be a conscious decision in everyday actions within engineering, maintenance, operations, and management. To change the culture means each group must understand the language of reliability and work in a cooperative manner for a common goal of identifying problems by money issues and establishing a work priority for quickly correcting the vital few issues. The reliability target in Figure 1 is precarious as it can easily roll from neutral stability position to lower levels of reactive stages with small losses of teamwork or other insults.

The Motivation For Improving Reliability

Enhancing reliability satisfies customers with on-time delivery of products through increased production equipment reliability and reduced warranty problems from products that fail early. Higher reliability reduces the cost for equipment failures that decrease production and limit gross profits from plants operating at maximum capacity as with commodity products and high demand proprietary products. Boosting reliability improves business performance. The clear reason for improving reliability is spelled with one word: money.

We speak of reliability, but we measure failures. Failures demonstrate evidence of lack of reliability. Reliability problems are failures, and failures cost money in an economic enterprise.

Failures in most continuous process industries are measured in downtime for the process. Similarly, failures are also cutbacks in output because cutbacks fail to achieve the desired economic results from the process or equipment.

Most people comprehend loss of reliability from equipment downtime. Fewer people can define when a cutback in output grows into a demonstrated failure. Definition of failure, which leads to a need for reliability improvements are driven by money considerations. Defining failures correctly is vital: failures galvanize organizations into action for making improvements to make more money.

Funding for reliability improvements must come from the cost of unreliability. At the heart of reliability improvements is the need to find affordable business solutions. Good reliability engineering work for business is the never-ending search for affordable improvements resulting in larger profits by cleverly solving nagging problems. Good reliability engineering is not the search for perfection but rather a search for effective business solutions to failure problems.

Reliability numbers (a value between zero and one) lack a motivation for making business improvements. However, reliability numbers spring to life when converted into monetary values expressing the cost of unreliability. Annualizing losses by means of the cost of unreliability immediately identifies for everyone the amount of money that can be spent to correct reliability problems. Clever solutions minimizing expenditures for corrections are the basis for hero awards in industry. Throwing money at reliability problems in the form of hardware and software may satisfy the angst, but does little for solving root cause(s) of problems/losses for the business enterprise. People are the largest contribution to reliability problems--see Figure 3.

Reliability requirements for businesses change because of competitive conditions and business risks. Reliability values are not fixed and immutable, but change with business conditions. Different business conditions require use of different reliability engineering tools for solving business problems.

You don't need the best reliability in the world for your business—you just need an improvement over your fiercest competitor so your business is the low cost provider. Motivations for reliability improvements are driven by the cost of unreliability, and how unreliability affects the bottom line for the business.

Reliability As An Art And Science

The world became more complicated in the late 1920s and early 1930s as demand for telephones and electron vacuum tubes grew. Higher consumer demands for these new products imposed a requirement for making them more economical and more reliable. These two demands spurred early reliability studies.

During World War II, airborne radios delivered into remote theaters of war had appalling reliability. Only ~17% of them worked upon arrival into the battle zone. War efforts also produced a new weapon of terror--the V-2 rocket. The V-2 rocket had a demonstrated reliability of 1 success out of 11 attempts for a calculated reliability of 9.1%--this was a great result for frontier technology but a terrible success rate considering the consumption of limited resources.

Robert Lussor, an electrical engineer, is generally acknowledged as the individual who first quantified reliability studies of V-1 rockets. He used principles learned from the study of electron vacuum tube reliability. His studies resulted in Werner Von Braun's redesign leading to the V-2 rocket. The V-2 rocket used the principles of redundancy to enhance the rocket's reliability. The V-2 results are written in the history books for a demonstrated reliability improvement program that resulted in the building of more than 8,000 V-2 rocket motors of which 6,300 were fired. Compare the V-2 quantities to only 44 SCUD missiles fired during the Gulf war and most people today still remember terror falling from the skies via CNN broadcasts.

The Korean War was a war of "high" technology used in large numbers—gas turbines, helicopters, miniature electron vacuum tubes, etc. US Government studies showed $2 of maintenance costs for every $1 of capital costs during the Korean War. High maintenance costs led to establishment of reliability requirements for procurement of military equipment and new military standard (MIL-STD) documents. This was a watershed event, which established an emerging technology requiring reliability for new equipment and survivability during field use.

The first textbooks were written for the emerging field of reliability during the early 1960's as a spin-off of NASA activities for manned space programs. During this period some claimed NASA could identify every rocket failure but could not correct reliability problems. This embarrassing reliability situation improved and use of reliability engineering principles quickly produced successes.

During the 1960s, '70s, and '80s applications of reliability principles were put to work. Performance improved and cost reduction programs occurred in mainframe computers, gas turbine engines, nuclear reactors, electronics, automobiles, and consumer products using principles of reliability engineering.

During the mid 1990s, continuous process industries such as petrochemical and refining began active, formal, programs to improve reliability and decrease costs. Often this occurred when old improvement techniques lacked results for a highly competitive environment. New reliability techniques were required as a paradigm shift for improvements. New reliability programs required training of professional staffs to use the new engineering techniques, which were successful in other industries. Additionally, management overview programs were launched to educate managers about reliability engineering principles to support, encourage, and facilitate training efforts for engineers (Barringer 1994).

Books on the subject of reliability engineering have exploded in sales volumes during the 1990s. The new books are an engineering oriented rebirth of earlier, highly mathematical, concepts. Most recent books use a more easily understood engineering format which discusses principles while putting statistics into a variety of software packages relying on use of personal computers to solve complicated equations. Today, reliability is perceived as having grown from a central theme of improving military projects to concentrate on commercial needs (Morris 1995).

In the late '90s, the largest number of reliability engineers in the world is concentrated in the automotive industry. Some automotive companies estimate warranty cost represents 1/3 the cost for a new automobile. This cost pressure results in reliability engineers working to reduce the cost of unreliability in the automotive industry for one reason--prevent loss of money.

ISO quality programs around the world work under the 9000-series of specifications. Quality standards for North American automotive operations are called the QS 9000-series because the standard has an added a specific reliability tool called failure modes and effects. Inclusion of this reliability tool addresses a need to ferret out reliability problems before they are built into the product.

Reliability Engineering Tools

Many concepts and practical engineering tools are available for making reliability decisions. Knowing about reliability tools is one thing, but using reliability tools for reducing the high cost of unreliability is what counts for improving plants and businesses. The improvement programs must start with a sound foundation as illustrated in Figure 4 and reliability grows as a hierarchy of events. A few reliability engineering tools are described below to illustrated the breadth of techniques now available for making business improvements:

Acquiring reliability data-Accurate failure data is required for making good reliability decisions. Many factories, chemical plants, and refineries have recorded and stored 10 to 20 years of failure data in maintenance information systems. Yet, the cry is still the same: "Where is my data for making reliability improvements?" (Barringer 1995). Most industries are sitting on the equivalent of a gold mine of data. Industry must educate and train engineers to mine the gold and recognize value in the data banks for making reliability improvements.

Often failure data is viewed as having little value. Engineers have not been trained how to handle suspensions (i.e., non-failures or failures from different failure modes currently under investigation) in the data. Failure data often cannot be plotted using conventional X-Y plots and thus statistical concepts must be borrowed to convert the scalar data into X-Y plots.

Everyone wants to reach into a competitors data bank for failures thinking the "grass is always greener on the other side"—it isn't any greener on the other side. Using plant data for quantifying failure characteristics is important because it reflects actual results of procurement practices, maintenance practices, operating practices, and life cycle actions in real world conditions.

Plant failure data is valuable for projecting paradigm shifts using new facts for improvements. Fresh data is acquired accurately and analyzed rigorously when organizations observe that failure data is actually used for decisions. Failure reporting and corrective actions systems (FRACAS) are considered an early and important element for initiating improvements by acquiring reliability data correctly and using it in a closed loop system for improvements.

Reactive organizations lack data and have little interest in failure data. Preventive organizations begin to use data for making decisions. Predictive organizations acquire data in huge quantities, Proactive organizations know how to analyze the failure data. Reliability-driven organizations know how to use the data to make money.

Reliability indices-Reliability data can be converted into uncomplicated, figure-of-merit, performance indices. Consider these indices as coarsely divided meter-sticks and not as precision micrometers.

One simple, arithmetic concept, is very useful for “getting a grip” on reliability by using mean times to/between failure. MTBF or MTTF is often found arithmetically from the summation of ages to failure divided by the number of failures—this is a simple, gross indicator of reliability as shown in Figure 5 for MTTF on pumps.

Reliability is observed when mean time to failure (MTTF) for non-repairable items or mean time between failure (MTBF) for repairable items is long compared to the mission time. Likewise, small values for mean time indices, compared to the mission time, reflect unreliability.

Reciprocals of MTBF or MTTF provide failure rates, which are commonly displayed in tables for reliability data. Mean time indices are understandable by engineers but failure rates are usually better for making calculations.

Accuracy of these simple indices are improved when large numbers of data are screened using well know statistical tools. When only a small volume of data is available the data is best analyzed using Weibull analysis techniques to arrive at MTBF or MTTF values.

It is important to understand the data taxonomy (The classification of data in an ordered system that indicates natural relationships.) and the indices derived from analysis. This avoids confusion and everyone talking about different facets of the same problem but using confusing facts. Consider the facts from Figure 6 concerning taxonomy.

For the same equipment, the MTBF can be different depending upon the grade of installation and the grade of operation. This situation is emphasized in Figure 7 showing different conditions for a centrifugal pump.

Reactive organizations do not calculate MTBF/MTTF because they lack data. Preventive organizations usually know MTBF/MTTF for rotating equipment. Predictive organizations use MTBF/MTTF for their assessment programs, Proactive organizations know MTBF/MTTF for both rotating and non-rotating equipment and they're excited about the opportunities for reducing failure costs for non-rotating equipment. Reliability-driven organizations use the MTBF/MTTF data for knowledgeable acquisition of new equipment to eliminate old, nagging problems so they can make more money.

Decision trees-Decision trees are useful for merging the probability values for success and failure with financial results to arrive at the expected monetary result. Decision trees are good tools for assessing failure uncertainty in accounting terms.

Decision trees are helpful for engineers and accountants to find a common ground for discussing mutual problems. Problems for engineers involve chances for failure, and problems for accountants involve expected monetary results from an outcome of events. This tool provides in a win-win situation for factual discussion of a business event to arrive at decisions, which are helpful for the business by both engineering and accounting. See Figure 8 for an example of decision trees.

Without a mechanism such as decision trees, engineers and accountants consider problems as having deterministic answers rather than probabilistic answers. Unfortunately, discussions about decision trees can become one-sided as accountants have received some training in the use of decision trees but few engineers have been involved in their use. Using decision trees for reliability efforts provides engineers with a business growth opportunity and facts about how much money can be spent for making reliability improvements.

Reactive organizations don't know about the tool called decision trees. Preventive organizations have heard about the tool. Predictive organizations are beginning to use decision trees. Proactive organizations use the tool occasionally for making equipment decisions. Reliability-driven organizations know how to use the tool to make money.

Availability concepts, effectiveness equation and costs-Availability values are commonly discussed in engineering circles as the ratio of up-time to total time available. Higher values are good and lower values are inferior. Unfortunately, many capital equipment decisions are made on availability values without regard for other criteria such as where, what, and how much is best place for investments in a plant equipment.

A better criterion is the effectiveness equation, which is seldom discussed. The effectiveness equation is the product of reliability, availability, maintainability, and production capability. Each properly defined measure in the effectiveness equation has values between 0 and 1. The effectiveness equation is useful for pointing out opportunities for improvement and is much more useful than simply discussing a single availability index. Refer to Figure 9 for examples from several plants,

One direct measure of reliability, which is understandable to everyone, is the cost of unreliability measured in money values as shown in Figure 10 for a plant with several logical blocks. The cost of unreliability is used less frequently than other values cited above. The cost of unreliability has the best opportunity of causing decisive action than use of reliability values between 0 and 1. Everyone understands and acts on money issues. The cost of unreliability galvanizes both engineers and business people into action for a common goal in ways not available with simple indices. Merging cost of unreliability with availability and effectiveness is important because businesses are run for making money. Money measures are the best common denominator for measuring reliability in industry.

Reactive organizations can not use the tools because they're busy fixing equipment and thus are not interested. Preventive organizations begin to use the availability concepts as an index. Predictive organizations begin to think about the reliability portion of the equation. Proactive organizations know how to use the availability, reliability, and maintainability portions of the effectiveness equation. Reliability-driven organizations know how to use effectiveness equations and life cycle costs to make financial decisions.

Probability plots-The chaos of failure data can be converted into straight-line plots of time-to-failure against cumulative chances for the failure. Most engineers need graphical representation of data to fully understand problems. Without graphs, the scatter in the data often overwhelms engineers and they lack good, graphical tools for plotting data because X-Y facts are not available with only age to failure values. The concept is simple: no graph means no comprehension of the failure data.--thus probability plots give engineers straight lines to relate age to failure as the percentage of products that will fail.

Probability plots are well known to statisticians and other technically skilled personnel in the field of biology and medicine. Probability tools are growing in importance in the field of reliability with software (Fulton 1998a) which runs on personal computers, which generate the curves with ease as shown in Figure 11 for pump seals.

Weibull probability charts are the tool of choice for reliability work, because Weibull probability charts often tell about failure modes (how components die, i.e., infant mortality, chance failures, or wear out failure modes). Of course once important information about failure modes is identified, then strategies are set for guiding root cause analysis to solve the true cause of failures rather than wasting time and money working on symptoms of failures (Abernethy 1998).

Weibull charts are particularly valuable for pointing the noses of engineers in the correct direction for finding root causes of problems even with a few data points as Weibull plots provide evidence for root cause analysis. Larger quantities of data add confidence to the decision making process, but at considerable greater expense for acquiring both failures and data. The motivation for using probability charts is to understand failure data and reduce costly failures by appropriate corrective actions.

Recently, Weibull plots have been used to study processes to identify the reliability of processes using the daily production numbers. The plots have been helpful for showing whether the problems are related to production or to maintenance. Also the plots show the demonstrated capacity of the process and when consideration is given to the scatter from controlled processes, the Weibull plots are helpful for identifying the name plate capacity of the process. Refer to Figure 12 for a production process.

Reactive organizations see no need for probability plots because the lack data. Preventive organizations can perceive the need for finding failure modes to make their preventive action more effective. Predictive organizations want to know the failure modes and chances for failure at a given time. Proactive organizations use them for both failure information and optimizing cost. Reliability-driven organizations use probability plots for condensing their failure details for use in constructing reliability models to engineer the availability and reliability of their plants.

Bathtub curves-These simple, highly idealized curves reflect birth problems, chance failures during the useful life phase, and death problems for a population of components or assemblies. Seldom does a curve exist for specific devices because generous amounts of specific failure data are lacking. The value of bathtub curves lies in understanding concepts behind different failure rates and the "medicine" required for corrective action. An example of a bathtub curve is shown in Figure 13.

Bathtub curves described by (Moubray 1997) and (Smith 1993) describe how failure rates are portrayed in graphs to aid decisions for reducing costs. The most often cited use of these concepts concerns how United Airlines analyzed their failure data in the late 1960s to change maintenance strategies which resulted in holding maintenance cost almost constant for 10 years during an inflationary period. This feat was accomplished by applying the correct reliability-centered maintenance (RCM) "medicine" to appropriate age-reliability patterns for aircraft equipment.

The thrust of RCM effort is to avoid wasting money by doing valueless work. Bathtub curves promote RCM objectives by using reliability engineering tools and principles. RCM objectives are to:

- Preserve system function (the emphasis is on systems and not the individual components or subsystems),
- Understand how loss of system function is connected to the failure by identifying specific failure modes,
- Prioritize the importance of failure modes to allocated budgets and resources to the vital few important items, and
- Apply preventive maintenance (PM) efforts to prevent or mitigate failure, detect onset of a failure, or discovering hidden failures so that PM effort is cost effective.

Reactive organizations think bathtub concepts apply to personal hygiene (bathing) and therefore see no need for the concept. Preventive organizations have difficulty with the infant mortality failure modes and the strategy of run to failure as being most cost effective. Predictive organizations use the facts to search for correct replacement intervals and know when to go on alert for pending problems. Proactive organizations use bathtub concepts to know you must have three different strategies at work to respond to different failure modes. Reliability-driven organizations think bathtub concepts are a way of life for making maintenance decisions.

Pareto distributions and critical items lists-The simplest and most effective reliability tool is the Pareto distribution using costs. Working on and correcting the vital few problems that give the largest financial gain are critical to business results. Separate the vital few problems from the trivial many problems by ranking the financial impacts of problems (not nose counts of incidents as often preferred by engineers). Then work only on vital problems. When the major problems have been solved, then the smaller problems will come to the surface for solving.

Pareto distributions for reliability focus problem solving efforts only on key problems which offer the greatest improvement potential driven by a ranking of the cost of unreliability. In short, 10-20% of the items on the list will account for 60-80% of the financial impact. These few items offer the greatest opportunity for a continuous improvement process. The visual format of the ranked cost of unreliability (again, not nose counts of problem occurrences) focuses attention on solving the largest problem first and reserves the "nits and lice" problems to last place because of their lack of bottom line financial impact. See Figure 14 for a Pareto ranking example.

Pareto lists of the cost of unreliability must include parts, labor, expense, <u>and</u> the value of gross margin lost by the business as a result of the unreliability. Unreliability costs must include gross margin losses when the plant is "sold out", and exclude gross margins when the plant has idle capacity and is "under sold". This puts the cost of unreliability into its proper financial perspective. Lack of including appropriate business costs in the cost of unreliability causes many engineers to make the wrong decision in promoting improvement projects and justifying equipment for solving business problems.

Of course communicating improvement programs to management is very important for any reliability improvement program. Communicate only the vital few items on the Pareto distributions to keep management apprised for their support by using routine progress reports and lists of critical items. This requires publication of a critical item list and frequent updates as problems are corrected. Critical items are failures or potential failures, which significantly affect safety, operating successes, or cause large repair or replacement costs.

Management teams are overwhelmed by too much trivial information on pet projects. Management needs to know the vital few problems are being addressed with solutions for accomplishments and not merely engineering activity. Critical item lists provide details about the vital few problems along with plans for solving vital problems, and details of before/after results. The critical item list is effort directed at managing your manger by simplifying the continuous improvement list.

Reactive organizations are busy responding to the squeaky wheel and everything is priority number one so they work considerable amounts of overtime to attack the multitude of problems. Preventive organizations prioritize on nose counts of problems. Predictive organizations combine both nose counts of problems and cost priorities to set work priorities. Proactive organizations use cost Pareto distributions to set their work priorities. Reliability-driven organizations use Pareto cost distributions and equipment histories to plan for reducing the long term cost of ownership by solving problems when they acquire new equipment or engage in modernization/turnaround decisions.

Reliability block diagrams-Every plant has equipment and processes failures resulting in a domino effect of more problems. Drawing appropriate process/equipment blocks to identify key elements for which failure data exists is an important event. Reliability block diagrams reduce system complexity into simplified models for studying problems and gaining insight into means of economic improvements. Refer to Figure 15 for a series model and Figure 16 for a parallel model.

Frequently the best block diagram is also the simplest block, and requires drawing a single block around the entire plant because this addresses the practical definition for failure. Clearly catastrophic failures, which are frequently step functions, get reported accurately. However problems of slow deterioration to a point that is considered failure are seldom reported correctly. Slow deterioration in production is called a cutback. Assignable causes for cutback failures should be listed and age to failures recorded along with the cost of unreliability for the problem causing the slow deterioration.

Beginning with the single large block, reliability block diagrams can be made more complicated (and more realistic) by drawing smaller and smaller blocks to describe failures. Of course this can be carried to the extreme with block diagrams for each component. In this manner, the entire process and equipment list can be studied for reengineering considerations based on justifiable reductions in the cost of unreliability.

Reliability models realistically assess plant conditions when both actual failure rates and predominate failure modes are included in the calculation process by use of fault tree analysis. When combined with costs, repair times, and chance events of Monte Carlo simulations, models are very helpful for demonstrating operating conditions experienced in a plant. Good simulation models help determine maintenance strategies and turnaround timing for equipment renewal.

Monte Carlo computer simulation models are usually based on simple, heuristic rules. Heuristic rules are based on observed behavior of components or systems. Heuristic rules are easy to construct using knowledge based computer systems although they cannot anticipate all potential failure events.

The heartbeat of reliability models is to stimulate creative ideas for solving costly problems and to prevent replication of the same old problems because "we've always done things this way". Reliability models offer a scientific method for studying actions, responses, and costs in the virtual laboratory of the computer using actual failure data from existing plants. Models provide a way to search for lowest cost operating conditions by predicting the outcome of conditions, events, and equipment.

Reactive organizations see no value in block diagrams -- they "know" their problems. Preventive organizations will listen to the concepts and await success stories from other in their industry. Predictive organizations use the models to forecast the number of failures to expect each year to help organize their budgeting activities. Proactive organizations use model to make decisions about current and future plans to reduce costs. Reliability-driven organizations use models as a routing tool to identify competitive opportunities for improving their operations to reduce costs and avoid failures.

Failure modes effect and fault tree analysis-Failure modes effect analysis (FMEA) is an analysis tool for evaluating reliability by examining expected failure modes to find the effects of failure on equipment or systems so that problems can be eliminated.

FMEA is an inductive tool that starts at the bottom level of a system and works its way upward to the top levels. FMEA searches for potential failures and how failures will effect the overall system. FMEA is helpful for finding small failures that cascade to large problems, areas where fail safe or fail soft devices/methods are needed, secondary failure events, and single point failures that cause catastrophic failures. Simple FMEA studies can be enhanced by use of criticality analysis to reach FMECA status with more details on the chances for a costly problem to occur.

Fault tree analysis (FTA) is a deductive reliability analysis tool for evaluating reliability driven by top level views of what will fail and searches for root causes of the top-level event. FTA considers experience and biases such as "every time we build a plant for this product we have these types of failures—".

FTA provides both reliability assessments and fault probability perspectives. FTA helps look for the likelihood of an undesired event occurring and the combined effects of simultaneous non-critical events on top level problems. Fault trees are more limited in scope and easier to understand than FMEA. The issue is to define the top-level failure event and work down the fault tree to find reasons for failures and then prevent the root cause from occurring.

FMEA and FTA can be used qualitatively or quantitatively. Also they can be used together to reduce the overall study cost and produce answers quickly when both cost and time budgets are tightly constrained. FMEA and FTA tools are best used during the design and configuration stages of a project when changes for improvements can best be made with the change of a pencil (or a CAD drawing). Production personnel should request using these tools at the design review stage of projects.

Reactive organizations think any other tool added to their work list will over burden them and thus they are not interested. Preventive organizations like both tools and find the results from FMEA is particularly agreeable to the hourly workforce because they know the details and training time is short to get the FMEA process started. Predictive organizations combine both tools to identify where the problems may occur so they can predict the type of failure and they like both tools because they find what item many fail so they can prepare the planned work priorities. Proactive organizations use the results of FME and FTA to set their work priorities based on the cost consequences. Reliability-driven organizations use FMEA and FTA as a requirement for procurement of new equipment and to anticipate the results of equipment rebuilds and improvements as a way to minimize their expenditures for low long term cost of ownership.

Design reviews-Assessing reliability of projects during design phase reviews requires a critical look at equipment details to determine if reliability has been built into the design for meeting performance goals required by the project. Design reviews for reliability require many different disciplines to view the assessments at the three typical milestones:

1) Initial design,
2) Completion of development (pilot plant) testing, and
3) Preparation of drawings including process flow drawings.

Key design review questions look for cost effective answers to:

1) Where will failures occur and at what frequency,
2) Have we engineered maintenance staffs, turnaround renewal staffs, and
3) Will we achieve the project long-term life costs for the project?

If computed facts and figures are available from a design review, then reliability tools are being wisely used. If answers are based on rules-of-thumb that maintenance costs will be ~4-5% of installed capital, etc., then you have evidence of old problems once again replicated.

Reactive organizations have little need for design reviews because few new tasks are performed. Preventive organizations need the details to establish strategies for preventing expected failures. Predictive organizations want the details to estimate the time of failures to set work priorities. Proactive organizations use design reviews to make corrections before equipment is delivered. Reliability-driven organizations use design reviews to study cost alternatives to verify they are on the road to the lowest long term cost of ownership as it's easier to make changes at the time of specification than when bricks and mortar are in place.

Vendor and parts control-Supplier partnerships are bringing a refreshing view for controlling quality and grade of equipment and eliminating failures. Users and suppliers with strong commitments to partnership agreements follow a rocky road during the first two to three years of the relationship. Fortunately rocky roads are leading toward a mutual benefit—like two, young, newly-weds working out their agreements for their mutual benefits.

Net result of partnership agreements have shown:

- Fewer numbers of equipment models are being used with mutual effort to solve the old nagging problems,
- Factual discussions are underway concerning failure modes and efforts to build robustness into products (from the supplier), and
- Improvements are occurring in operating practices (from the end-user), which avoid destruction of good equipment.

Two other growth phases are needed to achieve good vendor control and good parts control to improve reliability:

- Users must supply vendors with failure data and root causes for failures as these facts are not available to suppliers at a reasonable cost, and
- Much equipment must either be de-rated to achieve reliability or higher-grade equipment must be initially selected to achieve greater inherent reliability without adding numerous spares.

A few good vendors with reliable equipment are preferred to many vendors with unreliable equipment. Both users and suppliers must increase their fundamental understanding of reliability issues to reach a cost-effective balance that results in the lowest long-term cost of ownership.

Equipment users must also use reliability qualification tests (RQT) to demonstrate or measure the reliability of equipment. User must specify reliability needed for equipment, and equipment suppliers must know their equipment capability. In general, both parties in most industries have a wide gap, which is bridged by salesmanship on one side and preferential awarding of contracts on the other side. Both issues can be solved by partnership agreements for mutual advantages.

Reactive organizations find partnerships offensive because they can buy equipment cheaper from outside sources than from a partnership. Preventive organizations like the use of supplier partnerships because combined efforts are producing fewer failures by the preventive actions of both sides of the partnership. Predictive organizations get equipment with known failure rates and known failure modes which makes failure prediction easier and more effective. Proactive organizations use their expertise with the suppliers to reengineers and redesign troublesome equipment based on facts from the field to make the equipment better. Reliability-driven organizations use facts from the failure data and models of the equipment to predict improvements and to know how much the improvements are worth at time of procurement by evaluating the long-term cost of ownership.

Thermal analysis (TA)-An important influence on product reliability is temperature. Increasing, equipment in all production facilities is migrating toward electronic devices, which are highly susceptible to increased failure rates at elevated temperatures. The Arrhenius equation is an excellent tool for scaling failure rates starting with values given in electronic reference books.

Specifications for equipment need to address both high- and low-temperatures along with a formal analysis for assessing how equipment capabilities will meet required conditions. Don't overlook increased failure rates of equipment operating continuously at high temperatures. Many companies are enamored with how well new electronic devices work in test environments. The rush to more electronic devices will place more devices in an accelerated aging failure mode.

Reactive organizations operate with fans on hot electrical systems--they don't have time to fix the root of the problem. Preventive organizations set up schedules to change out the components on a schedule. Predictive organizations measure and monitor the conditions to forecast the failures. Proactive organizations get to the root of thermal problems and institute cost effective solutions to prevent failures. Reliability-driven organizations use thermal analysis to avoid problems as part of their plan for purchasing equipment that has low failures rates with long-term low cost of ownership.

Environmental stress screening (ESS)-Four strong stress actors substantially influence planning for ESS:

- thermal cycling,
- vibrations,
- corrosion, and
- number of stress cycles.

These strong stresses are accompanied by many lesser conditions, which reduce reliability—particularly, when strong stresses are accompanied by interaction influences of lesser stresses. Each industry and plant have unique stress conditions to be examined.

Experience now shows many processing plant outages are caused by non-rotating equipment. Non-rotating equipment reliability problems have always existed but were hidden by larger outages from rotating equipment—now most rotating equipment losses have been solved. Many plant outages today are clearly due to insufficient ESS testing for the four strong stresses destroying plant reliability. It is now times to maintain basic rotating equipment programs and start new programs for improving reliability by emphasizing ESS tests.

Few specific conditions can be given for the corrective action of ESS problems because each case is different. One situation is clear—it's time to seriously regard ESS problems as a primary source of downtime and equipment outages in most continuous process industries. Solutions for ESS problems will not be simple or inexpensive and risk based inspection concepts are appropriate for understanding where work is appropriate.

Reactive organizations expect failures will occur from ESS and respond as good fire fighters. Preventive organizations set up the schedules to change out components on a schedule. Predictive organizations measure and monitor the conditions to forecast the failures from the main effects of ESS. Proactive organizations get to the root of ESS problems and institute cost effective solutions to prevent failures from the main effects and the interaction influences. Reliability-driven organizations use ESS to avoid problems as part of their plan for purchasing equipment that has low failures rates with long-term low cost of ownership by understanding the stress conditions and taking into account the trade-offs for buying better equipment to avoid failures..

Crow/AMSAA reliability growth models-Failure data is used to build simple log-log plots for the purpose of predicting future failures and identifying if failure trends are improving or deteriorating. Stable processes produce straight lines and quickly show trends to answer the basic question: Are we getting better or are we getting worse? Fortunately, software is available to make these answers easier (Fulton 1998b) as shown in Figure 17.

Most equipment needs growth in MTTF, which occurs through the continuous improvement effort. Reliability growth usually occurs from many minor, low costs, improvements. Growth curves are usually log-log curves of cumulative MTBF or cumulative failures versus cumulative time. Log-log plots using cumulative data usually returns a straight line, which easily shows deviations (either good or bad results) from the trend line. Figure 18 shows a plot of a cumulative MTBF versus cumulative time distribution and MTBF is climbing.

Crow/AMSAA models are particularly useful when the failures include mixed failure modes. They overcome a limitation of Weibull probability plots by allowing mixed failure modes.

Most organizations will verbalize they are making improvements--even when they aren't. The Crow/AMSAA plots are verification of claims based on facts. When the growth curve format is used for cumulative failures, it is easy to forecast the time interval until the next failure will occur. This alone is a good reason for predicting maintenance budgets for breakdown events and making plans to minimize losses. As with all forecasts, they will be in error—the question is how much error.

Goals can be set for reliability improvements and management can monitor the results with one glance at a chart. Individuals, or one single department, seldom make big breakthroughs for reliability, and a team effort is most frequently required. Reliability growth curves shows progress of the improvement team and concentrating on correcting the vital few problems gives rapid growth curves when producing the largest results. Generally improvements follow the typical test (or operate), analyze, and fix (TAAF) methodology

Reactive organizations haven't heard of Crow/AMSSA models and see no need for them. Preventive organizations like the concept of knowing when failure will occur so they can prevent the failure. Predictive organizations recognize the opportunities for predicting when failures will occur so they are prepared for the pending failure. Proactive organizations use cost Crow/AMSAA models to anticipate, redirect the work initiatives to prevent problems. Reliability-driven organizations use Crow/AMSAA models to show where they would have been without the improvements and to use the models to predict the cost gains they will make from the life cycle cost decisions using long term cost of ownership criteria.

Reliability policies-The objective of a reliability policy is to prevent unreliability problems early in the formative stage by channeling corporate efforts to make things happen according to a plan rather than reacting to events. Policy statements signed and implemented by leaders of organizations are in a state of development today. Reliability policies are evolutionary progressions from other documents within a company, which are driven by economics and common sense. Reliability policies must fit into and support other corporate policies for quality, safety, risk assessment, and financial returns. Reliability policies must address life-time-costs of potential actions in the use of equipment and processes for manufacturing of the company's products.

Reliability policy development is at the same point safety policies were 50 years ago or 40 years ago for quality policies, and 10 years ago for environmental policies. Reliability policy is simply a money issue worthy of corporate communication effort. The responsibility for reliability policies lies clearly with top management to display leadership and set reliability policy as a serious effort for making cost improvements in both equipment and processes. This effort is required to breakdown the walls that exist and to erase the view that production breaks things and the job of maintenance is to fix them. Policies are needed to achieve the teamwork effort for controlling our cost of unreliability.

When reliability policies are in place, then reliability audits (similar to financial and quality audits) are possible. Reliability audits ask--Is the organization doing things right to make improvements, and have problems, conflicts, and errors been reduced? The main objective of a reliability audit is demonstration of continuous improvement by reducing the cost of unreliability. Management has the responsibility for both policy and audits.

Reactive organizations see no value in reliability policies as they represent long range issues when dealing in a short-term environment. Preventive organizations like reliability policies because they support concepts of preventing failures. Predictive organizations recognize the value of reliability policies as they provide guidance for their actions. Proactive organizations use policies as being in concert with their long-term issues. Reliability-driven organizations use policies as a guiding light for all their actions directed toward trade-offs for the long-term cost of ownership criteria.

Benchmarking reliability-Benchmarking finds and studies the best world-class organizations with reliability standards.

A recent reliability benchmarking study (Criscimagna 1995) shows the following list of important reliability tasks performed by companies in their benchmark study:

Tool Used	% Companies Involved
FRACS	88.3
Design Review	83.8
Sub/Vendor Control	72.1
Parts Control	71.2
RQT	70.3
FMEA/FMECA	68.5
Predictions	62.2
TAAF	59.5
Thermal Analysis	58.6
ESS	54.1

Benchmark studies allow adjustments to internal systems to meet or exceed the best standards found by the benchmark. Often benchmark studies are based on consultants collecting data from a variety of sources and assembling the data into statistics so that plants under study have a goal to meet or exceed. Each plant must assess local conditions to determine which benchmarked reliability tools are appropriate for use.

Reactive organizations find see benchmarks amusing as they find not applicability to their operations and they have little or nothing to offer in response. Preventive and predictive organizations search for holes to fill with new reliability techniques for their activities. Proactive organizations use these benchmarks to validate their actions match best practices. Reliability-driven organizations look at the details of benchmarking as "been there and done that" and we're moving on to other refinements directed at improved long-term cost of ownership.

Summary

We talk about reliability but we deal with failures, which add to the cost of doing business. Businesses cannot afford too little reliability because of high failure costs or too much reliability because of high capital costs. The cost of unreliability must be engineered and controlled.

Many new reliability tools are available for use. Many new books on the subject are available. Staffs must be trained in the use of new tools to gain a competitive advantage for businesses willing to invest in increasing skills to reduce costs. Reliability in many ways is a "pay me now or pay me later situation". Reliability tools provide a new focus on old problems and offer new tools to attack business problems.

Reliability improvement programs generally start from a need for improvement because of too many failures and high costs. Evolution occurs in the programs as the organization matures and grows to appreciate the improvements of fewer failures and lower costs. When the hierarchy of needs has been satisfied to keep the plant running, then longer-term issues begin to predominate and achieving a low long-term cost of ownership is important.

Cutting edge companies are using these new tools cost effectively. Can your business wait to gain an advantage?

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BIOGRAPHIC INFORMATION-

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Manufacturing, engineering, and reliability consultant and author of the basic reliability training course **Reliability Engineering Principles**. More than thirty-five years of engineering and manufacturing experience in design, production, quality, maintenance, and reliability of technical products. Contributor to **The New Weibull Handbook**, a reliability engineering text published by Dr. Robert B. Abernethy. Named as inventor in six U.S.A. Patents. Registered Professional Engineer in Texas. Education includes a MS and BS in Mechanical Engineering from North Carolina State University, and participated in Harvard University's three week Manufacturing Strategy conference. Visit the world wide web site at **http://www.barringer1.com** for other background details or send e-mail to **hpaul@barringer1.com** concerning LCC or reliability issues.

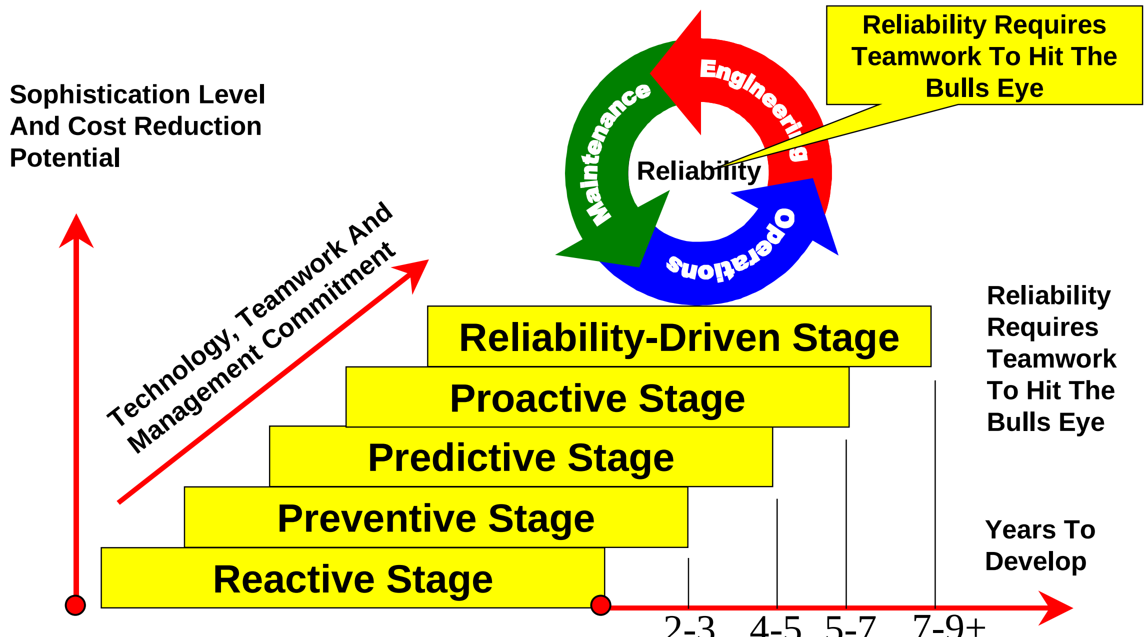


Figure 1: Reliability Program Development Stages

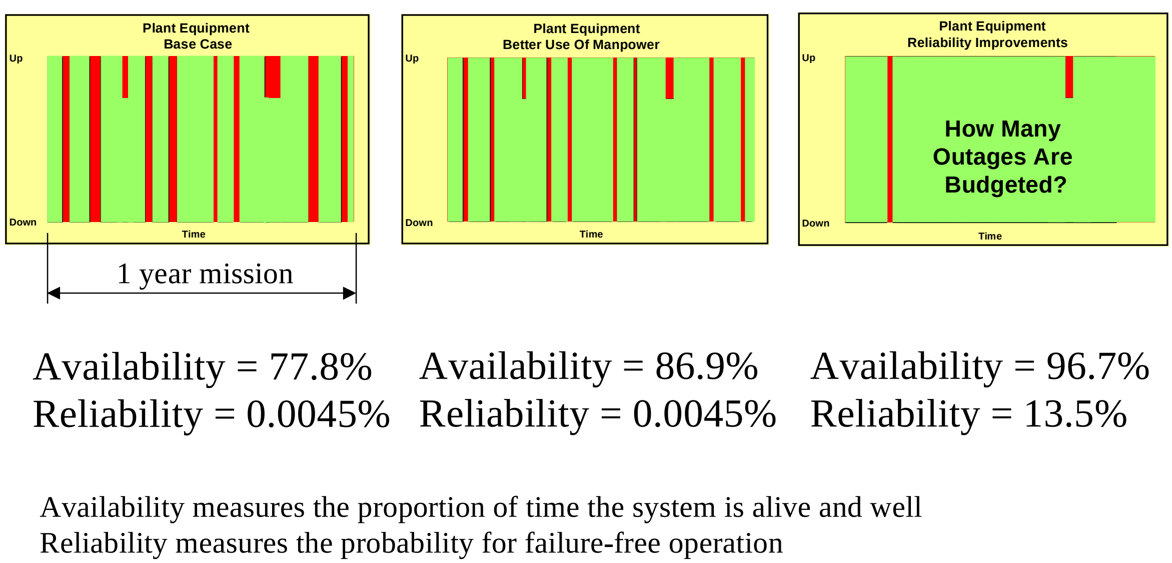


Figure 2: Plant Availability And Reliability For Three Different Conditions

Early Plant Life	Frequency %
• Design Error	**35**
• Fabrication Error	1
• Random Component Failure	18
• Operator Error	12
• Procedure Error & Unknowns	10
• Maintenance Error	12
• Unknown	12
	100

Mature Plants	
• People	**38**
• Procedures + Processes	34
• Equipment	28
	100

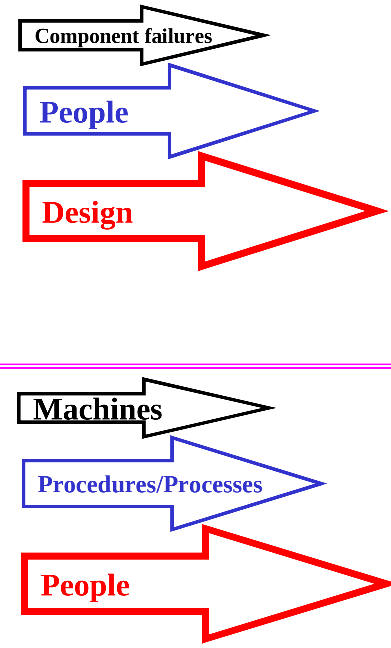


Figure 3: People And Their Contribution To Reliability Problems

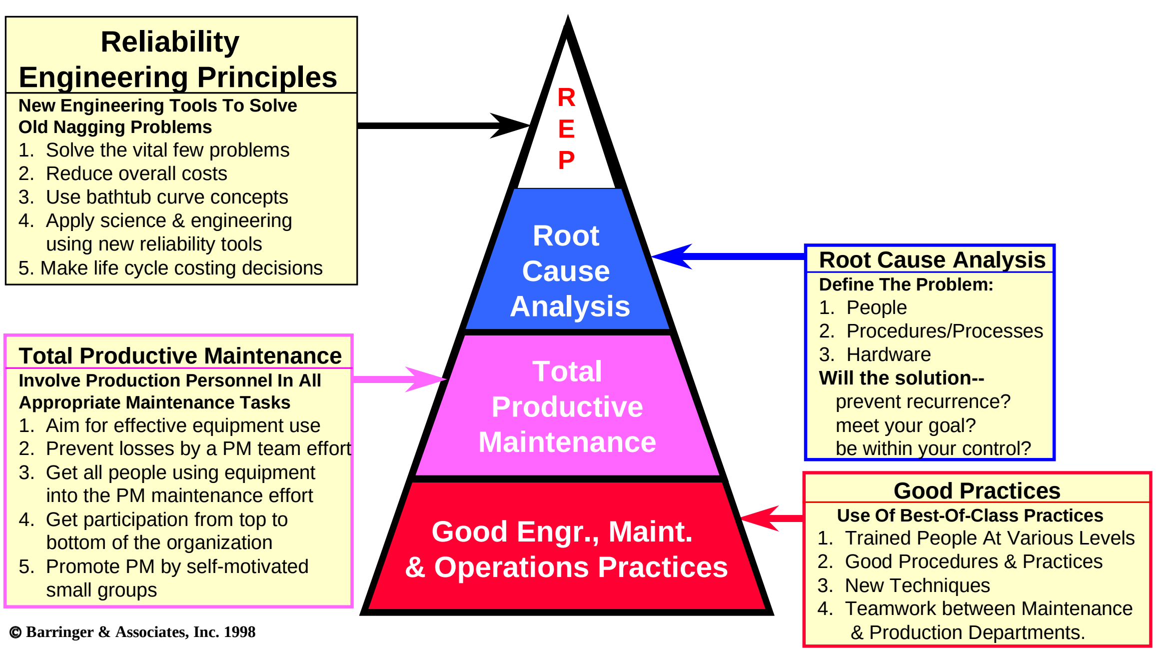


Figure 4: Reliability Heirachy

$$\text{MTBF \& MTTF} = \frac{\Sigma \text{ life}}{\Sigma \text{ failures}}$$

This MTTF data from production, maintenance, and purchasing records

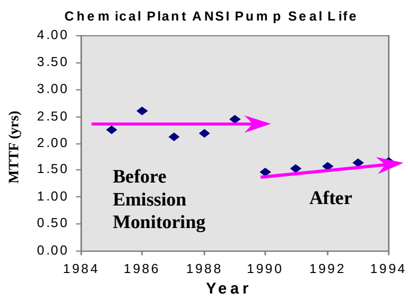
Remember: MTTF is a meter-stick—not a micrometer!!

Chemical Plant ANSI Pump Life

Year	Number Of Unspared Pumps	Number Of Spared Pumps	Total Hours Of Pump Operation	Number Of Seal Failures	Seal MTTF (yrs)	Seal Failure Rate (fail/hr)	Conditions
1985	937	2996	21,330,000	1083	2.25	50.8E-6	No
1986	943	2996	21,380,000	937	2.60	43.8E-6	Emission
1987	950	2998	21,450,000	1156	2.12	53.9E-6	Monitoring
1988	950	3008	21,500,000	1127	2.18	52.4E-6	
1989	953	3012	21,540,000	1003	2.45	46.6E-6	
1990	955	3028	21,630,000	1689	1.46	78.1E-6	
1991	957	3036	21,680,000	1628	1.52	75.1E-6	
1992	963	3048	21,790,000	1581	1.57	72.6E-6	
1993	955	3038	21,670,000	1517	1.63	70.0E-6	Emission
1994	951	3026	21,580,000	1487	1.66	68.9E-6	Monitoring

Refinery API Pump Life

Year	Number Of Unspared Pumps	Number Of Spared Pumps	Total Hours Of Pump Operation	Number Of Seal Failures	Seal MTTF (yrs)	Seal Failure Rate (fail/hr)	Conditions
1985	313	1542	9,500,000	415	2.61	43.7E-6	No
1986	313	1542	9,500,000	398	2.72	41.9E-6	Emission
1987	313	1548	9,520,000	380	2.86	39.9E-6	Monitoring
1988	310	1560	9,550,000	361	3.02	37.8E-6	
1989	305	1580	9,590,000	343	3.19	35.8E-6	
1990	295	1580	9,500,000	535	2.03	56.3E-6	
1991	290	1590	9,500,000	481	2.25	50.6E-6	
1992	280	1598	9,450,000	403	2.68	42.6E-6	
1993	270	1602	9,380,000	354	3.02	37.7E-6	Emission
1994	265	1610	9,370,000	278	3.85	29.7E-6	Monitoring



Note: Assume spared pumps run one-half of the time for determining the number of operating hours.

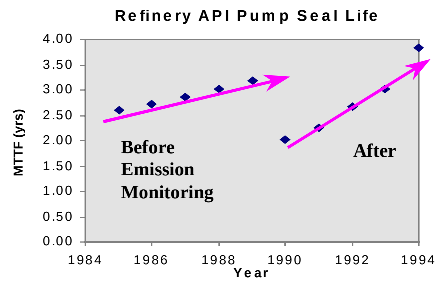


Figure 5: MTTF As Gross Indicator For Reliability

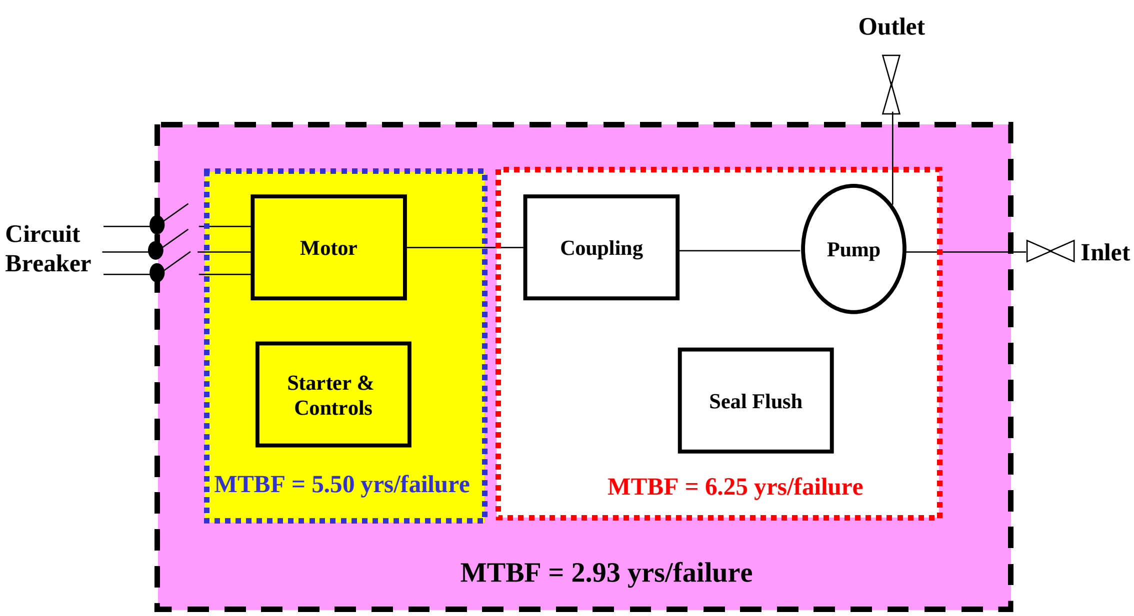


Figure 6: Taxonomy And MTBF Issues

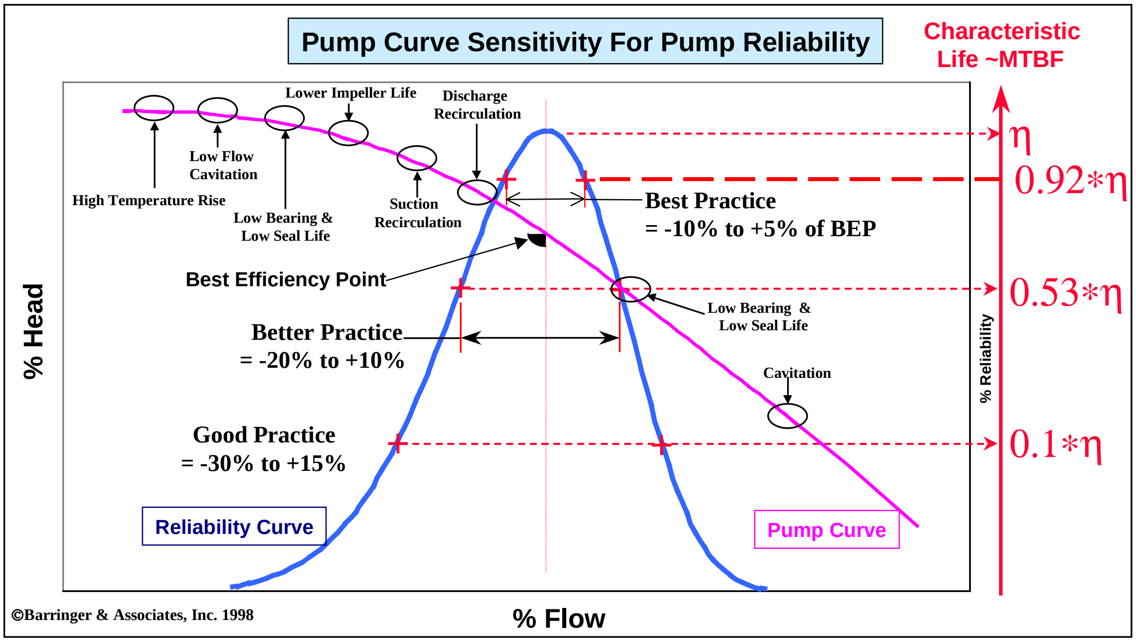
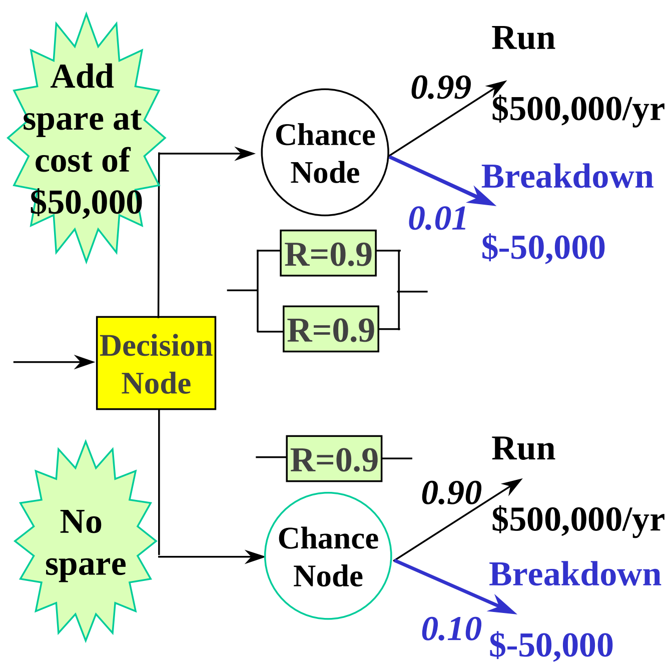


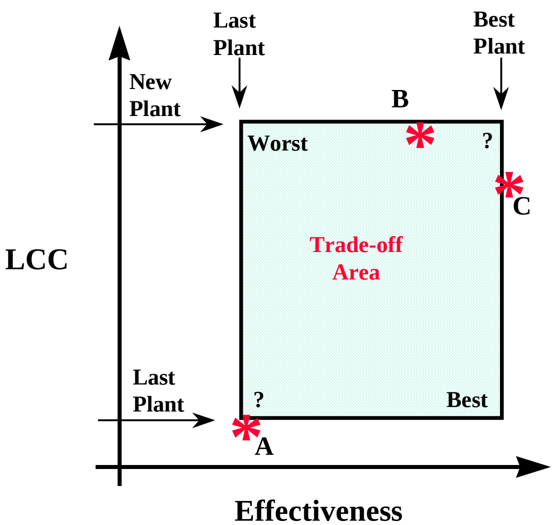
Figure 7: Installation/Use Practices and Effects On Life For Centrifugal Pumps



Equipment reliabilities are shown for a one year mission interval even though the plant will operate 20 years.

To spare or not to spare, that is the question.

Figure 8: Decision Tree--To Spare Or Not To Spare?



Parameter	A Last Plant	B New Plant	C Best Plant
Availability	0.95	0.95	0.98
Reliability	0.3	0.4	0.6
Maintainability	0.7	0.7	0.7
Capability	0.7	0.8	0.6
Effectiveness	0.14	0.22	0.25
LCC	80	100	95

Figure 9: Effectiveness & Costs For Several Plants

Cost Of Unreliability Block Diagram Of Plant

	A	B	C	Summary	
MTBF	43,800	8,760	17,520	5,153	hrs/fail.
Corrective Time/Fail.	18	24	83	40.6	hrs/fail
Losses: Lost Time	3.6	24	41.5	69.1	hrs/yr
Gross Margin Lost	$36,000	$240,000	$415,000	$691,000	(1) $/yr
Scrap Disposal $'s	$1,000	$5,000	$2,500	$8,500	$/yr
Breakdown Maint. $'s	$18,000	$120,000	$207,500	$345,500	(2) $/yr
Total	$55,000	$365,000 (2)	$625,000 (1)	$1,045,000 *Cost Of Unreliabilty:*	$/yr

Figure 10: Cost Of Unreliabilty For A Plant

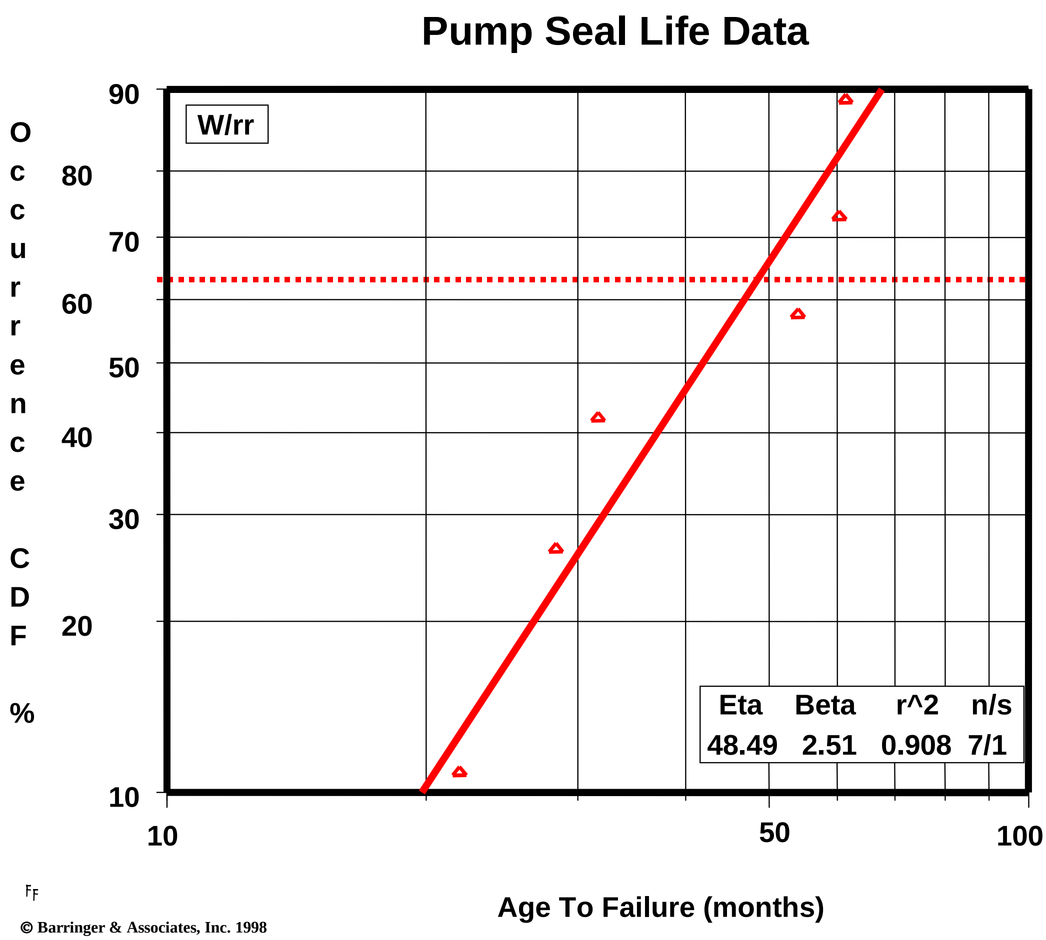


Figure 11: Weibull Plot Of Pump Seal Failures

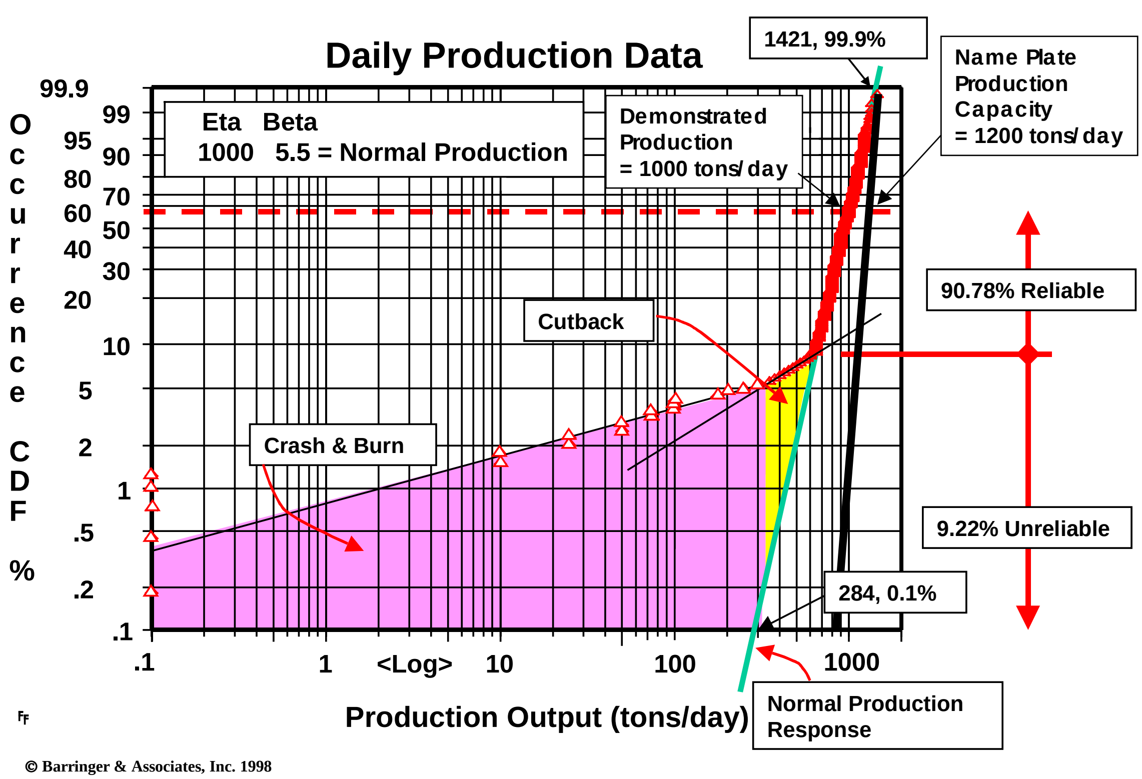


Figure 12: Weibull Plot For Process Reliability

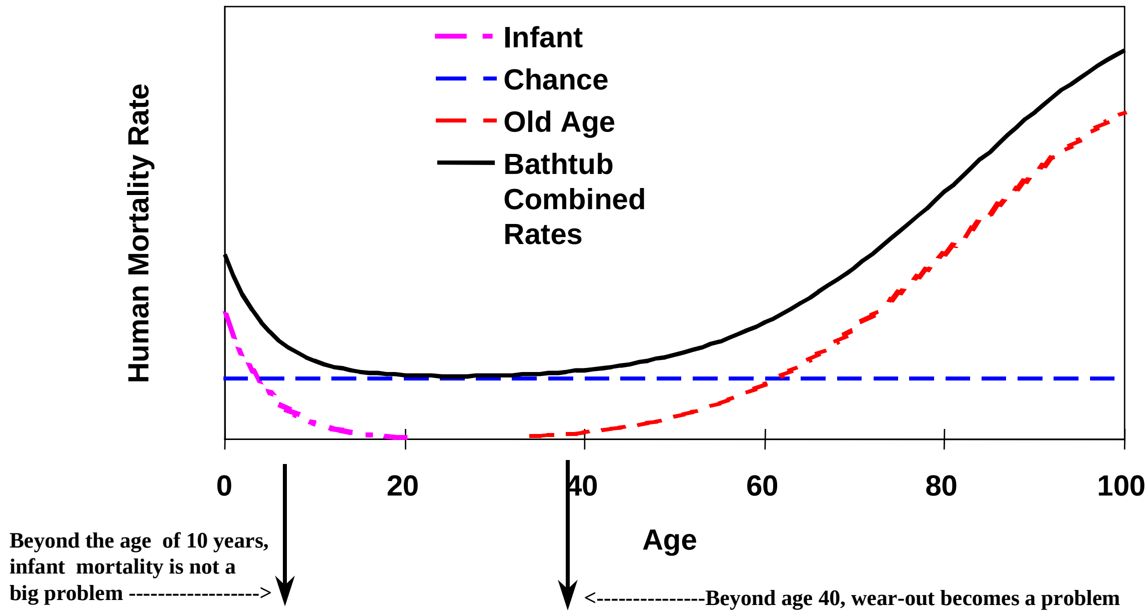


Figure 13: Human Bathtub Curve

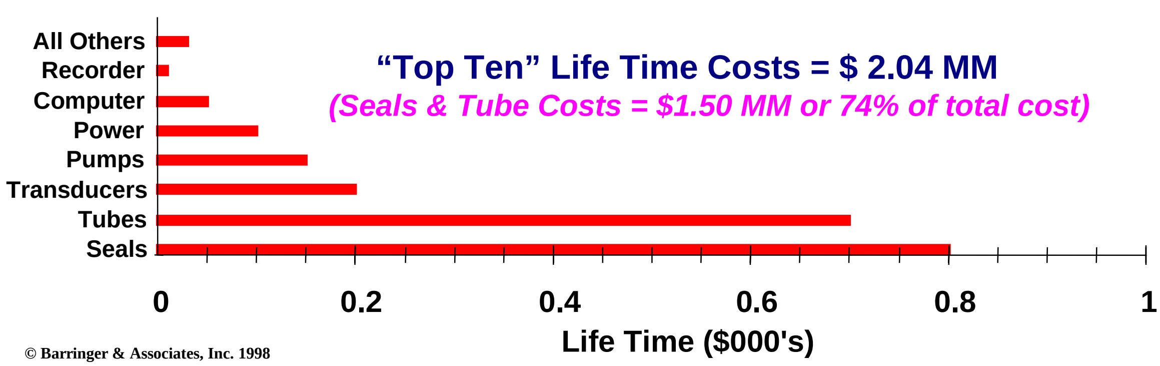


Figure 14: Pareto Distribution Of Costs

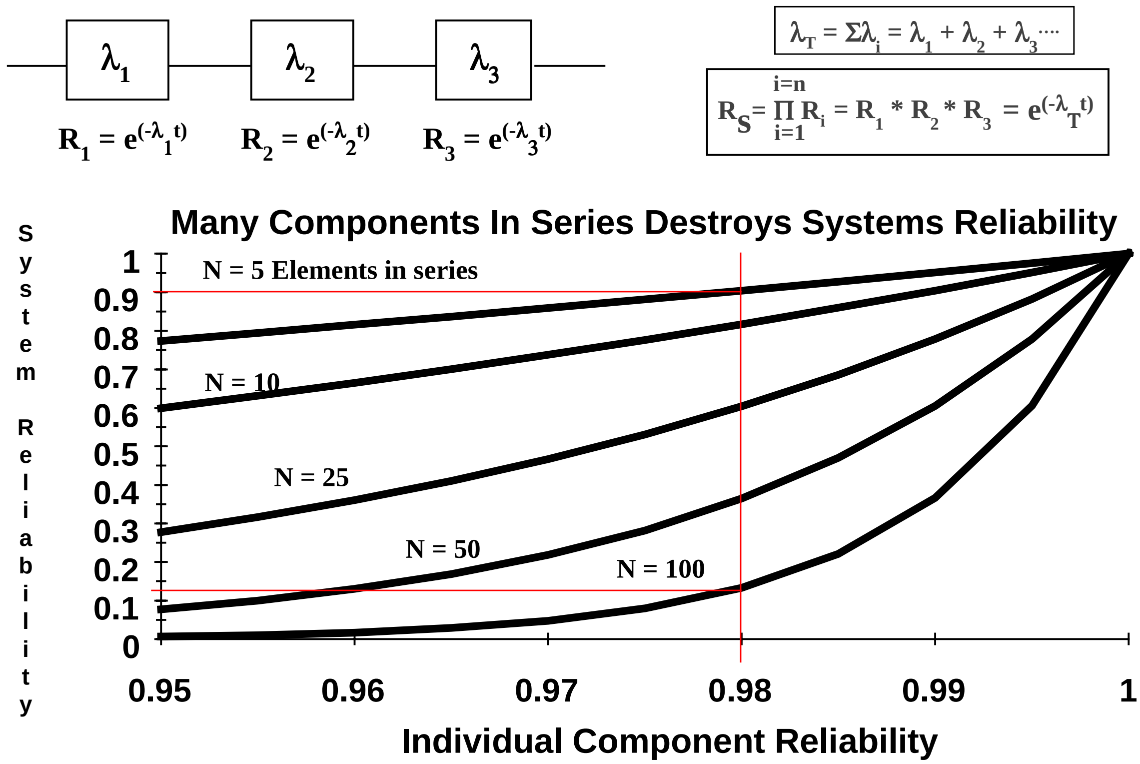


Figure 15: Results Of Series Reliability Models

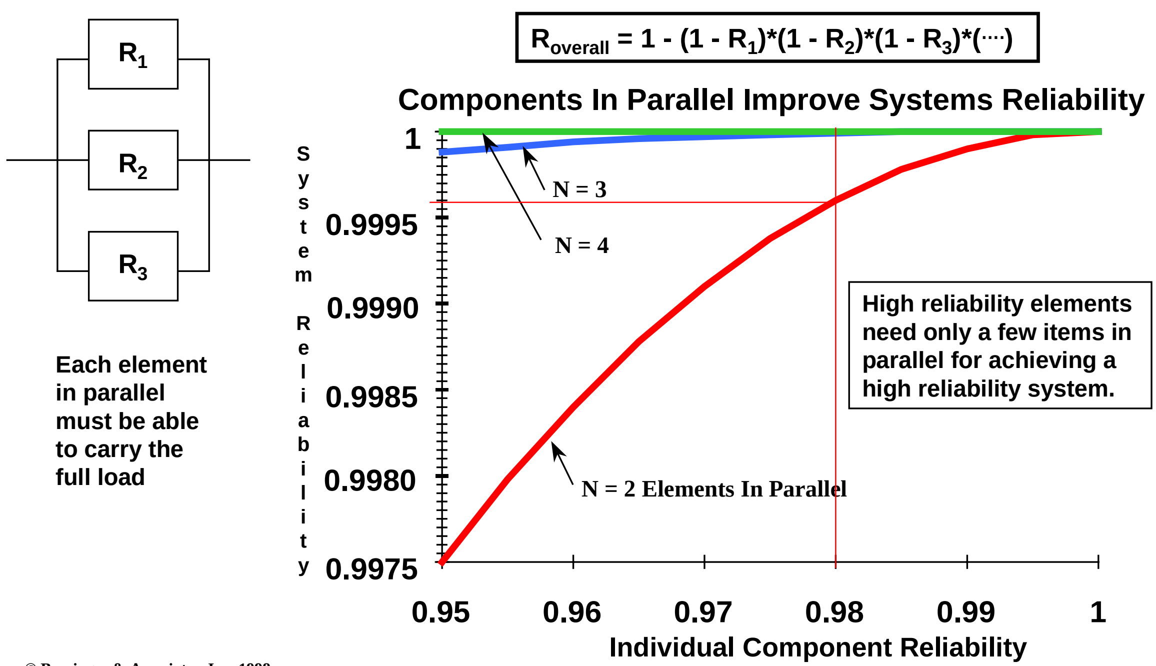
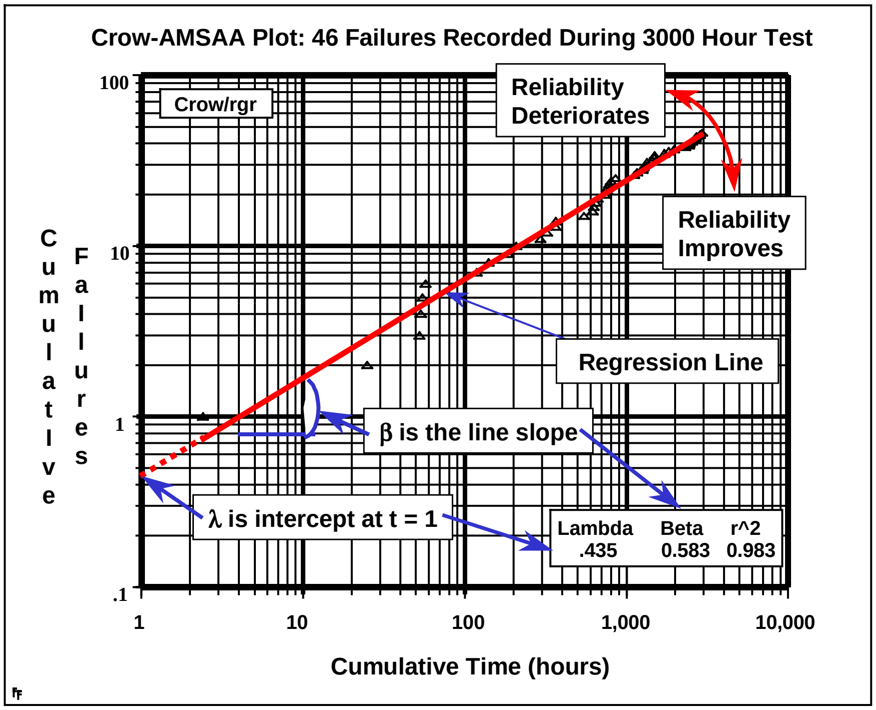


Figure 16: Results Of Parallel Reliability Models



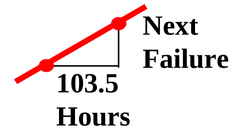


Figure 17: Crow/AMSA Plot Of Cumulative Failures

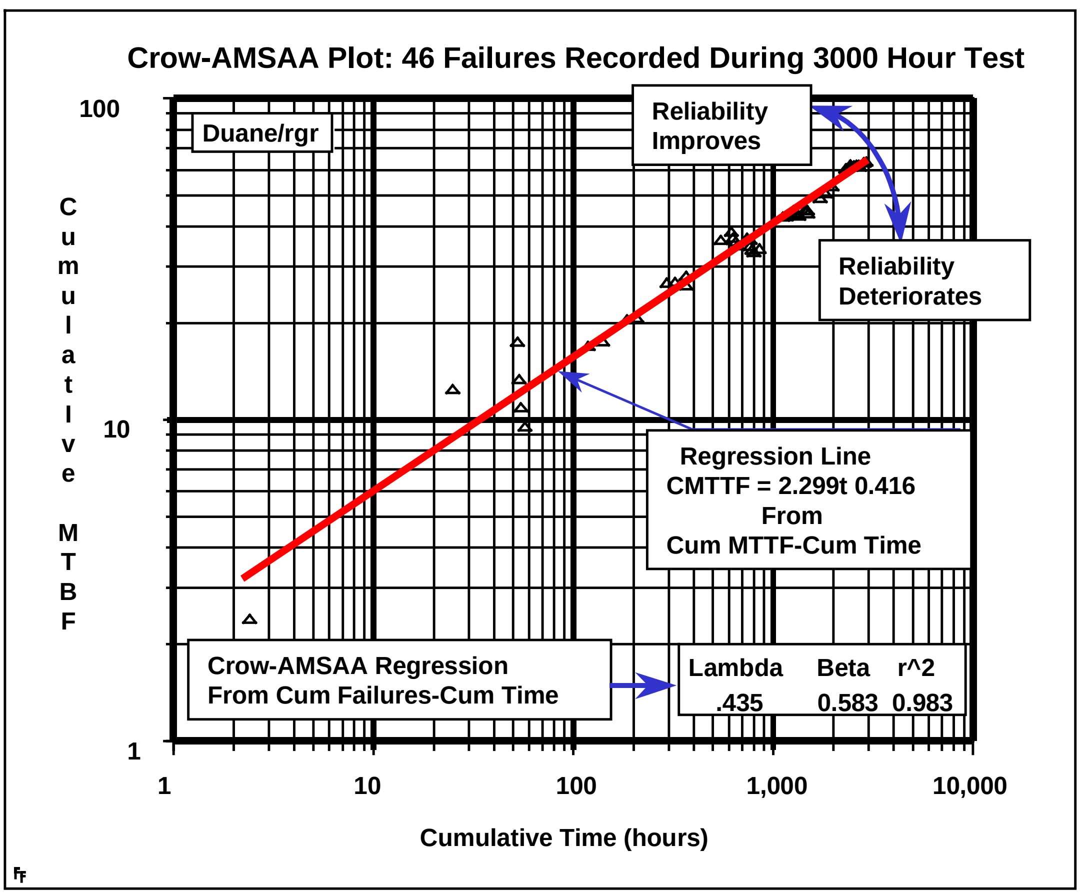


Figure 18: Cum MTBF vs Cum Time