An Overview Of Reliability Engineering Principles

H. Paul Barringer, P.E.
Barringer & Associates, Inc.
P. O. Box 3985
Humble, TX 77347-3985

Phone: 281-852-6810
FAX: 281-852-3749

ENERGY WEEK 1996
Organizing Sponsors: API and ASME

Organized by
PennWell Conferences & Exhibitions
Houston, TX
January 29 - February 2, 1996

An Overview Of Reliability Engineering Principles

H. Paul Barringer, P.E., Barringer & Associates, Inc., P.O. Box 3985, Humble, TX 77347, Phone: 713-852-6810, FAX: 713-852-3749

Abstract

Reliability is the probability of equipment or processes to function without failure when operated correctly for a given interval of time under stated conditions. Equipment and processes failures waste money on unreliability problems. The business issue of reliability is control of failures to reduce costs and improve operations by enhancing business performance with affordable levels of reliability. Reliability numbers by themselves lack motivation for improvements. However, converting unreliability into monetary values, causes numbers to spring to life and guides actions for making cost effective changes, by using actual plant data for costs and failures. Reliability engineering tools are discussed which assist plant improvement programs for reducing the high cost of unreliability.

Reliability Definitions

Reliability has many definitions. For things that cannot be repaired: Reliability is the duration or probability of failure-free performance under stated conditions. For things that can be repaired: Reliability is the probability that an item can perform its intended function for a specified interval under stated conditions. For those who wish simplicity, a single word definition is: dependability.

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, cutbacks in output are also failures 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, is a vital: failures galvanize organizations into action for making improvements.

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 is 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.

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 telephones and electron vacuum tubes grew in demand. Higher demands for these new products required making them more economically and improving their reliability. These two new technologies 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-1 rocket. The V-1 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 8000 V-2 rocket motors.

The Korean War was a war of new 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 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 text books 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 higher 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 reliability engineering principles.

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 (Barringer 1993). 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 early to mid 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).

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. A few reliability engineering tools are described below to illustrated the breadth of techniques now available:

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 in the data (i.e., non-failures or failures from different failure modes currently under investigation) and failure data often cannot be plotted using conventional 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. For these reasons, plant failure data is extremely valuable for projecting paradigm shifts using new criteria 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.

Reliability indices-Reliability data can be converted into uncomplicated, figure-of-merit, performance indices. Consider these indices as yardsticks and not as micrometers. One simple, arithmetic concept, is very useful for "getting a grip" on reliability by using mean times to/between failure derived from the summation of ages to failure divided by the number of failures—this is a simple, gross indicator of reliability.

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.

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 results in a win-win situation for factual discussion of a business event to arrive a decisions which are helpful for the business by both engineering and accounting.

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.

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 criteria 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.

One direct measure of reliability which is understandable to everyone is the cost of unreliability measured in currency. 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 seems to understand and act 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.

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, engineers are often overwhelmed by the scatter in the data and they lack good, graphical tools for plotting data because X-Y facts are not available with only age to failure values.

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 the use of personal computers which generate the curves with ease (Fulton 1995a). 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 wearout 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 1993).

Weibull charts are particularly valuable for pointing noses in the correct direction for finding root causes of problems even with a few data points. 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.

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 is lacking. The value of bathtub curves lies in understanding concepts behind different failure rates and the "medicine" required for corrective action.

Bathtub curves described by (Moubray 1992) and (Smith 1993) describe how a variety of failure rates are portrayed in graphs to aid in 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 right reliability-centered maintenance (RCM) "medicine" to the appropriate age-reliability patterns for aircraft equipment.

The thrust of RCM effort is to avoid wasting money in doing work without value. Bathtub curves promote RCM objectives by using reliability engineering tools and principles. RCM objectives are to: 1) preserve system function, 2) understand how the loss of system function is connected to the failure by specific failure modes, 3) prioritize the importance of failure modes to allocated budgets and resources to the vital few important items, and 4) 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.

Pareto distributions and critical items lists-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 by ranking the financial impacts of problems (not the nose counts of incidents as is often preferred by engineers) and then work only on vital problems.

Pareto distributions for reliability focus problem solving efforts on key problems offering the greatest potential for improvements using 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 (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.

Pareto lists of the cost of unreliability must include parts, labor, expense, and 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 critical items lists. This requires maintenance and publication of a critical items list. 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 items lists provide details about the vital few problems along with plans for solving vital problems, and details of before/after results. The critical items list is effort directed at managing your manger by simplifying the continuous improvement list.

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.

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 near actual 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.

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. 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 FMEAs.

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.

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: of 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) have we predicted with confidence where our failures will occur and with what frequency, 2) have we engineered maintenance staffs, turnaround renewal staffs, and will costs meet the project criteria. 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.

Vendor and parts control-Supplier partnerships are bringing a refreshing view for controlling quality and grade of equipment. 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: 1) fewer numbers of equipment models are being used with mutual effort to solve the old nagging problems, 2) factual discussions are underway concerning failure modes and efforts to build robustness into products (from the supplier), and 3) improvements are occurring in operating practices (from the end user) which avoids destruction of good equipment.

Two other growth phases are needed to achieve good vendor control and good parts control to improve reliability: 1) users must supply vendors with failure data and root causes for failures because the facts are not available to the suppliers at a reasonable cost, and 2) much equipment must either be derated 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 far better than numerous 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.

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.

Environmental stress screening (ESS)-Four strong stress actors substantially influence planning for ESS: 1) thermal cycling, 2) vibrations, 3) corrosion, and 4) 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 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 time 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.

Reliability growth monitoring-Most equipment needs growth in MTTF which occurs through the continuous improvement effort. Reliability growth usually occurs from many minor, low cost, improvements. Growth curves are usually log-log curves of cumulative MTBF or cumulative failures versus cumulative time. Log-log plots are used because the cumulative data usually returns a straight line which easily shows deviations (either good or bad results) from the trend line.

Goals can be set for reliability improvements and management can monitor the results with one glance at a chart. Seldom does one individual or one single department 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.

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. Fortunately, software is available to make these answers easier (Fulton 1995b).

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, 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.

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
FMEA/FMECA	68.5
RQT	70.3
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.

Summary

We talk about reliability but we deal with failures which add to the cost of doing business. Businesses cannot afford too little reliability nor too much reliability. 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". Cutting edge companies are using these new tools cost effectively. Can your business wait to gain an advantage?

References

Abernethy, Dr. Robert B., 1993, **The New Weibull Handbook**, Self published, North Palm Beach, FL, Phone: 407-842-4082.

Barringer, H. Paul, 1993, **Reliability Engineering Principles**, Self published, Humble, TX, Phone: 713-852-6810.

Barringer, H. Paul, 1994, **Management Overview: Reliability Engineering Principles**, Self published, Humble, TX, Phone: 713-852-6810.

Barringer, H. Paul, and Weber, David P., 1995, “Where Is My Data For Making Reliability Improvements”, *Hydrocarbons Processing Magazine 4th International Reliability Conference*, Houston, TX, November 15-17, 1995.

Criscimagna, Ned H., 1995, **Benchmarking Commercial Reliability Practices**, Reliability Analysis Center, Rome, NY.

Fulton, Wes, 1995a, **WeibullSMITH™** DOS version 6.2 and **WinSMITH™** version 1.0 for Windows 3.1 and Windows 95, Fulton Findings, Torrance, CA, Phone: 310-548-6358.

Fulton, Wes, 1995b, **VisualSMITH™** version 2.2, Fulton Findings, Torrance, CA, Phone: 310-548-6358.

Morris, Seymour and Nicholls, David, et. al., 1995, **Reliability Toolkit: Commercial Practices Editions-A Practical Guide for Commercial Products and Military Systems Under Acquisition Reform**, Reliability Analysis Center, Rome NY.

Moubray, John, 1992, **Reliability-centered Maintenance**, Industrial Press, New York, Pages 12, 217.

Smith, Anthony M., 1993, **Reliability-Centered Maintenance**, McGraw-Hill, New York, Pages 36, 44.