APPLIED RISK AND RELIABILITY FOR TURBOMACHINERY

PART I—RELIABILITY PROCESSES

by
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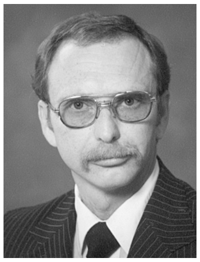

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ABSTRACT

There are several methods of analysis to define the reliability of the critical rotating equipment at various facilities within a company. Part I of this tutorial is intended to present several of these methods. The following Part II presents the calculations.

INTRODUCTION

In the mid 1980s, the author's supervisor gave him an "opportunity" to better define the critical machinery reliability as turnarounds were extended. The task was to develop an equation that would produce a number to be used as a guide such that the plant management would have a feeling as to the risk for postponing the next olefin unit turnaround or minimizing the amount of inspection performed on the major rotating equipment, e.g., minor or major overhaul(s). Based on the critical machinery on the history, design, vibration, and process conditions he developed a weighted number that he tried to use as an indicator to justify the overhaul requirements. At the time, this was not accepted well by the plant management because other facilities in the company had longer/shorter shutdown intervals as well as published reports of other companies in the same commodity chemical industry and the "Solomon" report that was published every two years did not agree with his conclusions derived from this number. During this period of time there were two methods:

- Kepner-Tregoe's® Problem Solving and Decision Making
- Managerial Analytics, a Monsanto Chemical Company event analysis system

In later years several other methods of potential problem and/or root cause analysis—hazard and operability analysis (HAZOP), Federal Emergency Management Agency (FEMA), failure mode effect and criticality analysis (FMECA), event-tree analysis (ETA), Delphi, method organization for a systematic analysis of risks (MOSAR), management oversight risk tree (MORT), Weibull Analysis, and Six Sigma—have been developed to aid in quantifying the risk of extending the operational time of the critical turbomachinery.

KEPNER-TREGOE®

Kepner-Tregoe® Problem Solving and Decision Making (PSDM) is a step-by-step process that helps people resolve business. Used in organizations worldwide, PSDM helps individuals, groups, and/or teams efficiently organize and analyze vast amounts of information and take the appropriate action.

This process provides a framework for problem solving and decision making that can be integrated into standard operating procedures. It is used to enhance other operational improvement tools such as Six Sigma, Lean Manufacturing, and others.

PSDM comprises four distinct processes:

- *Situation Appraisal* is used to separate, clarify, and prioritize concerns. When confusion is mounting, the correct approach is unclear, or priorities overwhelm plans, Situation Appraisal can be used.
- *Problem Analysis* is used to find the cause of a positive or negative deviation. When people, machinery, systems, or processes are not performing as expected, Problem Analysis points to the relevant information and leads the way to the root cause.
- *Decision Analysis* is used for making a choice; it is intended to clarify the purpose and balances risks and benefits to arrive at a supported choice.
- *Potential Problem/Opportunity Analysis* is used to protect and leverage actions or plans. Potential Problem Analysis should define the driving factors and identifies ways to lower risk. When one action is taken, new opportunities, good or bad, may arise. These opportunities must be recognized and acted on to maximize the benefits and minimize the risks.

MANAGERIAL ANALYTICS

Managerial Analytics (MA) is an analytical identification process developed by the Monsanto Company. Managing change and using change to manage requires the use of some combination of the five basic analytical processes.

- *Event Analysis* is a systematic process to identify events and events of change that impact the reliability of the turbomachinery. Events and events of change from the past and present have an impact on the present and future reliability. Events of change could be the stopping of wash oil injection or the rising of the sodium concentration in the steam or not repairing the spare rotor.

Step 1. First person responsibility
Step 2. Recognize events and their relationships
Step 3. Establish priority
Step 4. Separate and sequence components

Step 5. Identify intended nominal first person results
Step 6. Identify resolution resources, threats, and opportunities
Step 7. Identify intended nominal first person action
Step 8. Select the analytical processes
Step 9. Statement for the first analysis

- *Deviation Analysis* is a process to help determine the unknown cause of an observed effect deviating from a standard effect in order to decide on action. This is used for both positive and negative deviations and in other words events of change that have happened.

Step 1. Statement of the deviation effect
Step 2. Deviation effect specifications
Step 3. Unique characteristics of the "involved" dimensions
Step 4. Change events
Step 5. Possible causes
Step 6. Test possible causes
Step 7. Set priority on possible causes
Step 8. Verification of cause

- *Action Analysis* is used to select a single course of action from several courses of action. This is based on the projected performance of the action to attain a set of desired effects and assessing the impacts of and to that action if it were taken.

Step 1. Statement of the intended nominal action
Step 2. Set the desired effects
Step 3. Classify the desired effects
Step 4. Weight the want effects
Step 5. Generate action alternatives
Step 6. Filter the action alternatives through "must" effects
Step 7. Score action alternatives to the "wanted" effects
Step 8. Impact evaluation
    Step a. Identify an action alternative
    Step b. Identify impacts
    Step c. Identify potential deviations
    Step d. Assess impacts on the environment
    Step e. Summarize potential deviations and their likely causes
    Step f. Plan actions to manage likely causes
    Step g. Plan actions to manage potential deviations
Step 9. Make best balanced selection

- *Action Planning* helps to decide "What will be done?", "Who will do it?", and "When it will be done" to reach one or more desired future effects that are not expected to occur unless something is done. It involves a set of interrelated and interdependent actions.

Step 1. Define the action required
Step 2. Define person(s) who have the prime responsibility to complete the required action
Step 3. Define support resources
Step 4. Define the date and time to initiate the action
Step 5. Define the projected time of completion of the action

- *Potential Deviation Analysis* is a process used to examine a planned action or a future event of change for significant impacts and deviations, and to plan additional actions to manage these results.

Section 1. Statement of the intended nominal action
Section 2. Identification of potential deviations
    Step a. Identify a planned action
    Step b. Identify impacts
    Step c. Identify potential deviations
    Step d. Assess impacts to the environment
    Step e. Summarize potential deviations and their likely causes
Section 3. Action planning for potential deviations
    Step a. Plan actions to manage likely cause
    Step b. Plan action to manage potential deviation
    Step c. Revise the action plan

ROOT CAUSE ANALYSIS (RCA)

Define the Problem

Cause and Effect

There are five elements of a cause and effect chart.

1. Primary effect:
    a. A singular effect of consequence that we wish to eliminate or mitigate
    b. The "what" in the problem definition
    c. It is always the most present cause in the analysis and frequently the most significant.
    d. It is the point at which we begin to ask "why."

2. Actions and condition causes:
    a. They are both causes, actions are momentary and conditions exist over time.
    b. Actions can become conditions and conditions can become actions.
    c. Actions and conditions interact to create effect.

3. Casual connection caused by:
    a. Forces that cause going from present to past.
    b. Elicits a more specific response
    c. Minimizes storytelling
    d. If a cause "connects" it adds to the visual dialogue and therefore has value.

4. Evidence is the data that supports a conclusion and is presented as:
    a. Sensed—It is processed through our senses of sight, sound, smell, taste, and touch. Sensed is the highest quality evidence.
    b. Inferred—The ability to infer is derived from our understanding of known and repeated casual relationships. Inference is the next highest quality of evidence.
    c. Evidence is important because:
        i. It supports the reality of any single cause.
        ii. Solutions should only be applied to evidence-based causes.
        iii. It minimizes the influence of politics and power plays.

5. "Stop" or a "?"

Problem Definition

There are four elements of problem definition.

1. What—What is the problem?
2. When—When did it happen?
3. Where—Where did it happen?
4. Significance—Why are we working on this?

Identify Effective Solutions

The root cause is not what we seek, it is effective solutions.

1. Challenge each cause.
2. Offer possible solutions for each cause.

Implement the Best Solutions

1. Prevents recurrences
    a. Prevents or mitigates this problem
    b. Prevents similar problems
    c. Does not create additional problems or unacceptable situations

2. Within your control
    a. Your control may be you, your department, your company, your suppliers, or your customers.
    b. Nature is not within your control.
    c. The facilitator is rarely the problem owner.

3. Meets your goals and objectives
    a. The goals of the overall organization
    b. The goals of your department or group

c. Your individual goals and objectives
d. Must provide reasonable value

RELIABILITY ASSESSMENT OF ROTATING EQUIPMENT

Reliability assessment of rotating equipment (RARE) is one tool of an overall maintenance and turnaround strategy of critical rotating equipment.

Origin of Initial Program and Concept

The Hartford Steam Boiler Inspection & Insurance Company (HSB) expected the companies they insured to follow the steam turbine overhaul intervals recommended by the original equipment manufacturer (OEM). Due to world market pressure and technological advancements companies began extending the intervals between major unit turnarounds. These companies depended on the expertise of their rotating equipment engineers to help define how long they could reliably operate between turnarounds. Their goal was to lengthen the interval between major overhaul outages to coincide with the need for other inspections and testing mandated by government agencies or process needs. During the 70s and 80s the chemical, petrochemical, and refining industries would perform a major overhaul of their critical machinery every four to six years as a standard practice. As operating companies extended their turnaround intervals HSB became concerned about the increased risk their customers were taking. At this point in time, data showing the effects or risks of stretching run times between overhauls were not available. HSB decided to develop a program that would quantify these risks for their customers. M&M Engineering, a part of the HSB company at that time, was given the assignment to develop a tool to assess the reliability of steam turbines. The tool is called Steam Turbine Reliability Assessment Program (STRAP). HSB did not plan to use this program to structure premiums. The vision was to require a STRAP analysis whenever a company chose to run longer than the OEM recommended practice. If STRAP showed that they were at low risk then HSB would authorize or accept the company's plans, but if STRAP showed the company to have a high risk they were told that they needed to implement some risk reduction procedures or improvements to mitigate some of these risks.

Consortium of Companies

With this vision, M&M Engineering pulled together a group of recognized industry experts in the turbomachinery field. The experts brought with them their individual company's reliability assessment techniques, industry standards (API, ASME, etc.), recognized industry best practices, new technologies, and most important their personal experience.

Starting with a blank sheet of paper the group spent countless hours defining, developing, categorizing, and weighing questions and responses. The caveat for this group was when completed they would take this program back to their respective companies and use it as another tool to justify turbine improvements that would improve reliability and extend run lengths, which then resulted in a significant savings of money.

The turbine data accumulated, which consisted of original design specifications, history, uprates, upgrades, failures, and site specific information, were then entered into the program developed by M&M Engineering. The algorithms in the program took the weighted turbine data and generated a risk index number (RIN). The RIN is the number of days that the turbine will be down, during the run extension. It is based on statistical information that is calculated from the data contained in the database for the same general type of turbine. The program gives 25 specific items to be addressed and calculates a return on the investment (ROI) using site pricing data. Armed with this information the rotating equipment engineer and managers can make informed decisions to accept the projected risk or to take corrective actions to minimize or mitigate the risks that were defined. Like home and car insurance, risk can never be eliminated but most risks can be minimized, then it becomes a decision on what level of risk the plant/company is willing to accept. With this information long-term shutdown strategy can be developed that is based on the operation, maintenance, and reliability practices of the unit.

STEAM TURBINE RISK ASSESSMENT PROGRAM

1. General Information Data Sheet
    a. Plant specifics?
    b. Size or class of the turbine (five categories)?
    c. Age of the turbine?
    d. Manufacturer of the turbine?
    e. What is the turbine driving?
    f. When the turbine was last dismantled?
    g. Etc.?
2. Turbine Performance (Design and Actual)
    a. Horsepower?
    b. Speed?
    c. Inlet flow?
    d. Temperature?
    e. Pressure?
    f. Etc.?
3. Site and Utility Data
    a. Location?
    b. Steam generation?
    c. Etc.?
4. Construction Features
    a. Type of turbine?
    b. Critical speed?
    c. Control system?
    d. Etc.?
5. Spares
    a. Complete turbines?
    b. Bearing sets?
    c. Complete rotor sets?
    d. Stationary diaphragms?
    e. Case?
    f. Nozzles blocks?
    g. Where are they stored?
    h. Couplings?
    i. Labyrinth seal sets?
    j. Control valve parts/governor valve assemblies?
    k. How many days are required to prepare the rotor for installation?
    l. Is there a periodic inspection for signs of corrosion on the spare parts?
6. Maintenance and Repairs
    a. How many hours to the repair shop?
    b. How often do you drain water from the oil reservoir?
    c. Do you drain it at startup?
    d. Turbine overhauls?
    e. Are there documented detailed overhaul procedures for this/similar turbines?
    f. How is the lube oil system cleaned during overhauls?
    g. Qualifications?
    h. Foundation inspection?
    i. Alignment?
    j. Inspections?
    k. Oil systems?
7. Turbine Operation
    a. Procedures?
        i. Do the plant's written steam turbine operating procedures include:
            (1) Prestartup checklist?
            (2) Overspeed tests?

      (3) Putting turbine on slow roll?
      (4) Normal operations?
    ii. Do you have a procedure for lining up sealing steam?
    iii. Is there a formal management of change?
  b. Tests?
    i. When is the governor or valve rack exercised online?
    ii. When do you test the trip and throttle valve?
    iii. When do you test the nonreturn valve?
  c. Qualifications?
    i. Do operators have the authority to shut down the turbine?

8. Monitoring and Protection
  a. Which of the following parameters are monitored and trended?
    i. Turbine steam inlet temperature?
    ii. Bearing metal temperatures?
    iii. Thrust?
    iv. Vibration?
    v. Lube oil pressure?
  b. Do the following parameters trigger an operating–specific alarm?
    i. Turbine steam inlet temperatures?
    ii. Bearing metal temperatures?
    iii. Thrust?
    iv. Vibration—radial?
  c. Do the following parameters trigger an alarm followed by a trip?
    i. Vibration—radial?
    ii. Thrust?

9. Upgrades—Have the following components been upgraded?
  a. Rotor assembly?
  b. Bearings?
  c. Casing?
  d. Coupling?
  e. Seals?
  f. Trip and throttle valve?
  g. Miscellaneous?

10. Steam System
  a. What supplies steam to the turbine?
  b. What type of make up water does it use?
  c. What type of condensate polishing does this unit use?
  d. Is steam purity monitored?
  e. Etc.?

11. Past Failures/Problems
  a. Turbine internal components?
  b. Bearings?
  c. Casing?
  d. Coupling?
  e. Seals?
  f. Trip and throttle valve and its components?
  g. Governor?
  h. Fouling?

12. Consequence Data
  a. Plant production in dollars per day (minimum/maximum)?
  b. What is the cost if the turbine goes down?
  c. What other costs are there if the turbine shuts down?
  d. How does the plant typically handle a rub during the startup of this turbine?
  e. How would the plant typically handle fouling of this turbine during normal operation?

The total number of possible questions is about 3000, but for a large steam turbine 350 to 400 questions are normally answered.

Question Weighting

The team of experts then weighted each of the 3000+ questions and their respective answers based on their experience and knowledge. As part of the development of failure probabilities, the team needed to set a baseline interval for overhaul outages.

They decided to use a six year dismantle overhaul schedule frequency for Class 1 to 4 turbines and a five year overhaul schedule frequency for Class 5 turbines. Thus, the baseline probabilities developed were based on the turbine operating for six years or five years without opening the case. Since risk is calculated by multiplying probability times the consequence, the calculated risk would be for a six year/five year interval. Thus, the risk calculated would be in days of lost production over a five or six year interval. Because some STRAP users do not divulge financial data about production revenue, converting the days in lost production to dollars cannot be performed for all turbines. It was decided to create the term “risk index number,” which would allow all turbines to be compared to each other. The RIN is the risk of failure in days of lost production over a six year interval for Class 1 to 4 turbines and over a five year interval for Class 5 turbines.

On the basis of the input data and the likelihood-consequence information, a risk for operation of the turbine may be calculated as a function of time between the dismantle inspections. In each case, a quantified list of recommendations to mitigate the risk will also be reported based on the greatest contribution to the risk. Inspection outage plans then may be tailored to optimize the time between overhauls on the basis of acceptable level of risk. The risk index number is a number generated by the program based on:

- The questions and their corresponding answers.
- Industry standards (ASME, API, etc.).
- Accepted industry practices.
- Latest technology.
- Relative to other turbines in the company and/or the number of turbines of the same design in the database.

Probability

The probability of failure of a component is the risk of failure in days of lost production (RIN) divided by the consequence of that component. Since risk is the product of probability time’s consequence there are questions that will significantly affect the RIN if answered with a poor option or not answered at all. An example of this is that the question of “testing of overspeed trip” and an answer of “never tested” would have a significant impact on the RIN and the recommendations by increasing the probability of failure.

Program Aids

The program has several aids for the user in an effort to make the output meet the user needs while providing the best output. Some of the aids are:

- Check for missing answers.
- Check for inconsistent answers.
- Etc.

Results and Comparisons

STRAP will compare the turbines with:

- Other turbines in the company.
- All the turbines in the database.
- Turbines in the same class.
- Turbines by the same manufacturer.
- Turbines in the same industry.
- Etc.

Recommendations

STRAP makes recommendations to improve the reliability of the turbine(s) based on return of investment. It is then up to the engineers to decide which recommendation can be executed, in what order, and during an outage and/or online.

Impact

Based upon the consequence data of the operating unit that has been input to the program, the ROI can be calculated. Some of the basic questions are:

- Unit production rate?
- Effect on the plant if a unit goes down per day?
- Impact of a trip of the turbine?
- Etc.?

RELIABILITY ASSESSMENT OF COMPRESSORS

The reliability assessment of compressors (RAC) program has been developed in a very similar manner to the STRAP program. Compressors are divided into the types of service to which they are being applied. In addition the program requires all the constituents on a percent molecular weight basis. In reality the RAC program is far more complicated than the STRAP program. There are a number of:

A. General Information
  1. What group this compressor belongs to?
    a. Charge gas/cracked gas?
    b. Air?
    c. Ammonia?
    d. Chlorine?
    e. Oxygen?
    f. Refrigeration (clean gas)?
    g. Other?
  2. What industry environment this compressor operates in?
    a. Chemical/petrochemical?
    b. Gas?
    c. Refining?
    d. Other?
  3. Compressor General Details?
    a. Compressor manufacturer (there are a multitude of manufacturers)?
    b. Model number?
    c. Serial number?
    d. Date manufactured?
    e. Compressor duty?
    f. Driver?
    g. Number of years in service?

B. Construction
  1. Type of end seals?
  2. Type of interstage seals?
  3. Internal coatings?
  4. Has the rotor been high-speed balanced?
  5. Do you have a lube and oil system designed API 614?
  6. Type of bearings?
  7. Materials of construction?
  8. Type of coupling(s)?
  9. What is the number of impellers?

C. Past Failures/Problems
  1. Has the compressor ever had past failures or problems?
  2. Has the compressor ever operated in reverse?
  3. How often does the compressor have vibration problems?
  4. Has the lube oil system been contaminated?
  5. Has the seal oil system been contaminated?
  6. Has the buffer gas consumption increased?
  7. Have you experienced compressor trips due to instrumentation problems?
  8. Has the compressor ever been oversped?
  9. Have you ever had problems with kinking in the past?

D. Design Versus Actual
  1. Inlet
    a. Pressure?
    b. Temperature?
    c. Molecular weight?
  2. Discharge
    a. Pressure?
    b. Temperature?
    c. Molecular weight?
  3. Brake horsepower required?
  4. Speed?
  5. Estimated surge ICFM?

E. Process Gas Data
  1. Is the process dry or wet?
  2. Is the process gas corrosive?
  3. Does the process foul?
  4. Do you monitor gas composition online?
  5. What molecular weight was the compressor designed for?
  6. What is the current molecular weight of the process?
  7. Process stream
    a. Air (MW 28.966)
    b. Carbon monoxide (MW 28.010)
    c. Ethylene (MW 28.052)
    d. Propane (MW 44.094)

F. Site Data
G. Control Systems
H. Lube Oil Systems
I. Spares
J. Maintenance and Repairs
K. Operation
L. Monitoring and Protection
M. Rerates and Upgrades
N. Seal Fluid System
O. Environment and Business Consequence Data

CONCLUSION

The Reliability Assessment of Rotating Equipment (RARE) is the combination of both the STRAP and RAC programs. Depending on the maintenance strategy of the company and/or the facility, either/or STRAP and RARE programs can be a significant benefit in assessing the critical machinery performance and identifying the areas that could or should be addressed to improve the reliability and define the obstacles to extending the run time between minor and major overhauls with an acceptable risk.

APPLIED RISK AND RELIABILITY FOR TURBOMACHINERY

PART II—RELIABILITY CALCULATIONS

by
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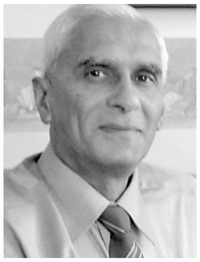


Shiraz A. Pradhan is a Consulting Engineer, with ExxonMobil Chemical Company, in Baytown, Texas. His recent experiences include the design, commissioning, and startups of oxoalcohol, halobutyle, polyethylene, polypropylene, and fluids' projects in the Far East, South America, and the U.S. He previously worked with Esso/Imperial Oil in Canada as Machinery Engineer and with British Gas Corporation in the United Kingdom as Senior Project Leader. He has been involved in reliability audits and service factor improvement projects in ammonia, fertilizer, PVC, olefins and polyolfins plants, and oil and gas pipeline projects internationally.

Mr. Pradhan has a degree (Mechanical Engineering) from the University of Nairobi, and an M.S. degree from Lehigh University in Pennsylvania. He holds the title of European Engineer (FEENI, Paris), is a fellow of the Institution of Mechanical Engineers, U.K., and is a registered Professional Engineer in the Province of Ontario, Canada.

INTRODUCTION

Reliability is critical for all industries. For the petrochemical industry it assumes added significance because much equipment is unspared or has minimal redundancy. Table 1 shows a comparison between the commercial airlines, nuclear, and petrochemical industries.

Table 1. System Characteristics for Different Industries.

System	Commercial Airlines	Nuclear	Petrochemical
Mission Length, Hr	<50	<5000*	8760> T > 70000
Access During Mission	NIL	NIL	NIL
Access Between Mission	Full	Limited	FULL if a planned IRD**

* Depending on mandated maintenance
** Inspection, Repair Downtime

COMPARISON BETWEEN ELECTRONICS AND MECHANICAL SYSTEMS

In electronic component reliability assessment the concept of constant failure rate is used (Ireson, et al., 1996). This is not the case for mechanical and machinery components. There are many reasons for this. Machinery components follow:

- Have increasing failure rate pattern
- Are not standardized like electrical components
- Have more failure modes than electronic components

Fundamental to reliability assessment of mechanical components is the need for failure distribution and supporting data that describe the behavior of the components in the real world. This is more easily said than done.

Cumulative Distribution Function

For reliability prediction one would like to know the probability of a failure occurring before a time t. This can be derived by the equation:

F (t), Probability of a failure before time t =

$$\int_{-\infty}^{t} f(t)dt \tag{1}$$

As t approaches infinity, F(t) approaches 1.

Reliability Function

Reliability function is complementary to the cumulative distribution function and gives the probability of survival of a component or system to specified time t.

$$R(t) = 1 - F(t) = \int_{t}^{-\infty} f(t)dt \tag{2}$$

Failure Rate or Hazard Function

This function allows the determination of the failure probability of a system or component in a small increment of time Δt, having survived to time t.

$$h(t) = \frac{f(t)}{R(t)} \tag{3}$$

Failure Distributions for Mechanical Systems

Exponential Distribution

This distribution is used extensively in the electronic industry and for some mechanical system's reliability assessment as well:

$$f(t) = \lambda e^{(-\lambda t)} \ for\ t > 0 \tag{4}$$

where λ = failure rate per unit time

$$and\ \lambda = 1 / MTBF \tag{5}$$

where MTBF = mean time between failure.

The reliability function for exponential distribution is:

$$R(t) = e^{-(\lambda t)} \tag{6}$$

For equipment that follows exponential distribution, the probability of having exactly k failures by time T is given by the Microsoft® Excel function:

$$POISSON(k, \lambda t, False) \tag{7}$$

Some characteristics of the exponential distribution are:

- Applies to situations where failure events are random and not due to wear, age, or deterioration
- Is a memoryless distribution. This means that the probability of failure is the same in all intervals of time.
- Has constant hazard rate
- This distribution is often applied to systems that are repairable.

Normal Distribution

This distribution is applied to situations where the failures are due to wear. However mathematics of failure rate or hazard rate are complex.

Log Normal Distribution

This distribution has wide applicability to mechanical systems where failures are due to crack propagation, corrosion, and stress-temperature phenomenon.

Weibull Distribution

Weibull distribution (Dodson, 1994) is one of the most versatile of the failure distributions and has wide applicability for mechanical systems. It is defined by two parameters: η called the characteristic life or scale factor and a constant β called the shape parameter. The Weibull probability density function is:

$$f(t) = \frac{\beta}{\eta\beta} t^{\beta-1} e^{-(t/\eta)}\beta \tag{8}$$

The Weibull reliability function is:

$$R(t) = e^{-(t/\eta)\beta} \tag{9}$$

The characteristic life, η, is the age at which 63.2 percent of the population will have failed.

The shape parameter β has several cases of interest in mechanical reliability assessment.

- *When β <1*—This indicates a decreasing hazard rate. In mechanical systems this is the initial run-in phase where faulty components with defects fail. With time these early failures diminish. This phase is often called the infant mortality or burn-in phase.
- *When β = 1*—This is a special case of Weibull distribution when it becomes an exponential distribution. As previously noted, for the exponential distribution the hazard rate is constant and failures are random. This phase designates the useful life of the component. The failure rate is reciprocal of the MTBF.
- *When β = 2*—the hazard rate is increasing linearly with time. This case is known as Rayleigh distribution.
- *When β = 2.5*—the hazard rate is increasing and the distribution approximates the log normal distribution.
- *When β = 3.5*—For this case the hazard rate is increasing and the distribution approximates a normal distribution.

Figure 1 shows these various cases.

Bathtub Curve

A bathtub curve is a plot of hazard rate against time. Figure 2 shows the curves for electronic and mechanical systems.

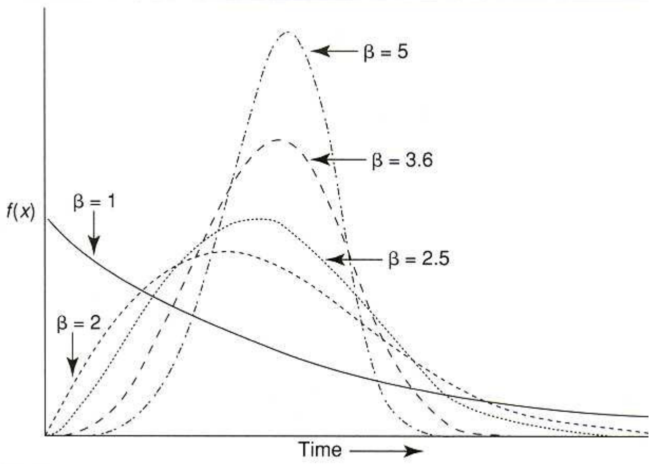


Figure 1. The Weibull Probability Density Function.

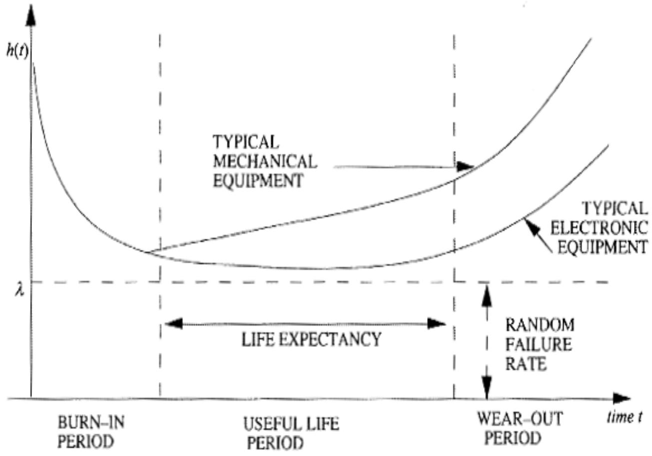


Figure 2. Bathtub Curve for Mechanical and Electronic Components.

APPLICATIONS OF FAILURE DISTRIBUTIONS

Example 1

In this example there are two identical pumps in parallel as shown in Figure 3. They have negative exponential failure distribution and therefore:

$$\lambda_A = \lambda_B = \lambda \tag{10}$$

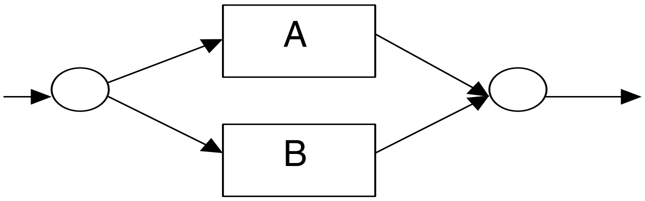


Figure 3. Two Pumps in Parallel.

Survival of one pump is sufficient to assure the success of the system. For this case the reliability of the system is given by:

$$R_t = R_A + R_B - R_A \times R_B \tag{11}$$

$$= 2e^{-\lambda t} - e^{-2\lambda t} \tag{12}$$

- Assume pump MTBF = 36 months (3 years)

Failure rate, $\lambda = 1/\ \mathrm{MTBF} = 1/3 = 0.333$ failures/year
Mission time = 1 year

- For a single pump, the reliability is:

$$R = e^{-0.333 \times 1}$$
$$= 71 \text{ percent and failure probability is 29 percent}$$

- For a parallel pump, system reliability is:

$$R = 2e^{-0.333 \times 1} - e^{-2 \times 0.333 \times 1}$$
$$= 1.4335 - 0.5137$$
$$= 92 \text{ percent and failure probability is 8 percent}$$

We will now evaluate the situation when one pump fails and the sister pump is operating without backup (Figure 4). Assume that pump mean time to repair (MTTR) = six days. Evaluating the probability of success for six days when the spare pump is operating without backup:

- Repair time = 6 days = 6/365 = 0.0164 years

$$R = e^{-0.333 \times 0.0164}$$
$$= 99.45 \text{ percent and failure probability is 0.55 percent}$$

Installing a spare pump reduces the probability of system failure from 29 percent to less than 1 percent.

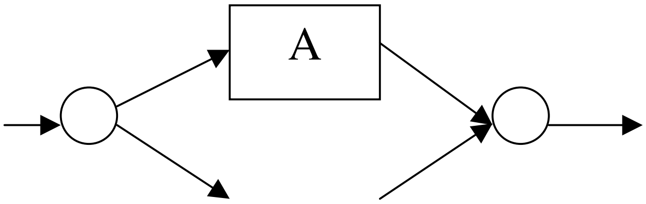


Figure 4. Only One Pump in Service.

Example 2

A screw compressor has a failure rate of 0.0666 failure/year. What is the probability of two failures in exactly five years? This problem is solved by Equation (7).

- POISSON(k,λT,False)

$\Lambda T = 0.0666 \times 5 = 0.333$
$k = 2$

The POISSON expression answer for the above values is 3.9 percent.

Risk Based Maintenance

With a spared system one is often faced with deciding if the repair of failed equipment should be carried out in an expedited or emergency basis. A typical situation is the repair strategy for, say, boiler feedwater pumps when the main pump has failed. Should it be repaired on an emergency basis? Plant operators have no confidence in the operating pump. Figure 5 can be used to aid in this decision. It relates the MTBF of the spare pump with MTTR or days unavailable and reliability.

How long can the spared pump be out for repair so as not to compromise the target reliability of 99 percent. The following facts will aid in the decision:

- The spare pump is running satisfactorily.
- Its MTBF is 15 months.

In Figure 5 the x-axis is entered at 15 months and intersects the reliability line of 99 percent at a horizontal line that corresponds to an allowable outage of nine days. In this case there is no need to do emergency repair.

Example 3

In this example we will use a commercially available Weibull program to plot the Weibull for a set of reactor pump seals. There are two pumps in service and seven seal failures. Inputting the times to failure in the program yields the Weibull plot shown in Figure 6.

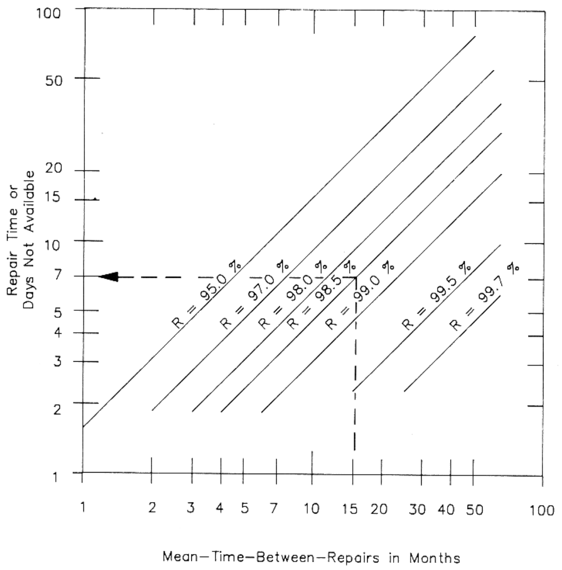
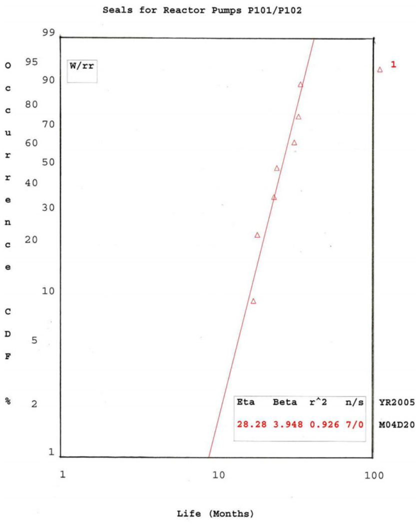


Figure 5. Reliability Versus Mean Time Between Failure and Repair Time. (Courtesy Bloch and Geitner, 1990)

- Each Weibull distribution is applicable to a single failure mode of the equipment.
- Weibull plots as a straight line
- Statistically more data points give greater accuracy to the plot.
- The r^2 in the plot gives an indication of the good fit. $r^2 = 1$ is best.
- In engineering sometimes we are forced to work with fewer data points. This increases the uncertainty of the plot.



Input Data: Reactor Seal Failures

Failure #	Time to Failure
1	17
2	18
3	23
4	24
5	31
6	33
7	34

Figure 6. Weibull Plot for Reactor Pump Seals.

The Beta (β) or the shape factor = 3.95 and the characteristic life (η) = 28.3 months. This suggests that for these pump seals hazard function is increasing and the seals have a wear-out mode.

Table 2 is an example of a Microsoft® Excel function reliability calculator that can be programmed. It takes Beta (β) and the characteristic life (η) from the Weibull plot and calculates the probability of failure and its converse, the reliability of the pump seals, based on the Weibull reliability function [Equation (9)] for a range of desired operating months.

Table 2. Reliability Calculator for Reactor Pump Seals, Based on Weibull.

Beta	3.948	Months	Failure Probability	Reliability
Eta (Months)	28.3	28	0.62	0.38
		27	0.57	0.43
		26	0.51	0.49
		25	0.46	0.54
		24	0.41	0.59
		23	0.36	0.64
		22	0.31	0.69
		21	0.27	0.73
		20	0.22	0.78
		19	0.19	0.81
		18	0.15	0.85
		17	0.13	0.87
		16	0.10	0.90
		15	0.08	0.92
		14	0.06	0.94
		13	0.05	0.95
		12	0.03	0.97
		11	0.02	0.98
		10	0.02	0.98
		9	0.01	0.99
		8	0.01	0.99

In Table 3, the Weibull equation is solved for critical values. From this table it is possible to get the expected time to failure for any desired reliability.

Table 3. Inverse Weibull: Time to Failure for Desired Reliability.

Beta = 3.98	**Reliability**	**Time to Failure (Months)**
Eta = 28.28 Months	0.01	41.637
	0.1	34.932
	0.5	25.773
	0.75	20.627
	0.8	19.341
	0.9	15.993
	0.99	8.820

Reliability Simulations

In multicomponent systems the mathematics gets too complex for closed form solutions. In such cases simulation is the next best approach. With the availability of computers, simulations have become relatively easy. The objective of the simulations is to predict the central tendency of a given variable. In this case it is to predict the probability of failure of a complex system. The algorithm for Monte Carlo simulations for mechanical systems is developed from the basic Weibull reliability function [Equation (8)], and noting that the failure function is:

$$F(t) = 1 - R(t) \tag{13}$$

Taking logarithm of both sides, it yields the equation for the time to failure, t.

$$Time\ to\ Failure = \eta \left[In\left(\frac{1}{1 - F(t)} \right) \right]^{1/\beta} \tag{14}$$

Inputting a random number for the F(t) in Equation (14) yields an estimate of time to failure, t, for a given set of the Beta and Eta. With modern computers it is possible to execute several thousand simulations.

Example 4

Reliability/Risk and Maintenance Planning

A machinery engineer is faced with a decision to recommend to management if a turbine, which has operated successfully for four years, should be overhauled in the fifth or the sixth year of operation? In this example only three components of the turbine for which Weibull data are available from similar machines are considered. A commercially available reliability program was used for the simulation.

Figure 7 shows the reliability block diagram (RBD) of the turbine and Table 4 shows the input data for the program.

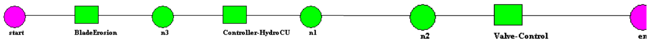


Figure 7. Reliability Block Diagram of the Turbine.

Table 4. Inputs for Turbine Components.

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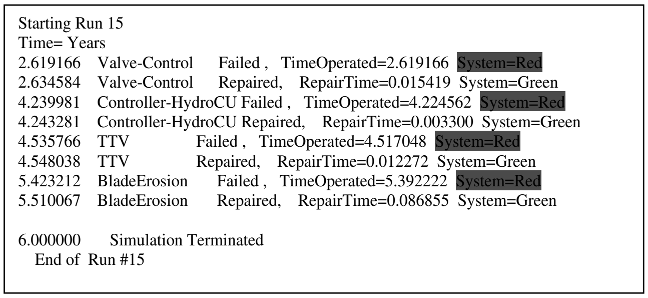
   Block Name              Failure Distro  Param1     Param2    Param3
___________________________________        _(Beta)_____(Eta)__________
  BladeErosion             Weibull         4.20000   8.50000   0.00000
  Controller-HydroCU       Weibull         1.50000   11.0000   0.00000
  TTV                      Weibull         4.70000   8.50000   0.00000
   Valve-Control           Weibull         1.50000   10.0000   0.00000
```

The methodology for making a risk-based decision is as follows:

- Step 1—Assemble failure distribution for each component. The data for the turbine components are from the maintenance/failure histories from the operating plant, original equipment manufacturer’s (OEM) data, and public domain databases (Table 4).
- Step 2—Make program simulations:
  - Number of program simulations: 1000
  - Mission times: five years and six years. The simulation program is run from time t = 0 to t = 6.
- Step 3—From the event log feature of the reliability program, assemble histograms of the number of failures for each component of the turbine for each successive year of mission time until the sixth year. The histograms essentially confirm the trend in the wear-out modes of the turbine components. Figure 8 shows a sample output from the event log and Figure 9 shows a histogram for the turbine components.



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Starting Run 15
Time= Years
2.619166  Valve-Control      Failed ,  TimeOperated=2.619166  System=Red
2.634584  Valve-Control      Repaired,   RepairTime=0.015419  System=Green
4.239981  Controller-HydroCU Failed ,  TimeOperated=4.224562  System=Red
4.243281  Controller-HydroCU Repaired,   RepairTime=0.003300  System=Green
4.535766  TTV                Failed ,  TimeOperated=4.517048  System=Red
4.548038  TTV                Repaired,   RepairTime=0.012272  System=Green
5.423212  BladeErosion       Failed ,  TimeOperated=5.392222  System=Red
5.510067  BladeErosion       Repaired,   RepairTime=0.086855  System=Green

6.000000     Simulation Terminated
   End of  Run #15
```

Figure 8. Sample Output from Event Log for Run #15.

- Step 4—Calculate the reliability of each component for a mission time of five and six years having survived four years.

Use the Weibull reliability function [Equation (9)]:

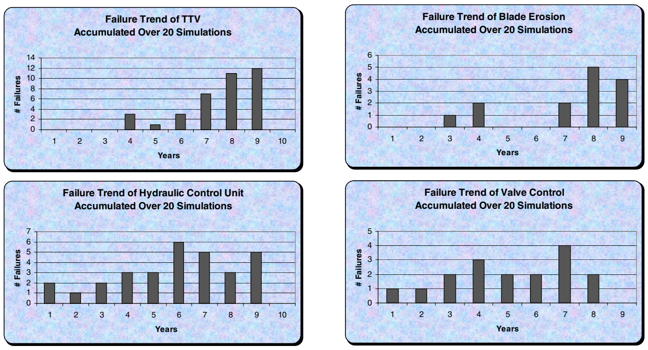

Figure 9. Histograms of Component Failures with Time.

$$R(t) = e^{-(t/n)\beta} \tag{15}$$

- Sample calculations for trip and throttle valve (TTV):

Beta = 3.8
Eta = 9 years

- Reliability at time = 4 years

R(4 yr) = $e^{-(4/9)3.8}$ = 95.5 percent

- Reliability at time = 5 years

R(5 yr) = $e^{-(5/9)3.8}$ = 89.8 percent

Thus, R (5yr/having survived 4 yr) = R(5 yr)/R(4 yr) = 89.8/95.5 = 94.0 percent
Failure probability = 1 − 94.0 = 6 percent

- Reliability at time = 6 years

R(6 yr) = $e^{-(6/9)3.8}$ = 80.7 percent

Thus, R (6 yr/ having survived 4 yr) = R(6 yr)/R(4 yr) = 80.7/95.5 = 84.5 percent
Failure probability = 1 − 84.5 = 15.5 percent

Table 5 and Figure 10 show the relative reliabilities and failure probabilities for the turbine components.

Table 5. Relative Reliabilities and Probabilities of Failure for Turbine Components.

Component	Reliability (5 yr /having survived 4 yr)	Failure Prob. (5 yr /having survived 4 yr)	Reliability (6 yr /having survived 4 yr)	Failure Prob. (5 yr /having survived 4 yr)
Control Valve	90.43	9.57	80.9	19.1
Controller Hydraulic CU	91.65	8.35	83.2	16.8
Trip and Throttle Valve	94.05	5.95	84.5	15.5
Blade Erosion	98.7	1.3	96.4	3.6

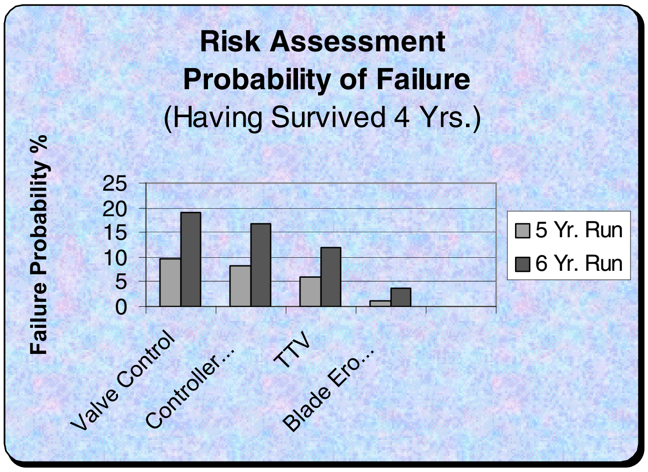

Figure 10. Relative Probability of Failure for Turbine Components (Example 3).

The analysis shows that there is an 11 percent additional risk in extending the operation from the fifth to the sixth year. The total risk is 19 percent for the control valve.

Example 5

A gas turbine generator (GTG) system is arranged in parallel as shown in Figure 11. Survival of one GTG line is sufficient for system success. All components have negative exponential distribution. The desire is to:

- Forecast the system reliability and availability for a mission time of two years.
- Assess system vulnerability when one GTG is out for planned maintenance for 10 days.

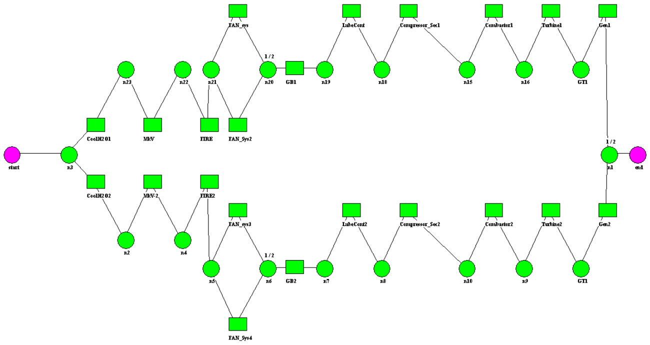

Figure 11. Two GTGs in Parallel.

The reliability program model comprises all the components of the GTGs including the gearboxs, turbine and compressor sections, the generator, and the auxiliaries such as cooling water, lube system, control system, and fire suppression system.

The results (Table 6) indicate that for two GTGs in parallel and for a mission time of two years, the system reliability will be 99 percent with a mean system failure rate of 0.01 failure in two years. The mean availability is >99 percent.

Table 6. Results of Simulation: GTGs in Parallel, Mission Time = Two Years.

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Results from 100 run(s):

Parameter        Minimum        Mean           Maximum        Standard Deviation
Total Costs      66.00          67.62          72.66          1.37
Ao               0.991366829    0.999913668    1.0000000000   0.000858989
MTBDE            1.982734       >1.999827      >2.000000      n/a
MDT (1 runs)     0.017266       0.017266       0.017266       n/a
MTBM             0.283248       >1.439166      >2.000000      n/a
MRT (79 runs)    0.003004       0.013159       0.030500       0.006948
%Green Time      95.527907      98.950059      100.000000     1.002106
%Yellow Time     0.000000       1.041308       4.065847       0.975965
% Red Time       0.000000       0.008633       0.863317       0.085899
System Failures  0              0.010000       1              0.099499

R(t=2.000000) =0.990000
```

When one GTG is down for planned maintenance of 10 days, the results (Table 7) show that the system is vulnerable to failure within the 10 days. For the duration of the10 days the system reliability is only 97 percent and there is a potential of a mean failure of 0.03.

REFERENCES

Ireson, W. G., Coombs, C. F., Jr., and Moss, R. Y., 1996, *Handbook of Reliability Engineering and Management*, Second Edition, New York, New York: McGraw Hill.

Dodson, B., 1994, *Weibull Analysis*, Milwaukee, Wisconsin: ASQ Press.

Bloch, H. and Geitner, F., 1990, *Machinery Reliability Assessment*, New York, New York: Van Nostrand Reinhold.

Table 7. Results of Simulation: One GTG Out for Overhaul, Mission Time = 10 Days.

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Results from 100 run(s):

Parameter          Minimum        Mean           Maximum        Standard Deviation
Total Costs        11.30          11.33          12.50          0.17
Ao                 0.729199029    0.993634398    1.0000000000   0.037137561
MTBDE              0.019973       >0.027216      >0.027390      n/a
MDT (3 runs)       0.004199       0.005812       0.007417       0.001314
MTBM               0.019973       >0.027216      >0.027390      n/a
MRT (3 runs)       0.000000       0.003339       0.005819       0.002452
%Green Time        72.919903      99.363440      100.000000     3.713756
%Yellow Time       0.000000       0.000000       0.000000       0.000000
% Red Time         0.000000       0.636560       27.080097      3.713756
System Failures    0              0.030000       1              0.170587

R(t=0.027390) =0.970000
```