Reliability Of Critical Turbo/Compressor Equipment

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Fifth International Conference on Process Plant Reliability

Marriott Houston Westside
Houston, Texas

October 2-4, 1996

Organized by
Gulf Publishing Company
and
HYDROCARBON PROCESSING

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ABSTRACT

A methodology is presented to evaluate and determine the necessary level of reliability for process equipment such as large centrifugal compressors and turbines in a refinery environment.

RELIABILITY DEFINITIONS

For repairable equipment: Reliability is the probability that an item can perform its intended function for a specified interval under stated conditions. (MIL-STD-721) Reliability is concerned with avoiding events called failures. Reliability is calculated based on the lack of failures. Reliability involves uncertainty as the time of future failures are unknown although failure probability exist. Reliability is also a function of stress applied to the system and components.

A broader definition exists for business purposes: Reliability is the probability than an item can perform its intended function for a specified interval under stated conditions and achieve low long term cost of ownership for the system considering cost alternatives. In business, reliability values are not fixed but they always change because of competitive issues, business risks, and business conditions. For example: When plant volume was sold-out last year, demand for reliability was high as the cost for an outage was very severe; however, since the plant will be idle a portion of this year, demand for reliability is much lower as the cost for outages is also much smaller.

For business, the overriding reliability issue is cost—particularly the cost of <u>un</u>reliability for existing equipment caused by failures. Failure is a deteriorating event which renders equipment and processes as non-useful for the intended or specified purpose during a designated time interval (Barringer 1995). Failures include:

a) Stoppage due to malfunction.

b) Cessation of component function.

c) Cessation of meeting predetermined quality, quantity, and cost expectations

d) An unexpected occurrence that interrupts routine operation of a system.

Reliability, which is the absence of failures, is discussed but failures and cost impact of failures called unreliability are measured. Downtime stopping the production process results in unreliability and defines a failure—likewise, cutbacks/slow-downs in output because of equipment is also a failure Should turnarounds for equipment renewal also be counted as failures?—yes because these conditions are failures for equipment investors. (Barringer 1996) The key issue is identification of failures and handling the data suspensions for different failure modes.

NEED FOR ASSESSING RELIABILITY

Critical equipment plays an essential role in industry because of its lack of redundancy. Failure of critical equipment results in major economic failure of processes generating gross margin (approximately gross profit) for the enterprise. Lack of redundancy for critical equipment occurs because of the high cost of very reliable equipment and frequently the lack of space for installation of redundant equipment—even if it could be justified on the basis of economics.

Critical equipment is both expensive and highly reliable and lacks the opportunity to "crash a few pieces of equipment" to actually verify component life. The issue is to avoid the high cost of component failures. This requires the use of engineering projections to determine life estimates for the equipment—both art and science must be joined through the use of reliability engineering tools.

In short, reliability assessments have similarities to the testing for professional engineering licenses. The P.E. fundamentals exam, for engineers in training, has only one acceptable answer for each question. For the practical examination, after years of experience, each question has a different answer based on the stated assumptions for the solution. For reliability assessments, we only want one answer—however, we usually must live with a series of assumptions to force an uncertain answer that is questioned by everyone. Thus reliability assessments yield different answers (around a common point estimate) which are useful for guiding business actions.

For critical turbo machinery, the questions about reliability are:

a) How long will the equipment function before failure occurs?
b) What are chances a failure will occur in a specified interval for turnaround?
c) What is the best turnaround interval?
d) What is the inherent reliability of the equipment?
e) What are the risks for delaying repair/replacements?
f) How can assumptions about reliability be verified?
g) Where are numbers found to prepare calculations for use by work teams?
h) What extension in turnaround time can be obtained by component improvements?
i) Does justification exist for a spare system or spare components?

These questions will be answered for two turbines and compressors which have been in service for many years and have never experienced a failure in service. All numbers used for the following examples including equipment capital costs, spare parts, downtime, equipment life, and production loss numbers do not represent actual values for competitive reasons. Fictitious financial numbers are use for presentation purposes.

Turbine And Compressor

Two steam turbines and their interconnected process gas compressors were considered for a study. One system was installed in 1953 and has functioned successfully for 43 years without complete loss of the system. Likewise a second similar (not identical) system has been in operation since 1985 without complete loss of the system. Turnarounds have been performed on the systems at periods between two to five years to return the important elements of the system to zero time to reverse deterioration. The taxonomy for the turbo/compressor system is shown in Figure 1 with services and controls outside of the taxonomy block.

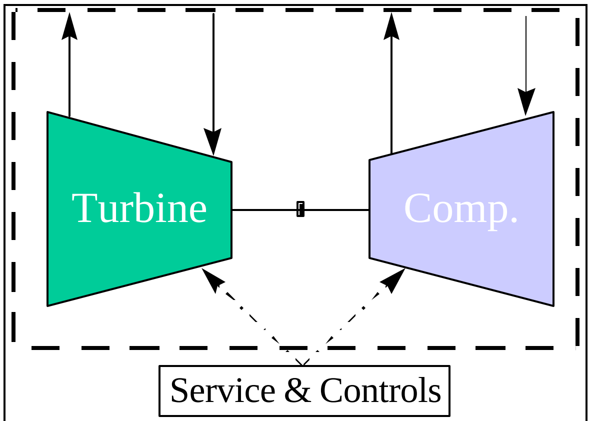

Figure 1: System Taxonomy

Compressor Description-

The compressor has five stages and all impellers face away from the coupling end of the machine. Gas enters the compressor vertically upwards is compressed through the five stages, and exits the compressor through the vertical discharge flange. Rotation of the compressor is clockwise as viewed from inlet of the compressor. All impellers are forged from modified 410 stainless steel, heat treated for long life in the process gas environment, and contain integral blades. Covers for the compressor wheels are made from forged material and electron beam welded to the wheel to form a precision matched set which is dynamically balanced. The compressor is assembled into a fabricated forged barrel with weld attached cast nozzles.

Tilting pad radial bearings are force-feed lubricated with oil seepage returned to the oil reservoir via a drain located in the lower half of the bearing housing. The outboard end of the compressor has a Kingsbury type thrust bearing. Redundant lubricating oil pumps, filters, valves, and coolers are provided for returning 10 micron oil to the compressor and turbine. Eight temperature sensing elements are provided for monitoring bearing temperatures. Four probes monitor the thrust bearing while four other probes monitor the two radial bearings.

Continuous service vibration monitoring probes provide eight channels of radial motion, four channels of axial motion, and a single keyphasor probe. Suitable signal conditioning equipment is provided.

A continuous base plate is installed under the compressor and turbine. The compressor is connected to the turbine by a non-lubricated flexible diaphragm coupling.

Turbine description-

The impulse, condensing turbine is rated at 3,000 horsepower. The turbine is designed for operation over the range of 8,000 to 14,000 rpm with maximum continuous operation at 12,500 rpm and over-speed set for 13,758 rpm. Steam is supplied at a maximum of 580 psig and 500 ^{o}F. The turbine has four stages. The first stage contains 118 blades, the second and third stage each contain 140 blades, and the fourth stage contains 86 blades. The mean tip speed of the final stage is 1289 feet per second. Blade roots are dovetailed and the shrouds are riveted.

The speed governor is an electronic, direct acting model. The governor is connected to an automatic valve with separate remote trip equipped with a manual exerciser.

Radial bearings are tilting pad with a 49.75 inch span between the bearings. The thrust bearing is also tilting pad with a single thrust collar. Four vibration detectors are mounted on the bearings with two axial movement detectors and one keyphazor sensor. Eight bearing temperature monitors are provided. Four devices monitor the two radial bearings and four are mounted on the thrust bearings.

The turbine is also equipped with a gland condenser.

Maintenance Reports

Maintenance records for two similar sets of critical equipment were available for review. One turbo/compressor was commissioned in 1953 and the other in 1985 with no records prior to 1986.

Most details in the maintenance records reflect filter changes, other PM actions, and numerous minor repairs while the equipment is operating including governor speed controls. The data thought to exist in computer records proved to be non-existent and mixed-up—in short, it represents real life conditions for data retrieval. Only a few major issues resulting in loss of production time have been reported by work order since 1986 as described in Tables 1-4. Of course the accuracy of data analysis is directly dependent upon accuracy of input data from maintenance records and extremely important actual failure data from previous turnaround autopsies is lacking.

Table 1: Turbine #1 Failure Data

Action	Date	$ Costs	Days Lost
Commissioned	1953		
Overhaul	5/4/88	120,000	14
Overhaul	1/14/92	300,000	24

Table 2: Turbine #2 Failure Data

Action	Date	$ Costs	Days Lost
Commissioned	1985		
Open/inspect	3/18/91	60,000	NA
Overhaul	10/23/91	175,000	14

Table 3: Compressor #1 Failure Data

Action	Date	$ Costs	Days Lost
Commissioned	1953		
Overhaul	12/4/89	175,000	14
Overhaul	1/14/92	200,000	24

Table 4: Compressor #2 Failure Data

Action	Date	$ Costs	Days Lost
Commissioned	1985		
Open/inspect	3/18/91	150,000	14

No records are available to document down time for each of the reports and the days down are estimated time out of service. Each day lost is valued at $100,000 lost gross margin. Of course actual dollar values are not described for competitive reasons.

Note that Turbine #1 and Compressor #1 were each overhauled on the 1/14/92 date. Also note that Turbine #2 was opened for inspection on 3/18/91 while Compressor #2 was out for overhaul thus downtime is not allocated to Turbine #2. No criteria is available to document specific reasons for initiating the overhaul activities. No records were maintained during the overhaul and the number of items actually found in need of replacement were not identified. In short, the data is highly deficient from lack of good autopsy reports which could have recorded valuable failure data prior to overhauls at scheduled turnarounds.

Based on the summary tables of maintenance activities which span a 100 month interval:

- Turbine #1 has been overhauled two times in a 100 month time interval.
- Turbine #2 has been overhauled one time in a 100 month time interval.
- Compressor #1 has been overhauled two times during a 100 month time interval.
- Compressor #2 has been overhauled one time during a 100 month time interval.

The first reliability indicator is mean time between failures. MTBF is a basic measure of reliability for repairable items: MTBF is the mean number of life units during which all parts of the item perform within their specified limits, during a particular measurement interval under stated conditions (MIL-STD-721). This definition is most frequently applied to chance failures with a constant failure rate. However, overhaul is a response to wear-out failures which show increasing failure rates. Thus MTBF only gives a rough reliability indicator using metrics found by (Σ Life)/(Σ Failures).

Data in Tables 1-4 show no failures. Thus MTBF cannot be calculated accurately. However, a lower value for MTBF can be found by assuming failure would have occurred the next day—this forces a number. Based on lack of a defined failure criteria, turbines show a mean time between overhaul of 200/3 = 66.7 months. Likewise, compressors have 200/3 = 66.7 months between overhauls. These metrics are found by (Σ Life)/(Σ Overhauls).

For the turbine/compressor system, the demonstrated life between overhauls is: two systems each operating 100 months or 200 months with 5 outages for overhaul (at one interval both the compressor and turbine were overhauled at the same time) for a system mean time between overhaul of 40 months or just over three years for each system.

The mean time between major maintenance actions for which lost production time was incurred for turbines are 200/3 = 66.7 months per lost production from a maintenance action. For compressors the numeric is 200/3 = 66.7 months per lost production time from a maintenance action.

For the system we get a mean time between major maintenance numeric of 200/5 = 40 months per maintenance action. Note the mean time results of the series system for turbine/compressor is always smaller than the worst performing element of the system.

These metrics are yardsticks for mean time between overhauls and mean time between major maintenance actions. These numerics represent worst case value for MTBF. Each numeric provides some guidance for practical matters but since they involve simple arithmetic, they cannot be converted into micrometers by adding decimal points nor do they provide good forecasting tools—however, some data is better than no data! Remember these numerics reflect what exists rather than the intrinsic capability of the equipment. This issue is highlighted by the need for two compressor overhauls on the same machine within a 37 month period indicating the quality of the overhaul did not renew the equipment to a zero time base.

From the record of Tables 1-4, little evidence suggest chance failures as the predominant failure mode. However, Bloch (1996) reports the percent of failure incidents for centrifugal pumps as:

> 30% for maintenance deficiencies (neglect, procedures), 25% for assembly-installation defects, 15% for off-design or unintended service conditions, and 12% for improper operation—this totals to 82% of the incidents responsible for failures which are in the category of chance failures.

Bloch's chance failure information may also apply to turbo-compressors. Clearly the absence of obvious chance failures for this turbine/compressor equipment speaks well to good maintenance and operations practices as the few outages recorded were for renewal of wear-out mechanisms.

Commercial Databases-

How do these turbine/compressor results compare to typical data? The OREDA handbook (OREDA-92) offers guidance with failure rates for gas turbines connected to rotary compressors with a critical failure rate of 1100 per million hours (including a special note that 85% of the failures result from the gear box). The OREDA taxonomy includes many other pieces of hardware in the system which are estimated to account for 60% of the non-gear box outages.

Thus the failure rate of the compressor and gas turbine are about (1-0.85)*(1-0.6)*1100 = 66 failures per million hours for the rotating system. Furthermore, assume the gas turbine is responsible for 75% of the failures in the 66 failures/million-hr. Thus (1-0.75)*66 = 16.5 failures/million-hr for only the compressor failure rate or 83 months per failure. The gas turbine failure rate is thus estimated as (66-16.5) = 49.5 failures/million-hr. Assume the failure rate for a steam turbine is about 1/3 the failure rate of a gas turbine to give a failure rate of 49.5*0.33 = 14.85 failures/million-hr which is about 92 months/failure.

So what do these estimates from OREDA data tell? Remember actual times to failure for the systems in Table 1-4 are not found because the equipment was overhauled before failure. The data does provide a time between overhauls for turbine and compressor of 66.7 months (which indicates the MTBF would be longer than the MTBO) are in the same ball park as obtained from the OREDA estimates of 92 months for turbine and 83 months for compressor. Remember these estimates are yardsticks—not micrometers.

As another estimate, data from steam turbines will have from 10 (NPRD-95) to 30 (Davidson 1988) failures per million hours. For practical purposes, average the failure rate for the steam turbine to 20 failures per million hours. This results in a mean time to failure of 68.5 months per failure.

Of course, connecting turbine (with failure rate ~14.85E-6) to the compressor (with failure rate ~16.5E-6) the system failure rate becomes (14.85+16.5) = 31.35 failures/million-hours which is equivalent to a system mean time between failure of 43.7 months/failure. This estimate compares to the worst case evaluation of 40 months per failure so in the aggregate the agreement is pretty good considering the uncertainties.

In short, how are the actual results compared to the OREDA estimates and data from other sources? The actual mean time between failures for turbines and compressors in Tables 1-4 will be longer than the mean time between overhaul. Thus the life predicted from the data of Tables 1-4 compare favorably with two sources considering the uncertainty in the estimates used to construct the failure rates. Make comparisons to commercial data sources to judge if equipment performance, based on the class or grade of equipment, is in the "ball park".

The information from Tables 1-4 look backward and helps justify the actions taken. Based on past actions, the MTBF for the turbine-compressor system is greater than 40 months per failure.

Table 5: Actual System Reliability

Turbine-Compressor System MTBF >= 40 months/failure	
Time Between Turnarounds, (months)	Chances For Survival %
12	74.1
24	54.9
36	40.7
48	30.1
60	22.3
72	16.5
84	12.2

Using the system information from Tables 1-4 and the exponential distribution for reliability, the following quick projections for reliability are shown in Table 5.

For chance failure modes, a uniform percentage of failures will occur each period because the equipment is renewed before wear-out failure modes become a problem. The odds for operating without failure (i.e., a measure of reliability) for a five year turnaround are 22.3%.

Suppose the equipment has reached the end of a four year period without a failure. What are the odds for achieving one more year without failure. This is an issue of conditional reliability (Kececioglu 1991). The odds (assuming use of the exponential distribution for chance failures) are 74.1% for operating the equipment for one more year. This occurs because the arithmetic used for calculating the MTBF used with the exponential distribution has no memory of previous history as all failures are treated as chance failures and the instantaneous failure rate is constant.

Since the constant failure rate model does not accurately represent the more likely wear-out failure mode, then why use it? The answer is simplicity—it's a method for getting a first grip on reliability issues. A reasonable, ball park, answer today is frequently much better than the true answer found ten years after the need has passed.

If the more likely wear-out mode is hypothesized then more facts are required and the analysis becomes more complicated. One of the better ways to get this information is to use Weibull analysis.

Weibull Analysis-

Weibull analysis is appropriate for components, and from assembly of the components a system model can be developed. Detailed age to failure data has not been recorded for any of the components. This will require making engineering estimates for the turbine and compressor using facts which are available from reliability experts (Weber 1996) with experience and data in the gas turbine industry. A request for actual Weibull data from the manufacturer of the turbine-compressor was not fruitful.

Generally speaking, gas turbine blades have shape factor, β, between 0.9 and 2.7 depending on the failure mode. The characteristic life, η, varies between 10,000 hours and 160,000 hours depending upon stress levels in their very high temperature environment.

Also generally speaking, gas turbine compressor blades have shape factor, β, between 1.2 and 6.6 depending on the failure mode. The characteristic life, η, varies between 10,000 hours and 300,000 hours depending upon stress levels in their severe flight environment.

For the purpose of this analysis, Table 6 assumes the following Weibull value--recognizing that actual Weibull failure data would not have the smooth and uniformly stepped failure data shown below:

Table 6: Assumed Raw Weibull Values			
(η values given in months, n = pieces)			
Item	β	η	n
Turbine:			
Row 1 Blade	2.7	1200	118
Row 2 Blade	2.6	1190	140
Row 3 Blade	2.5	1180	140
Row 4 Blade	2.4	1020	86
Row 1 Vane	3.2	1820	118
Row 2 Vane	3.1	1810	140
Row 3 Vane	3.0	1800	140
Row 4 Vane	2.9	1790	86
Blade Disks	4.5	3000	4
Journal Brgs	1	2000	2
Thrust Brg	1	1000	1
Turbine Shaft	1	1000	1
Coup.Diaph.	2	400	1
Compressor:			
Impeller 1	3.0	200	1
Impeller 2	2.9	180	1
Impeller 3	2.8	160	1
Impeller 4	2.7	140	1
Impeller 5	2.6	120	1
Journal Brgs	1	2000	2
Thrust Brg	1	1000	1
Comp. Shaft	1	1000	1

Table 7: Assumed Net Weibull Values		
(η_s given in months)		
Item	β	η_s
Turbine:		
Row 1 Blade	2.7	205
Row 2 Blade	2.6	179
Row 3 Blade	2.5	163
Row 4 Blade	2.4	159
Row 1 Vane	3.2	410
Row 2 Vane	3.1	368
Row 3 Vane	3.0	347
Row 4 Vane	2.9	385
Blade Disks	4.5	2205
Journal Brgs	1	1000
Thrust Brg	1	1000
Turbine Shaft	1	1000
Coup. Diaph.	2	400
Compressor:		
Impeller 1	3.0	200
Impeller 2	2.9	180
Impeller 3	2.8	160
Impeller 4	2.7	140
Impeller 5	2.6	120
Journal Brgs	1	1000
Thrust Brg	1	1000
Comp. Shaft	1	1000

Each stage of the turbine and compressor have multiple components as shown in Table 6 by the term, n = pieces, all with the same β values (and they could have different η values). Using the Weibull reproductive property (similar to the exponential distribution property) the characteristic life of each set of equipment for each stage (i.e., subassembly) can be calculated using the Weibull closure property, η_s, (Abernethy 1996) for Table 7.

$$\eta_s = \left(\sum_{i=1}^{n} \frac{1}{\eta_i^{\beta}}\right)^{-\frac{1}{\beta}}$$

For Weibull component distributions, beta values have some relationship to physical characteristics. When $\beta > 1$, wear-out, when $\beta \approx 1$, chance failures, and when $\beta < 1$, infant mortality.

The items listed in Table 7 are effectively in series (i.e., if one component in the turbine fails, the entire system fails, etc.) so the inherent reliability can be calculated as (with t = mission time):

$$R_s = \prod_{i=1}^{n}(R_i) \quad \text{where } R_i = e^{-(t/\eta_i)^{\beta_i}}$$

Consider turbine and coupling as one subsystem, and the compressor as a separate subsystem. The product of both subsystems will form the overall system.

Inherent reliability is shown in Table 8 based on the Weibull estimates shown in Table 7:

Table 8: Inherent System Reliability			
Turbine-Compressor System			
MTBF = ≈ 54 months/failure			
	% Chances For Survival		
Time Between Turn'rds (months)	Turbine System	Comp. System	Total System
12	95.9	96.0	92.0
24	90.1	90.0	81.1
36	82.3	81.2	66.8
48	72.4	69.6	50.5
60	61.2	56.0	34.3
72	49.3	41.9	20.6
84	37.7	28.7	10.8

So the actual MTBF is >= 40 months/failure and the inherent reliability is ~54 months/failure which is found by fitting a simple Weibull distribution to the total system reliability data versus time. This gives a rough approximation of: $R_{system}(t) = \exp(-(t/58)^{1.3})$.

Then calculating the MTBF = $58*\Gamma(1+1/1.3) = 54$ months/failure.

Why the difference between 40 and 54 failures per month? Some reasons are:

- No failures were incurred in the data from Tables 1-4 and thus 40 months/failure is a conservative figure.
- Errors in assumptions for the Weibull calculations from lack of design/build input facts.
- Many other similar reasons generally associated with lack of specific failure data.

Optimum Replacement Intervals

Using Weibull analysis and costs, the optimum replacement intervals can be calculated for each component as shown in Table 9 using optimum replacement calculations. By use of superposition, a composite system cost curve can be prepared to show the interval where system costs are least. In Table 9, planned repair costs occur during a normal process outage when failure is charged to other equipment, and unplanned repair cost will include charges for failure of the turbo machinery.

Table 9: Optimum Replacement Intervals

Item	Planned Replace Cost ($)	Unplan'd Replace Cost ($)	Optimum Interval (mos)
Turbine:			
Row 1 Blade	30,000	1,230,000	42.9
Row 2 Blade	32,000	1,232,000	37.0
Row 3 Blade	32,000	1,232,000	32.1
Row 4 Blade	45,000	1,245,000	35.0
Row 1 Vane	20,000	1,220,000	89.0
Row 2 Vane	20,000	1,220,000	77.0
Row 3 Vane	28,000	1,228,000	78.5
Row 4 Vane	36,000	1,236,000	92.0
Blade Disks	28,000	1,228,000	724.2
Journal Brgs	10,000	1,210,000	---
Thrust Brg	20,000	1,220,000	---
Turbine Shaft	50,000	1,250,000	---
Coup. Diaph.	10,000	35,000	261.4
Compressor:			
Impeller 1	40,000	1,240,000	51.3
Impeller 2	40,000	1,240,000	45.0
Impeller 3	40,000	1,240,000	35.0
Impeller 4	40,000	1,240,000	32.3
Impeller 5	40,000	1,240,000	26.9
Journal Brgs	10,000	1,210,000	---
Comp. Shaft	50,000	1,250,000	---
Thrust Brg	20,000	1,220,000	---

These optimum replacement curves have two general shapes when the cost of an unplanned replacement is much larger than the cost of a planned replacement. Where $\beta > 1$, the curves are roughly parabolic with open side up. Where β < or = 1, the curves have downward slope to the right with no minimum. Where the costs between planned replacements and unplanned replacements are less than ~3, then the curves also sweep downward and to the right as occurs when β is equal to or less than 1.

For the optimum replacement equation (Glasser 1969), the numerator consist of two terms which are summed. The first numerator term is the high cost of an unplanned, on-line, failure multiplied by the unreliability and this term increases with time. The second term of the numerator is the lower cost planned maintenance replacement cost off-line before failure multiplied by reliability, and this term decreases with time. The denominator of the optimum replacement equation is the mean time to failure within the replacement interval. This relationship is valid up to the age of the characteristic life of the component and does not reflect the second replacement which often occurs after the characteristic life has been reached. The optimum replacement equation prices-out success and failures.

Each individual optimum replacement curve for items listed in Table 7 are summed for each subsystem. The composite curve shows the optimum replacement interval which occurs at least cost. The curve also tells the minimum maintenance costs which are useful for life cycle costing.

Figure 2 describes the optimum turbine replacement interval, while Figure 3 describes the optimum compressor replacement interval. Optimum replacement intervals occur where costs reach a minimum.

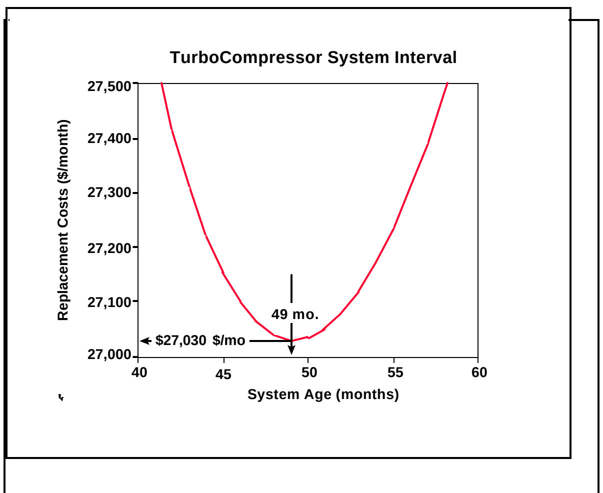

Figure 4: Turbine/Compressor Renewal

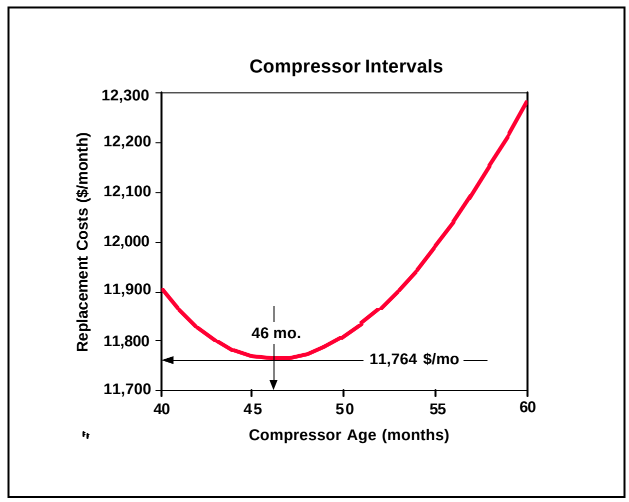

Figure 3: Compressor Renewal

Figure 2: Turbine Renewal

Figure 4 describes the optimum replacement cost for performing both turbine renewal and compressor renewal at the same time as a system. If the system is renewed early, then the high cost of early PM is found, and if renewal is delayed, then the high cost of delayed maintenance is incurred. In Figure 4, notice the cost penalty per month is not very high for action of 8 to 10 months either side of the optimum.

Figures 2-4 are developed by using Weibull data from Table 7 with the cost data from Table 9. Replacement costs are found using the optimum replacement data for each component from the optimum replacement option in WinSMITH™ Weibull probability software (Fulton 1996). Then by super position, the individual curves are added together for display as a total result in VisualSMITH™ software (Fulton 1995).

Suppose the planned replacement costs for Table 9 are increased (and this also increases a portion of the cost for an unplanned repair). What effect will the increase have on the optimum replacement interval? Higher costs increase the turnaround time for the next renewal—just as occurs in real life in most refineries and chemical plants. Depending on the specific situation, a 10% increase in cost will extend the turnaround time by much more than 10% depending on the cost and Weibull details.

System Reliability

System reliability is described in Figure 5 and this describes the inherent reliability of the system.

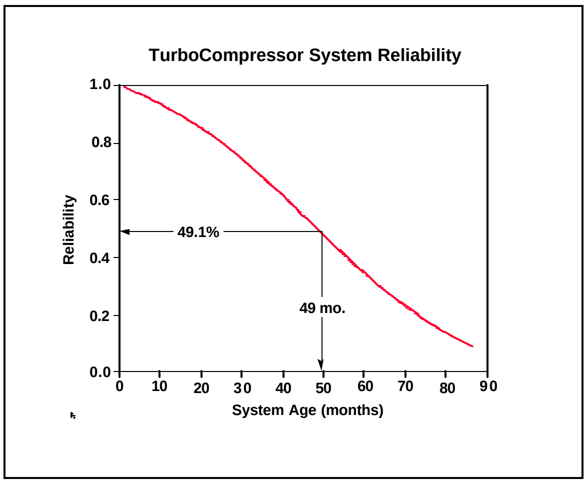

Figure 6: System Reliability

At the least cost replacement interval of 49 months, the system reliability is 49.1%. This is the same as saying the chance for failure is (1-0.491) = 50.9% and the specific date of failure is unknown.

Suppose the optimum renewal interval of 49 months has been reached, what are the chances for operating another 12 months without failure? This is a conditional probability question given the unit has survived to 49 months, and what will be the conditional reliability for completing a new mission of 12 more months at the conclusion of the 49 month success period.

$$R(T=49,t=12) = R(49+12)/R(49) = 0.330/0.491 = 67.3\%$$

The system results show very good odds for survival with almost 7 changes out of 10 for the system to survive for one more year (and the system renewal costs at 61 months is \$27,800 per month rather than \$27,000 for the 49 month interval). This critical turbo equipment example is similar to questions about human life. For a person at age 91 years old, the odds for surviving to 92 years of age is much better than for a 1 year old to survive to age 92 years.

Questions often arise about which component should be improved to increase the overall life and this reduce the system costs. The answer is rarely a single component will make big changes in reliability for a well designed system.   However, once the reliability model is constructed, “what-if games” can be played to change the Weibull characteristic life and then study the results on the final system.

Of course the usual place to begin searches for improvements is to consider changes in components with low characteristic life and small shape factors. A few “what-if” trials will give new insight into the improvement process and quickly disclose that many improvements are required to fix short life system problems—it requires an improvement program not a single magic bullet!

Justification Of Spare Equipment-

Three obvious choices exist for spare equipment using the optimum replacement interval of about four years (49 months):

1) Purchase no spares. Make no changes in operation. When turnaround is required, take the loss of 12 days production valued at $1.2E06. Incur $0.5E06 repair costs. Total costs for this strategy is $1.7E06.
2) Purchase a complete set of rotating elements and necessary critical hardware to minimize turnaround losses. Purchase spare parts assemblies at a cost of $0.6E6. Renew the system in 7 days with a loss of production of $0.7E06. Then spend $0.25E06 per turnaround to restore the spares for the next turnaround. (The restoration cost is lower than option 1 because of non-overtime and expedited costs.) Total costs for this strategy is $1.2E06 plus a one time expense of $0.6E06.
3) Purchase and install redundant equipment at an installed cost of $6.0E06. Incur no production losses at turnaround, and assume refurbishment cost is $0.35E06 per turnaround. (Refurbishment cost is higher than option 2 because extra hardware always results in higher costs and additional contingency charges.)

Table 8 describes the outflow of cash for a 20 year project life with equipment acquisition on a just-in-time basis. (Note: Each company will have it's own criteria for making investment decisions, and results of the decisions will be different—so do not expect the results to have only one answer!)

Table 9 describes cash outflows adjusted for discounted cash flow factors reflect a 15% DCF rate. Assume salvage value at end of the 20 year life equals disposal cost so the net value is zero.

Table 8: Comparison of $ Expenditures($E06)

Year	Status Quo	Purchase Spare Parts	Purchase Redundant Equipment
1	0	0	0
2	0	0	0
3	0	**-0.6**	**-6.0**
4	**-1.7**	**-0.95**	**-0.35**
5	0	0	0
6	0	0	0
7	0	0	0
8	**-1.7**	**-0.95**	**-0.35**
9	0	0	0
10	0	0	0
11	0	0	0
12	**-1.7**	**-0.95**	**-0.35**
13	0	0	0
14	0	0	0
15	0	0	0
16	**-1.7**	**-0.95**	**-0.35**
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
Total	**-6.8**	**-4.4**	**-7.4**

Table 9: Comparison of Discounted $ Expenditures($E06)

Year	DCF #s @ 15%	Status Quo	Buy Spare Parts	Purchase Redundant Equipment
1	0.8696	0	0	0
2	0.7561	0	0	0
3	0.6575	0	**-0.39**	**-3.94**
4	0.5718	**-0.97**	**-0.54**	**-0.20**
5	0.4972	0	0	0
6	0.4323	0	0	0
7	0.3759	0	0	0
8	0.3269	**-0.56**	**-0.31**	**-0.11**
9	0.2843	0	0	0
10	0.2472	0	0	0
11	0.2149	0	0	0
12	0.1869	**-0.32**	**-0.18**	**-0.07**
13	0.1625	0	0	0
14	0.1413	0	0	0
15	0.1229	0	0	0
16	0.1069	**-0.18**	**-0.10**	**-0.04**
17	0.0929	0	0	0
18	0.0808	0	0	0
19	0.0703	0	0	0
20	0.0611	0	0	0
NPV		**-2.03**	**-1.52**	**-4.36**

The selection process for justification of spare equipment will rank the alternatives based on the net present value (NPV). One of the key engineering issues is to provide alternatives with clear details so the information can be processed by the accounting department for a business team solution. Remember, no "single, right answer" exists every time considering changing business environments

Purchase of spare rotating elements and necessary critical hardware is the most cost effective action, followed by maintaining the status quo, and last is the acquisition of redundant equipment.

Existing equipment has never failed in service so how can spare equipment be justified? In ten years, two systems have been taken off line six times with $1.12E06 maintenance costs plus 80 days of lost production time valued at $8E06 for a total cost of $9.12E06 which is almost $1.0E06 per year of costs for the two systems or ~$0.5E06 per year for each system. When this critical rotating equipment is down, the refinery demonstrates a lack of reliability and plants are made to run—not be idle. The issue is making reliability pay its way.

In each of the cost calculations, a better solution can be obtained by running a Monte Carlo simulation to allow chance failures to occur and determine a better definition of what failures will occur and how the outflow of funds are balanced against the inflow of funds. The simulation data will provide a better set of financial information.

Answer To Reliability Questions-

The questions and answers are:

a) How long will the equipment function before failure occurs? A specific answer cannot be given, but Figure 5 describes the chances for success. The chances for failure are found by taking the complement of reliability.
b) What are the chances a failure will occur in a specified interval for turnaround? Refer to Table 8 and update the chances for survival using the conditional reliability calculations shown in the system reliability section.

c) What is the best turnaround interval? Refer to Figure 4 which shows a four year interval to be the most cost effective and for this system age the reliability is determined from Figure 5 as driven by the issue of renewal economics.

d) What is the inherent reliability of the equipment? Refer to Table 8 for the mission intervals and the chances for survival.

e) What are risks for delaying repair/replacements? Refer to the cost numbers in Figures 2-4.

f) How can assumptions about reliability be verified? Compare assumptions to existing databases and use internal Weibull failure databases.

g) Where are numbers found to prepare calculations for use by work teams? Consult manufactures databases and experts in the field—expect that most databases will be considered valuable trade secret information.

h) If specific components are improved, how much extension in turnaround time can be justified? This information is found using Monte Carlo simulation of models using assumptions about component life extensions and costs. Do not expect to correct only one problem on well designed equipment. An improvement program is usually required.

i) Does justification exist for a spare system or spare components? On-hand spare parts offer the most attractive investment alternative and adding redundant equipment is the least attractive alternative in Table 9.

Summary-

Methods are shown to answer typical questions about critical equipment replacements and turnarounds. Most of the details are synthesized from other engineering data to build a model. The amount of uncertainty in the numbers needs to be quantified by use of actual failure data from a variety of sources—most likely the engineering assumptions about life of components is too pessimistic and should be validated with actual results. "Critical equipment rarely has a convenient time for renewal outages and the time between turnarounds must be long, safe, and economical" (Geitner 1996).

Humans have a wonderful capability for keeping critical equipment operating. Notice in this case no failures of the system occurred for components such as controllers, linkages, valves, etc. This is because manual control was exercised to prevent the system from failing until the equipment could be repaired on the run.

Actual failure data, particularly from inspection reports at overhaul would provide key pieces of missing information. This lack of data is a common problem in equipment for refineries and chemical plants. A good autopsy report is necessary for both human beings and equipment to help channel resources to fix the correct problem using facts rather than opinions.

Industry wide groups are forming under the guidance of Center For Chemical Process Safety (CCPS) and Det Norske Veritas Technia (DNV). Participants in this effort will funnel chemical plant and refinery failures into databases which will be most helpful for future reliability studies. The continuous process industry needs data from this failure library which must be based on both failures and success—not just failure data alone (which gives results that are too pessimistic).

The best data for use in reliability studies will be found in each plant. The failure data must be collected and put into failure data libraries—particularly in Weibull formats. This data will reflect failures for specific classes of equipment, maintenance practices, operating practices, and so forth which are all unique to a specific site. The data from individual plants must be collected and used—do not only look to suppliers or manufactures for data which is available at local plants by use of a good failure reporting and corrective action system.

As with all reliability issues, good use of a well understood failure criteria is important for executing conditioned based maintenance decisions to supplement time based decisions for equipment turnarounds. Good monitoring equipment and careful analysis of predictive maintenance information is important for knowing when equipment is performing correctly and also for knowing when equipment should receive maintenance attention. As with all engineering analysis, careful and thoughtful use of good judgment should always be applied rather than simply following one scheme of analysis.

The authors solicit thoughtful comments about the approach, methodology, and other failure data that may be available for improving these studies.

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