Chapter 19: Reliability Growth Cause Analysis

These days, we know what needs to be done to make all our machines highly reliable and reduce their rates of failure. The results of research conducted across the world during the late twentieth century explained why machines fail—their parts are overstressed. Furthermore, we know that equipment and machine failures are not unlucky accidents; mostly, they are failed by our "gremlins." We also know that it is possible to choose the failure rate you want for your plant and equipment and then put into place the processes and methods that will naturally deliver it.

Creating high equipment reliability means removing the risk of errors and defects in everything that impacts equipment health. Use error-proof and mistake-proof tasks and methods. Run plant and equipment so that they live well within their engineered design envelope. Provide correct education and skills covering the proper operation of the plant and machinery to all—from manager to operator. Train them to understand their process' engineering so that they know how their plant works. Follow fault-free, accuracy-controlled, proof-tested procedures. Include independent double-checks and even triple-checks in tasks when the risk is great. Teach the procedures until your people are masters at doing them. Get people up and down the organization to help each other and learn from one another by applying the power of teaming up.

Failure Patterns and Failure Modes

Equipment failure follows one of the six probability patterns shown in Figure 19.1, made famous by the 1978 Nolan and Heap study of aircraft maintenance.[1] Evidence from airline industry maintenance in the 1960s and 1970s indicated that, together, failure patterns D, E, and F represented 89% of failures, with pattern F alone, showing infant mortality failure, representing 68%. Other airlines and the U.S. Navy conducted similar studies and confirmed the patterns.

Although the proportions varied between maritime and aerospace conditions, patterns D, E, and F dominated.[2] The curves explain that for most equipment, once the equipment is through its early life period, failure is not age related but is random. This does not mean there are no reasons for failure; rather, it means that the reasons arise by chance so when the event will happen is uncertain. Nolan and Heap questioned the practice of doing regular overhauls: if most equipment failures have nothing to do with the age of the equipment, why are parts replaced on a time basis? You could be throwing away a perfectly good part that is still suitable for many hours of service and you are introducing opportunity for error and defect creation with each intervention.

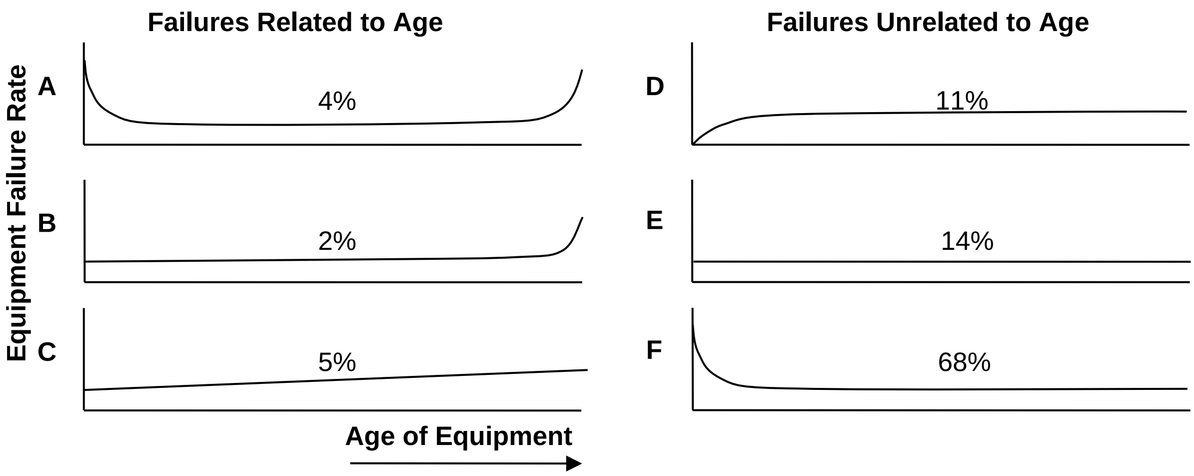


Figure 19.1—Six Failure Patterns Identified for Aircraft Equipment

The three lists in Figure 19.2 cover most of the types of solutions used to prevent equipment failure. The philosophy for preventing machinery failure is explained in the figure—remove the causes of each part's failure modes. If the parts do not fail, the machine does not stop. You can create any amount of equipment reliability that you want by controlling the failure rates of your equipment parts. The failure curves are malleable by continually removing the risks that cause equipment parts to fail. They can be changed by the selection of engineering, operating, and maintenance policies and practices. The evidence of successful reliability improvement shows up as declining rates of parts failure and greater equipment uptime.

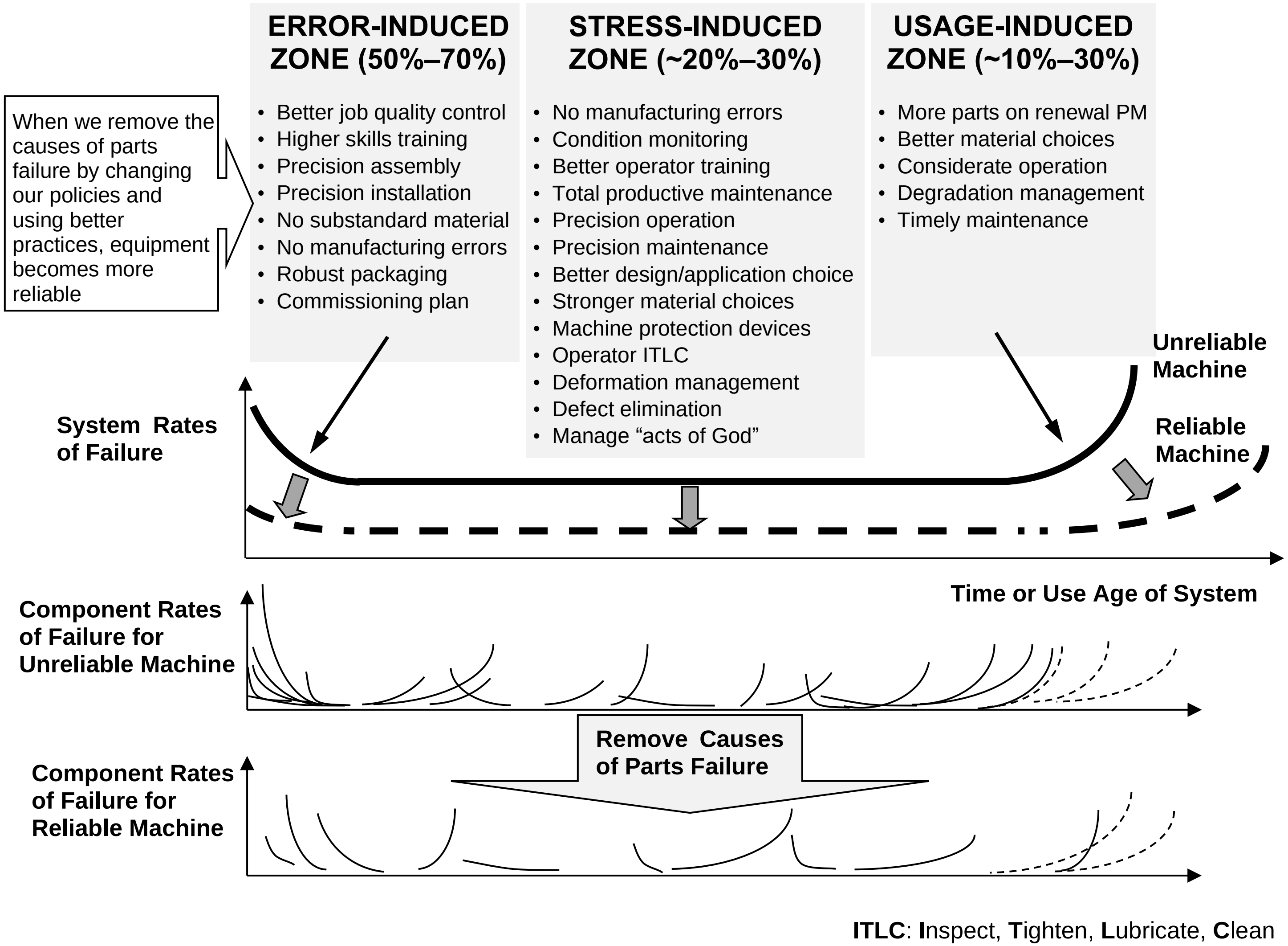


Figure 19.2—What to Do to Have Highly Reliable Machines

Figure 19.3 shows the changed failure rate of equipment that a Plant Wellness Way EAM System-of-Reliability delivers.

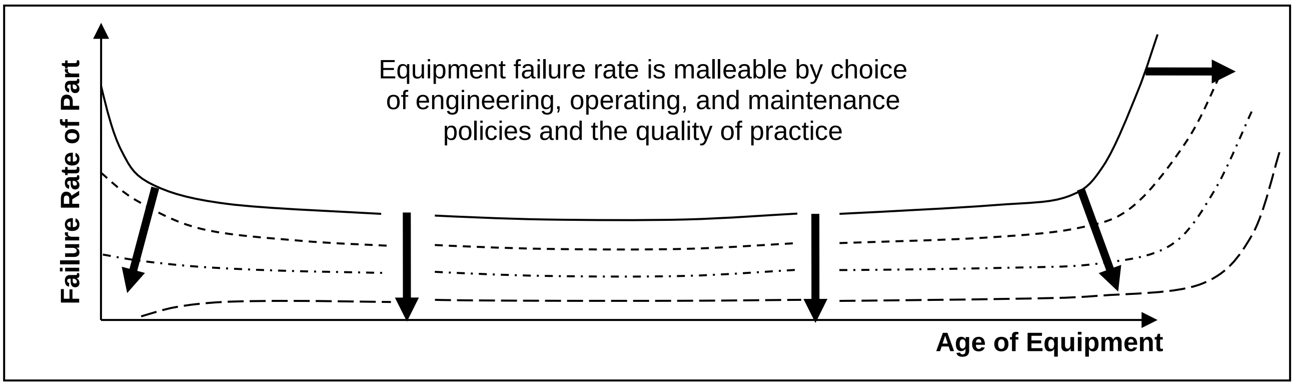


Figure 19.3—The Rate of Failure Is Malleable by Choice of Policies and Quality of Practices

The Role of Maintenance in Reliability Growth

There is only one reason companies do maintenance on their physical assets—because it's cheaper than not doing it. Unless doing maintenance makes a profit by saving money it is wasting money. In the end, maintenance is all about getting the most income from your physical assets.

You only undertake a maintenance program for an equipment item if by doing so it makes more life cycle profit for the business than the other options you could have taken. If maintenance on equipment costs companies more than letting an item fail and replacing it with a new item, you would not do maintenance because the operation would lose money.

You eventually replace equipment when the total cost of its continued use makes less profit over the same period than buying, installing, and using a more modern replacement. You buy new or replacement equipment because it makes more operating profit than maintaining and using the existing asset.

Doing maintenance is based on whether it is the most economic business choice. You don't maintain equipment because it needs care and repair; you do maintenance because it makes more money than doing any of the other equipment use and upkeep choices you could have made. Any company that does not annually do life cycle financial modelling of their equipment maintenance options verses their replacement options verses their hire and lease options, etc., would not know how to maximise their profits and is sure to be doing too much unnecessary maintenance and paying far too much in maintenance costs.

This means that at any time in the life of an operation the future maintenance effort undertaken must make more profit than doing other alternatives. To make the highest profit for the company, it also means your maintenance group and outsourced maintenance service providers need to be stopping, reducing, and solving the problems that cause maintenance. Maintenance makes a profit contribution every time it reduces the failure rate of maintained equipment. The best long-term justification for doing maintenance is to achieve the results shown in Figure 19.2—reduce the number and frequency of failing parts so your get more uptime at lower maintenance expense, to make more production at ever decreasing costs with ever greater profit.

If you only use maintenance for care and upkeep of your machines, without making the machinery more reliable, your maintenance efforts are not generating the most profit for your operation. It also means your plant and equipment are degrading faster and requiring new replacement sooner than is the case if a component reliability growth program were in use.

In Figure 19.2 are listed all the responsibilities that your maintenance group and subcontract service providers ought to be delivering for your company. The maintenance people should be positively contributing to every bulleted item noted in the tables, either by doing necessary actions themselves or by feeding back to the appropriate parties what they know and have learnt about the issue, so it is done more effectively and profitably in future.

To justify its existence in a modern company maintenance must become a profit centre and generate income. Maintenance is not done to care for and maintain equipment, maintenance is done to maximize profit because it generates more money than doing anything else.

Reliability Growth Cause Analysis

Reliability Growth Cause Analysis (RGCA) is a full technical and financial justification to introduce reliability growth strategies. RGCA is all about getting management support to put failure prevention and defect elimination into use quickly. Its purpose is to identify the causes of component failure and show the business value gained by preventing their initiation. You use it to fully understand how parts fail in service and to justify installing the right methods and practices in the life cycle to stop defect creation. Do that proactively, and you will get large operating profits from all the equipment failures you never have.

Improved reliability has a cause. Just like a failure has its causes, there are causes of greater reliability. You can wait for a failure to happen and then learn from the experience and change your processes to prevent it. That is root cause failure analysis. But it is not proactive behaviour. The approach quickly buries you in never-ending problems, and eventually you only make time to investigate catastrophes. You fix a few causes of failures, but not the thousands of defects waiting to create the next lot of disasters. What must be done is shown in Figure 19.4. You create higher reliability in a series arrangement by raising the reliability of each step. To get high plant reliability, stop the problems throughout the life cycle that will become equipment failures. Identify all potential troubles and prevent them from starting by implementing the processes and activities that cause high reliability. A Reliability Growth Cause Analysis is used to decide how to intentionally produce and profit from world-class reliability.

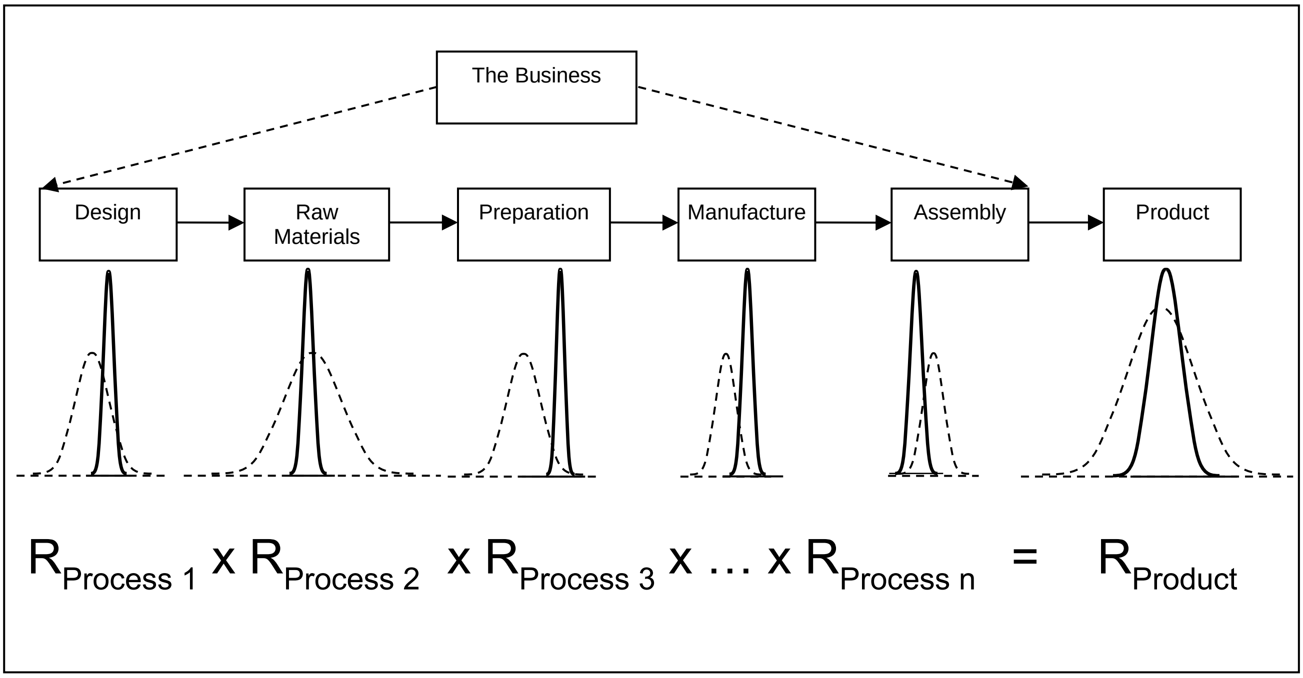


Figure 19.4—Eliminate Risk from Every Process Step and Equipment Part

The maps of your business processes, the workflow diagrams of your operating procedures, and the bills of materials for your equipment are the foundation documents for improving equipment reliability. They are respectively used to make more robust processes, to control human error, and to make a part's material-of-construction microstructure safe and healthy. Reliability Growth Cause Analysis lets you find effective ways to increase the reliability of an equipment part. It looks for what can be done to intentionally reduce stress and remove risk. Part number by part number, every identifiable way to remove and prevent stress, improve the working environment, or eliminate risk to reliability is identified. Every weakness, hazard, or danger is listed in a spreadsheet. Then the cures that bring sure reliability are selected, and you put them everywhere throughout your company.

The RGCA method adopts the same strategy for reliability growth that world-class leaders in industrial safety use for workplace safety improvement. They proactively improve safety by identifying risks and installing appropriate protection against harm before incidents happen. They don't let defects that can become accidents start in the first place. RGCA assumes that failures will happen to equipment parts because of defects created in life-cycle processes unless they are intentionally prevented. It requires recognizing what can cause risk during a part's lifetime and then making the necessary corrections to problematic tasks and introducing process improvements to prevent every cause from starting. Reliability increases by using the right practices and processes to prevent defects and risk alongside those that proactively promote health and wellness. RGCA requires you to identify ways that will drive reliability improvement and not simply prevent failure. Your aim is to never give a process step or part a reason to fail.

Each failure cause is analysed in detail and its POF mechanisms addressed. Table 19.1 shows the range of operational risk, technical, and financial information complied in an RGCA for each component failure cause. The final recommendations identify the strategies, practices, and skills needed in design, manufacturing, procurement, construction, warehousing, operations, and maintenance to deliver lifetime reliability. A robust and timely plan is then developed to introduce them into the organization, including all necessary documents, training, and skills development.

Failure Description: ____ **Cause No.:** ____ **Failure Cause:** _____________________________________
• Frequency of Cause:
• Time to Repair:
• TDAF Cost:

• Causes of Stress/Overload:
• Causes of Fatigue/Degradation:
• Current Risk Matrix Rating:
• Controls to Prevent Cause:
• Estimated Failures Prevented after Risk Controls in Use (/yr):
• New Risk Matrix Rating:
• TDAF Cost Savings from Higher Reliability:

Table 19.1—Reliability Growth Cause Analysis Requirements

RGCA requires us to ask how best to protect against failure-causing events and situations that can become future plant and machinery breakdowns. From design and capital equipment selection, through to board room decisions, and down to the operating procedures and maintenance practices, every phase of the component's life cycle is considered when looking at how to proactively prevent defects from starting. As you perform RGCA for a part, you outline its reliability creation strategy using a spreadsheet like that in Table 19.2. With full knowledge of what makes a part fail, you select the procedures, practices, and skills that prevent stress, fatigue, and degradation of the materials of construction. These are the actions that are incorporated into the organization's methodologies and practices and trained into its people. The size of the risk reduction required determines which reliability growth improvements you will use. At the completion of the RGCA, you will have a list of the necessary activities and quality standards that will deliver equipment part reliability with certainty. Those activities are put into place in your business processes, and the right skills are developed to an expert level in the people who need to do them.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**Reliability Growth Cause Analysis**														
2															
3	Business Process:		Department:					Date of Analysis:							
4	Equipment Number:		Equipment Name:					Operating Criticality Rating:							
5															
6–7			Step 1		Step 2		Step 3		Step 4		Step 5				
8	**Step/Item/Part Description:**														
9	**Procedure Description:**														
10	**Process Description:**														
11	**Part Number:**														
12	**Effect of Step/Item/Part Failure?**														
13	**Failure of Step/Item/Part Causes System Failure (Y/N)?**														
14	**Total TDAF Cost Savings Possible ($/yr):**														
15															
16	**Risks and Controls**														
17															
18	**Failure Mode 1:**														
19	Frequency of Cause 1:														
20	Time to Repair 1:														
21	TDAF Cost:														
22	Causes of Stress/Overload:														
23	Causes of Fatigue/Degradation:														
24	Current Risk Matrix Rating:														
25	Controls to Prevent Cause:														
26	Estimated Failures Prevented after Risk Controls in Use (/yr):														
27	New Risk Matrix Rating:														
28	TDAF Cost Savings with Higher Reliability:														
29															
30	**Failure Mode 2:**														
31	Frequency of Cause 2:														
32	Time to Repair 2:														
33	TDAF Cost:														
34	Causes of Stress/Overload:														
35	Causes of Fatigue/Degradation:														
36	Current Risk Matrix Rating:														
37	Controls to Prevent Cause 2:														
38	Estimated Failures Prevented after Risk Controls in Use (/yr):														
39	New Risk Matrix Rating:														
40	TDAF Cost Savings with Higher Reliability:														
41															
42	**Failure Mode 3:**														
43															
44	**TDAF Cost Savings ($/yr):**														

Table 19.2—Reliability Growth Cause Analysis Spreadsheet Template

Finding the causes of reliability growth requires time, effort, and resources to do the analysis and financial justification. But without making those changes, plant and equipment reliability can never get better. If high reliability were easy, every company would already have it. But high reliability is exceptional because it is demanding and challenging to do well. Few organizations know how to achieve the exacting standards and practices of world-class performance. Without a method to find exactly what to focus on, without the financial justification that high reliability is worthwhile, and without an achievable plan to deliver it, industrial organizations waste away.

Once an RGCA is performed and the right reliability growth actions, knowledge, and practices are identified, they apply to every similar situation. Do an RGCA for one bearing, and you have done it for all similar bearings. An analysis done for a production task applies to every such task done in the operation. Take the learning from each analysis and apply it to every similar situation across your business. When you transfer knowledge, you apply Series Reliability Property 3, and rapid reliability growth can happen in only a matter of weeks as best practices are cascaded across a business. Once the reliability improvement efforts identified in a RGCA are implemented, the chance of failure-causing incidents occurring drops. You get a big reduction in the number of equipment failures because the right actions to produce reliability are done at every stage in a process, workplace task, and throughout a part's life. Your operating profits will rapidly climb, and your safety and environmental performance will become top class.

Reliability Growth Cause Analysis Example 1

The following is an example RGCA for preventing failure of the inner raceway of a single row deep groove ball bearing like the one shown in Figure 19.5.

Figure 19.5—Roller Ball Bearing Arrangement

The process map for the shaft and bearing inner ring arrangement is drawn in Figure 19.6.

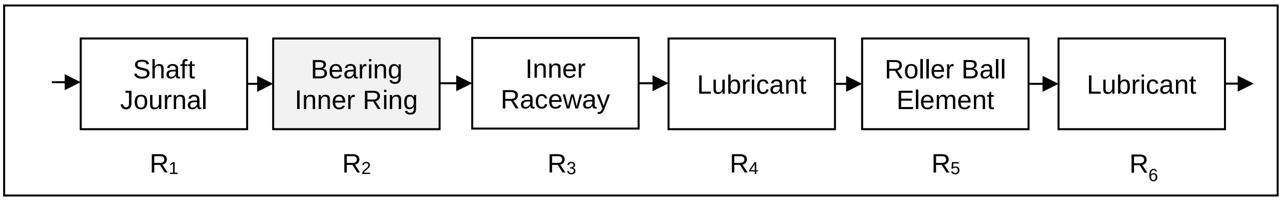


Figure 19.6—Process Map for Roller Bearing Located on a Journal]

In an RGCA, you are charged with finding all the causes of reliability improvement, including what can be done earlier in the life cycle to prevent a failure. First develop a list of known and possible inner ring and raceway failures based on experience and using the Physics of Failure Factors Analysis guidewords. The causes of inner raceway failure include a cracked ring, a scoured or scratched raceway, a brinelled and indented race, a loose-fitting ring, a race suffering electrically arcing, and so on. The next step is to ask what causes each mechanism. How can a particular cause mechanism arise during the life cycle? For example, how can the inner ring be cracked? A cracked ring can occur because of excessive interference fit on the shaft, because of a huge impact load, because the shaft is oval and the ring is forced out of shape, because a solid piece of material is trapped between the ring and shaft during the fitting, or because the shaft is heavily burred and when the ring is forced over the burr it is damaged in the installation process.

Once the causes are listed, they need to be prevented. For a cracked inner ring due to an excessive interference fit, you would ask, how is excessive shaft interference prevented? This problem results from incorrect tolerances between the inner ring and shaft. It is usually a manufacturing error of the shaft or the ring. Therefore, you must develop proactive measures to ensure that a ring is never fitted to an incorrectly made shaft or that an incorrectly made ring is never fitted to a good shaft. One solution is to measure the shaft and the ring with a micrometre and check that the sizes match the manufacturer's tolerance and form requirements for the model of bearing. An additional protection would be to confirm that the bearing model is correct for the service duty and operating temperatures. These checks become procedural requirements that are written into the ACE 3T procedure for the job. An example of the analysis and possible measures for preventing a cracked inner ring are listed in the "Failure Cause 1" column in Table 19.3.

Failure Description: Cracked Inner Roller Bearing Race		
	Failure Cause 1: Excessive Interference Fit	**Failure Cause 2:** Impact to Ring
Frequency of Cause:	Early life—1 per year	Random—3 per year
Time to Repair:	5 hours	10 hours
TDAF Cost:	$20,000	$25,000
Causes of Stress/Overload:	• Large shaft • Small bearing ring bore • Tight clearance	• Hammered when fitting • Start-up with equipment fully loaded
Causes of Fatigue/Degradation:	Not applicable	• Misaligned shafts • Loose ring moving on shaft • Loose clearance
Current Risk Matrix Rating:	Medium	Medium
Controls to Prevent Cause:	• Update all bearing fitting procedures to measure shaft and bore; confirm correct interference fit at operating temperature and train people annually • Update all machine procurement contracts to include quality check	• Update all bearing fitting procedures to include using only approved tools and equipment and train people annually; purchase necessary equipment, schedule necessary maintenance for equipment

	of shaft diameters before acceptance of machine for delivery • Update all bearing procurement contracts to include random inspections of tolerances • Update all design and drawing standards to include proof check that shaft measurements and tolerances on drawings suit operating conditions once bearing is selected	• Change operating procedures to remove load from equipment prior to restart and train people annually (Alternative: Soft start with ramp-up control if capital available) • Align shafts to procedure and train people annually • Update bearing fitting procedures to measure shaft and bore; confirm correct interference fit at operating temperature and train people annually
Estimated Failures Prevented after Risk Controls in Use (/yr):	All future failures	80% of future failures
New Risk Matrix Rating:	Low	Low
TDAF Cost Savings from Higher Reliability:	$20,000 per year	$60,000 per year

Table 19.3—Example Reliability Growth Cause Analysis on Inner Ring of a Roller Bearing

Continue with the next cause of a crack in the inner ring—heavy impact—and develop preventive actions. (Impact damage can occur when a ring is fitted to a shaft with hammer blows or overloaded in a press, brinelling during shipping and road transport, a badly aligned shaft cyclically vibrates the race and rolling elements together, or it suffers a huge start-up impact load.) The process continues for a shaft that is oval, for a solid piece of material trapped between the race and shaft during the fitting, for a heavily burred shaft, and so on. Each failure cause gets its own column, and the table grows until all causes are listed so they can be addressed with effective risk elimination or preventions activities. With each preventive measure put into place and made standard practice by using ACE 3T procedures and workforce training, the reliability of your equipment parts and plant increases.

Reliability Growth Cause Analysis Example 2

This example of a Reliability Growth Cause Analysis is for an internal combustion engine driving a fire pump in a gasoline fuel storage terminal. A fire pump engine is a vital element of the firefighting service if a fuel terminal has a blaze. It acts as a backup to an installed electric motor driven pump, which runs first to supply water to the terminal tanks' spray nozzles. If the electrical power supply fails, the engine-driven pump starts up and provides the water to fight the fire.

First identify each critical part in the asset. Exploded assembly drawings like that in Figure 19.7 and bill of materials parts lists identify the components in equipment.

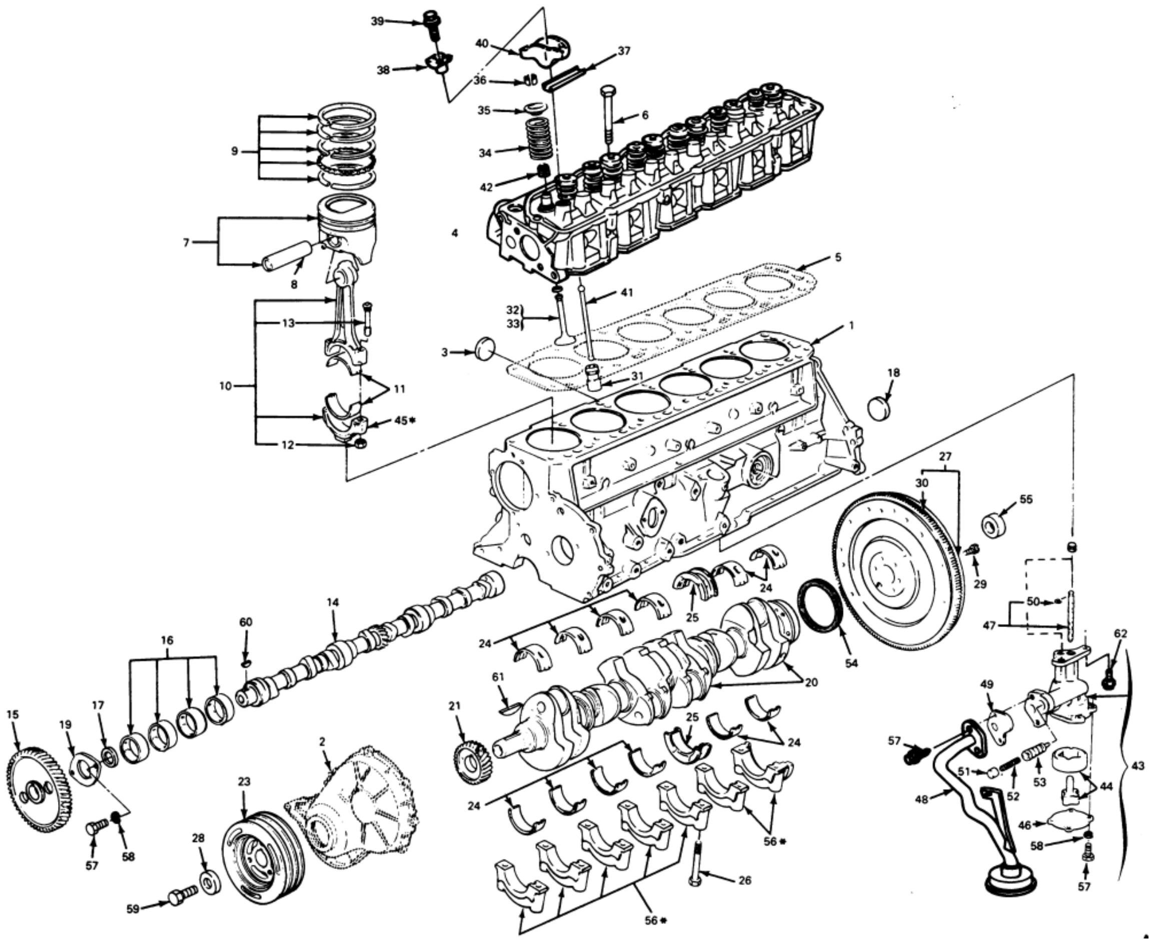
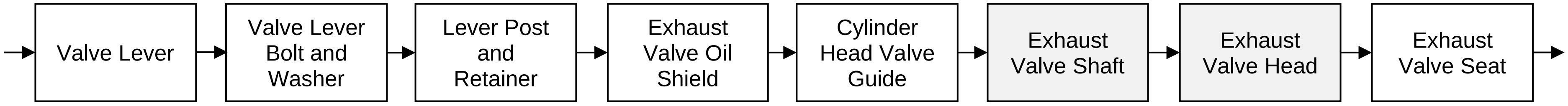


Figure 19.7—Combustion Engine Parts Exploded Drawing

The risk matrix used in this analysis is shown in Table 19.6 at the end of the example.

Process Map of Selected Parts Operation and Use

If the critical parts are not obvious, develop a process map of the parts in use when the machine is in operation and identify each item in the chain of parts that could cause the machine to fail. Diagrams like Figure 19.8 show series arrangements that are high-risk locations for failure. Then put each critical part through its RGCA, like Table 19.4, to identify ways to increase lifetime reliability.



The flowchart shows the sequence of parts required to operate the exhaust valve in the internal combustion engine shown in the exploded drawing (Figure 19.7). The exhaust valve is opened by a series of mechanical parts to release the compressed exhaust gases. The hot gases (greater than 1,000° C) flow past the valve head and the valve seat embedded in the cylinder head. The timing of the opening is set by mechanical connection to the position of the crank and can be adjusted somewhat to select the optimal point to maximize the removal of burnt gases.

Figure 19.8—Exhaust Valve Operation Process Drawing

Reliability Growth Cause Analysis for Exhaust Valve	
Step/Item/Part Description:	Item 41—Valve, Exhaust
Procedure/Drawing No. and Description:	Bill of materials and exploded parts drawing for internal combustion engine
Process Description:	Fuel terminal fire water supply pump drive motor—required operating life is 50 years (potential 100 years)
Part Number:	6505
Effect of Step/Item/Part Failure?	Engine cannot operate at full capacity because exhaust valve damage prevents compression. If valve failure occurs during firefighting duty, only the standby electric fire pump is available for backup duty.
Failure of Step/Item/Part Causes System Failure (Y/N)?	Yes—if not repaired at onset of valve damage, engine block head and cylinder block piston can be destroyed
Total TDAF Cost Savings Possible ($/yr):	A compete strip-down and rebuild of the engine costs $25,000, and 1-month downtime. Over a 50-year life, this produces an annualized cost of $500/year. Above the financial cost, the company's reputation with the regulators will suffer if the fire pump drive engine fails.
Risks and Controls	
Failure Stress Cause 1:	Exhaust valves' seat burned from normal use
Frequency of Cause 1:	The engine has a total of about 100 hours of operation per year. The motor is run for two hours each week on test and to prove that the fire water piping circuit does not leak. Valves could fail after about 4,000 hours of operation (around 40 years), although they are unlikely to fail before 3,000 hours in service (about 30 years).
Time to Repair 1:	Up to 1 month
TDAF Cost:	$25,000 once in a 50-year operating life with motor sent off site for urgent repair (annualized cost of $500)
Causes of Stress/Overload:	Not applicable
Causes of Fatigue/Degradation:	Exhausts valves are expected to degrade with use
Current Risk Matrix Rating:	This motor has a service life of 50 years as a fire pump prime mover in a tank terminal. Should it fail, the regulators will scrutinize the operation and become concerned that the company has poor maintenance practices. Likelihood 3; Consequence 3 = **M**
Controls to Prevent Cause:	Introduce planned replacement of all exhaust valves, seats, and valve guides at 3,000 hours or 25 years' service, whichever comes first
Estimated Failures Prevented after Risk Controls in Use (/yr):	No failures are expected due to this mode of failure if exhaust vales are replaced every 25 years

New Risk Matrix Rating:	Likelihood 1; Consequence 3 = **L/M**
TDAF Cost Savings with Higher Reliability:	The planned refurbishment requires new exhaust valves and reseating. It is a two-day job done on site. Cost is $5,000 every 25 years.
Failure Stress Cause 2:	Exhaust valve seat burned from a valve timing error
Frequency of Cause 2:	The engine is tuned once annually, or about every 100 hours of operation
Time to Repair 2:	Up to 1 month
TDAF Cost:	$25,000 once in 50 years motor sent off-site for urgent repair (annualized cost of $500)
Causes of Stress/Overload:	Localised high temperature at valve head edges and valve seat as exhaust gas flows past valve and seat due to valve closing late or opening early
Causes of Fatigue/Degradation:	Not applicable
Current Risk Matrix Rating:	The opportunity for a timing error arises annually and will not be corrected for twelve months, provided the error is then detected. In a 50-year operating life there will be 50 opportunities to mistakenly set valve timing. With 100 hours of annual service accumulated at a rate of two hours per week there is little time for the valve/seat to be burnt by one error. The valve is most likely to fail if the valve timing is not rectified for some years. Likelihood 3 ; Consequence 3 = **M**
Controls to Prevent Cause 2:	Introduce ACE 3T procedures to control tasks and to ensure a record of all valve timing adjustments is made and can be used to compare future settings.
Estimated Failures Prevented after Risk Controls in Use (/yr):	No failures are expected due to this mode of failure after ACE 3T procedures and recording is introduced
New Risk Matrix Rating:	Likelihood 1 ; Consequence 3 = **L/M**
TDAF Cost Savings with Higher Reliability:	No costs are expected in future from this failure mode when mitigation is performed
Failure Stress Cause 3:	Valve train and associated parts are wrongly installed, and components come loose or break, and valve falls into cylinder
Frequency of Cause 3:	This failure is only expected after a rebuild of the motor or a cylinder head is refurbished or replaced. The opportunity for this failure arises whenever other failure causes require the engine or cylinder heads to be removed. Errors in rebuilding such a complicated piece of equipment should be expected. It is estimated that once every twenty years a rebuild will arise, which is twice during the motor's operating life, and one of them will go wrong.
Time to Repair 3:	Up to 1 month

TDAF Cost:	$25,000 once in a 50-year operating life with motor sent off site for urgent repair (an annualized cost of $500)
Causes of Fatigue/Degradation:	Human error or faulty parts
Current Risk Matrix Rating:	Likelihood 3; Consequence 3 = **M**
Controls to Prevent Cause 3:	Introduce ACE 3T procedures to control engine rebuild and overhaul tasks. If work is done by a subcontractor or repair shop, ensure compliance with ACE 3T precision quality standards and implement tests and observation during rebuild to confirm compliance to quality requirements
Estimated Failures Prevented after Risk Controls in Use (/yr):	No failures are expected due to this mode of failure after ACE 3T procedures and recording are introduced
New Risk Matrix Rating:	Likelihood 1; Consequence 3 = **L/M**
TDAF Cost Savings with Higher Reliability:	No costs are expected in future from this failure mode when mitigation is performed
TDAF Cost Savings ($/yr):	Total annualized savings of $1,500 expected from the mitigations

Table 19.4—Reliability Growth Cause Analysis Development

Summary Table of Reliability Growth Cause Analysis Plan

Present the results of the RGCA in a summary table like Table 19.5. This table is what is used to show others the operational and financial benefits of doing the actions identified in the analysis.

Reliability Growth Cause Strategy for Exhaust Valve			
Failure Description: Failure of Exhaust Gas Valve in Fire Pump Drive Motor			
	Failure Stress Cause 1: Exhaust Valves' Seat Burned from Normal Use	**Failure Stress Cause 2:** Exhaust Valve Seat Burned from a Valve Timing Error	**Failure Stress Cause 3:** Valve train parts Are Wrongly Installed and Components Come Loose
Frequency of Cause:	Wear-out—1 per 50 years	Random—1 per 50 years	Early life failure—1 per 50 years
Time to Repair:	Up to 1 month	Up to 1 month	Up to 1 month
TDAF Cost:	$25,000	$25,000	$25,000
Causes of Stress/Overload:	Not applicable	Exhaust gases burn valve	Parts come loose and fail to operate properly or break
Causes of Fatigue/Degradation:	Gradual degradation from use	Not applicable	Not applicable
Current Risk Matrix Rating:	Medium	Medium	Medium
Controls to Prevent Cause:	Introduce planned replacement of all exhaust valves, seats, and valve guides at 3,000 hours or 25 years of service	Introduce ACE 3T procedures to control tasks and to ensure that a record of all valve timing adjustments is made and can be used to compare future settings	Introduce ACE 3T procedures to control engine rebuild and overhaul tasks
Estimated Failures Prevented after Risk Controls in Use (/yr):	All future failures prevented	All future failures prevented	All future failures prevented
New Risk Matrix Rating:	Low/Medium	Low/Medium	Low/Medium
TDAF Cost Savings from Higher Reliability:	$500 per year	$500 per year	$500 per year

Table 19.5—Reliability Growth Cause Analysis Strategy Summary

Risk Mitigation Assessment Matrix

Use the organisation's risk matrix to show the risk reduction achievable from the RGCA recommendations and the potential financial worth they represent.

E – Extreme risk: Detailed action plan required
H – High risk: Needs senior management attention
M – Medium risk: Specify management responsibility
L – Low risk: Manage by routine procedures

Extreme or **High** risk must be reported to Senior Management and require detailed treatment plans to reduce the risk to **Low** or **Medium**

	Consequence				
People	Injuries or ailments not requiring medical treatment	Minor injury or first aid treatment case	Serious injury causing hospitalization or multiple medical treatment cases	Life-threatening injury or multiple serious injuries causing hospitalization	Death or multiple life-threatening injuries
Reputation	Internal review	Scrutiny required by internal committees or internal audit to prevent escalation	Scrutiny required by clients or third parties, etc.	Intense public, political, and media scrutiny (e.g., front-page headlines, TV, etc.)	Legal action or commission of inquiry or adverse national media
Business Process & Systems	Minor errors in systems or processes requiring corrective action or minor delay without impact on overall schedule	Policy procedural rule occasionally not met, or services do not fully meet needs	One or more key accountability requirements not met; inconvenient but not client welfare threatening	Strategies not consistent with business objectives; trends show service is degraded	Critical system failure, bad policy advice, or ongoing noncompliance; business severely affected
Financial	<$500>	<$5,000>	<$50,000>	<$500,000>	<$5,000,000>
	Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**

	Probability:	**Historical:**			**1**	**2**	**3**	**4**	**5**
Likelihood	> 1 in 10	Is expected to occur in most circumstances	**5**	**Almost Certain**	**M**	**H**	**H**	**E**	**E**
	1 in 10–100	Will probably occur	**4**	**Likely**	**M**	**M**	**H**	**H**	**E**
	1 in 100–1,000	Might occur at some time in the future	**3**	**Possible**	**L**	**M**	1 **M**	**H**	**E**
	1 in 1,000–10,000	Could occur but doubtful	**2**	**Unlikely**	**L**	**M**	2 **M**	**H**	**H**
	1 in 10,000–100,000	May occur but only in exceptional circumstances	**1**	**Rare**	**L**	**L**	**M**	**M**	**H**

Table 19.6—Risk Management RGCA Strategy Effectiveness

Including POFFA in a Reliability Growth Cause Analysis

To improve the certainty of a comprehensive outcome when doing a Reliability Growth Cause Analysis, you can include a Physics of Failure Factors Analysis for every critical part. Once at-risk components that will stop the equipment are identified, you can use POFFA to find the cause mechanisms of stresses and the environmental conditions that lead to failure and identify where those situations arise. With the causes known, you build in protection at every stage of the life cycle to prevent the circumstances from developing. This Physics of Failure refinement of the RGCA methodology lets you create business processes across the life cycle that contain the proper actions and activities to deliver the least operational risk. An RGCA combined with POFFA helps you discover exactly what to do to produce outstanding reliability. Equally important, it gets you to identify how well each life-cycle task must be done so that exceptional reliability is guaranteed in your equipment.

Setting Reliability Standards That Deliver Outstandingly Reliable Equipment

Because high equipment reliability and production plant availability are business and life-cycle process outputs, you need to intentionally make your processes produce those results. Reliability starts with what the original equipment manufacturer made. If the reliability of an equipment design is inadequate for your needs, you will suffer high maintenance costs and get poor production results. The decision to buy machinery for a project is the outcome of a business process. The accuracy with which it is installed during construction is also a business process result. How well a machine is treated in operation is also a business choice. The reliability performance that you get from all your physical assets is a product of what you let your business processes do to them. To improve equipment reliability, you need to correct your business processes to make them deliver a better reliability result. You will need to work to the higher standards that produce the plant and equipment reliability you want. If you want world-class reliability, you will need to meet every quality standard that puts your machinery parts into their precision zones and then keeps them there.

Challenge Your Business to Meet High Precision Standards

Just because something is built to an internationally recognized standard or industry code, that does not make it good. Nor does using an international standard make for a risk-free design choice. For example, the specified tolerance for baseplate flatness designated in the American National Standards Institute (ANSI) pump standard is 0.375 mm/m (0.005 in/ft). The same requirement in the American Petroleum Institute (API) 610 pump standard is 0.150 mm/m (0.002 in/ft). That higher precision, with API 610 being two and a half times more demanding than ANSI, produces much higher pump reliability. API 610 pumps are designed to last many years between breakdowns; for the same service, ANSI pumps will likely last for much less time.

I began my career as a professional engineer in Perth, Western Australia, in one of the world’s first fully automated breweries. A brewery is a great place for a new engineer to learn the profession because the making and packaging of beer uses a wide range of plant and machinery in diverse process manufacturing operations. It’s a microcosm of the engineering world—from high-speed packaging equipment to agitated lauders, to specialty alloys for hot caustic washes, and distributed process control systems to run all the computer-controlled plants—you learn a lot in quick time. But one thing was done wrong to me.

I was told when I started as a new project engineer to use the same standards the brewery was built to. The company engineering standards stipulated the use of stainless-steel ANSI pumps. So, I bought ANSI standard pumps for many capital projects during the nearly eight years I worked at the brewery. I did not know, and no one ever told me, that if you buy an ANSI pump, you are very likely to bring your company a lot of breakdowns, problems, and high maintenance costs.

The allowed ANSI baseplate un-flatness of up to 0.375 mm/m before the base must be rectified is a massive soft foot distortion problem. A new ANSI pump can be distorted so severely that you will have many breakdowns from internal components twisted out of shape by the 0.375 mm/m soft foot. When you pay to get a new ANSI pump, you carry a big risk that you will also be buying many failures because the equipment standard allows huge variation to be passed off as good quality. The API 610 pump standard instead demands that flatness be no worse than 0.150 mm/m. At that level of quality, you are forced to address soft foot and thereby prevent pump distortion. Because of the better precision, pump reliability naturally increases. But you can do much better if you want to get truly outstanding reliability. The API pump flatness standard is still well short of what a world-class standard would be. A flatness of 0.05 mm/m (0.0007 in/ft) is readily achievable with modern machining equipment and practices.

This story illustrates how project engineers unwittingly destroy business profitability. Be careful what standards you select for your production equipment because that choice alone can be the cause of high maintenance costs. Once a bad machine is selected, the maintenance crew and the plant operators can do nothing to address it. All that is left for them to do during the operation phase is to keep fixing the machine when it fails.

Set Precision Targets for Accuracy-Controlled Reliability

It is useful to know what standards will deliver high machinery reliability. Table 19.7 lists suggestions for 3T standards of machinery built to precision maintenance quality. The table is for 2-, 4-, and 6-pole speed machinery. The values are unsuitable for high rotational speed machines. Such equipment needs even more exacting standards. The target value is the ideal outcome. The tolerance is the maximum allowance before rectification action must be taken immediately. The tolerance range is an engineering choice reflecting a balance between the consequence and likelihood of failure and the need to keep the plant in operation. An IT7 dimensional tolerance and a G2.5 balance are not precision values. But they are shown in the table as worst-case values so that machines can stay in operation until a maintenance shutdown can be planned. Sometimes you will set wider allowances and accept higher operating risk for the sake of expediency. But then you must watch the equipment condition and manage the risk well. Because machines are designed for a wide variety of duties, the suggestions in the table may not suit all operational situations. Every company must investigate and choose the quality standards it will live by in its operation. Subject matter experts are best placed to recommend the standards that bring high reliability.

ACE Standards for Creating Plant and Equipment Wellness and Machine Reliability							
No.	**Process Failure**	**Observation**	**Effect on Machine**	**Life Precision Requirement**	**Parameters**	**Target Value**	**Tolerance**
1	**Poor lubrication condition**	Chemistry; Contamination; Water	Short Component Life	Chemically correct, contaminant-free lubricant	Viscosity, additives, dissolved water, wear particle count	Right viscosity at operating temperature; correct proportion of additives; < 100 ppm water; ISO 4406 12/_/_ cleanliness	ISO 4406 14/_/_ cleanliness
2	**Wrong fits and tolerance**	Dimensions; Form	High Stress; Looseness; Vibration	Accurate fits and tolerance at operating temperature	Interference fit, operating temperature	Form IT5, operating temperature at design conditions	IT7
3	**Running off-centre**	Dimensions; Form	High Stress; Vibration	Shafts, bearings, and couplings running true to centre	Centre of rotation, run-out, tolerance and form accuracy	IT5	IT7
4	**Deformed, bent, buckled parts**	Dimensions; Form	High Stress; Vibration	Distortion-free equipment for its entire lifetime	Soft foot, structural distortion	IT5	IT7
5	**Excessive loads and forces**	Vibration	High Stress	Forces and loads into rigid mounts and supports	Design load, forces into solid locations, foundation rigidity	No looseness; safely absorb/dampen forces	
6	**Misaligned shafts**	Dimensions; Form	High Stress; Vibration	Accurate alignment of shafts at operating temperature	Shaft alignment, straightness, deflection	Coupling/feet offset 10 µm/20µm	20 µm/40µm
7	**Unbalanced rotors**	Dimensions; Form; Balance	High Stress; Vibration	High-quality balanced rotating parts	Rotor balance, centre of mass	G1	G2.5
8	**Induced and forced vibration**	Dimensions; Form	Vibration	Total machine vibration low	Machine vibration, machine distortion, structural rigidity	1.5 mm/s rms	4 mm/s rms
9	**Incorrectly tightened fasteners**	Tension	High Stress; Looseness	Correct torques and tensions in all components	Shank tension, looseness, fastener grade	±5% of correct tension	±10%
10	**Poor condition tools and measures**	Measurement Accuracy and Repeatability	High Stress; Looseness	Correct tools in precise condition to do task to proper standards	Good-as-new condition, reliably calibrated	As new condition/correctly calibrated	
11	**Inappropriate materials of construction**	Engineering Selection	High Stress	Only in-specification parts	Material of construction, dimensional specification	OEM-approved material and design specs	
12	**Root cause not removed**	Dimensions; Form; Precision Standards	High Stress; Looseness; Vibration	Failure cause removal during maintenance	Creative disassembly, defect elimination	Use creative disassembly and precision assembly	
13	**Precision skills and techniques not applied**	Dimensions; Form; Precision Standards	High Stress; Looseness; Vibration	Highly skilled technicians competent in precision techniques	Intelligent, competent, proactive, problem solvers	Equipment is consistently set up to world-class work quality standards	
14	**Assembly quality below standard**	Dimensions; Form; Precision Standards	High Stress; Looseness; Vibration	Proof test for precision assembly quality	Inspection test accuracy, precision standard	Ensure every activity is proven correct (apply Carpenter's Creed)	Milestone tasks tested
15	**Process out-of-control and/or not capable**	Dimensions; Form; Precision Standards	High Stress; Looseness; Vibration	A quality assurance system to make all the above happen	Quality control standards, process in statistical control	ACE 3T procedures	ITP (Inspection and Test Plan)
NOTE: *Suggested values for 2-, 4-, and 6-pole motor speeds. These parameters are indicative and may not apply to a particular machine. Confirm actual requirements with the manufacturer or an expert.*							

Table 19.7—Indicative Target Values for Reliable Machines (2-, 4-, and 6-Pole Motor Speeds)

FOOTNOTES

1. Stanley F. Nolan and Howard F. Heap, *Reliability Centred Maintenance* (San Francisco: Dolby Access Press, 1978).

2. Some dispute exists with the curves since it was not clear in the studies which items were parts and which were equipment, nor which items were refurbished and reused, and which were replaced with new. As per, David J, Sherwin, "A Critical Analysis of Reliability-Centered Maintenance as a Management Tool", International Conference of Maintenance Societies, Australia, 2000. Proceedings.