Chapter 11: Removing Risks and Raising Reliability

Equipment reliability is a measure of the odds that an item of equipment will last long enough to do its duty. It is the chance of a thing remaining usable until a particular point in time. When equipment operates at duty capacity for as long as expected, it is considered reliable. When the period between out-of-service episodes is too short, it is considered unreliable. You measure the reliability of equipment by its trouble-free time. If the equipment is meant to last for 10,000 hours (about 14 months of continuous operation), and it does last that long, it is 100% reliable to 10,000 hours. But if after 10,000 hours there is an occasional failure, its reliability beyond 10,000 hours is less than 100%. When we talk about and measure reliability, we must also say what period is involved. Table 11.1 defines the words and terms commonly used in reliability improvement.

Term	Definition
Critical Item	A part or assembly for which a failure mode(s) remains and has not been designed out. These items require operating and maintenance strategies to ensure a long, trouble-free life.
Criticality	A measure that combines severity (the cost and inconvenience of the failure) and frequency (how often a failure occurs) to indicate the overall risk caused by the item if it fails.
Failure	Any unwanted or disappointing behaviour of an item.
Failure Effect	The impact on performance from the item's failure.
Failure Mechanism or Failure Cause	The processes by which the failure mode(s) arise, including physical, mechanical, electrical, and chemical causes or other processes and their combinations. Knowledge of a failure mechanism provides insight into the conditions that cause failures.
Failure Mode	How a part or combination of parts fails. Failure modes can be electrical (open or short-circuit, stuck at high), physical (loss of speed, excessive noise), or functional (loss of power gain, communication loss, high error level).
Failure Site	The physical location where the failure mechanism is observed to occur; it is often the location of the highest stresses and lowest strength.
Redundancy	The use of duplicate or more items so upon the failure of one another takes over the role. It presumes the replicated item is ready and available to immediately take on the full service.
Reliability Improvement	Documented explanation of why known failure modes occur and how to address them. This is the basis for engineering, operating, and maintenance strategies for a part or assembly.

Table 11.1—Reliability Improvement Terms and Definitions

You can largely control how long you want equipment to be reliable. You get high equipment reliability by ensuring that the chance of parts failing is extremely low. The secret to remarkably long-lived, trouble-free machines is keeping their components at low stress so that there is no risk of microstructure deformation and providing a healthy contacting environment so that the material does not degrade. If there is nothing to cause a failure, a failure will not happen, and your equipment will continue in service at full capacity and full availability.

Equipment reliability needs to be seen as more than just a time span. Reliability is a business imperative for companies that use physical assets. You need highly reliable plant and equipment if you are to build a business that is a world-class performer. High-reliability organizations expect equipment to last a long time, and they are unhappy when it does not. Not only are they unhappy, but also, they take effective measures to learn from and improve because of failures.

Identifying Equipment Reliability Growth Opportunities

You must deeply want the production and profit benefits that equipment reliability brings before you will do what is necessary to get them. You get plant and equipment to operate trouble-free for a long time only when you do those activities that cause high reliability and do them well enough to produce high reliability. To get outstanding equipment reliability, you must control failures in your equipment across the life cycle and operate and maintain equipment with masterly precision. If you want high production uptime and low operating costs, you will need to implement engineering, purchasing, supply chain, storage, operating, and maintenance regimes and practices that deliver the reliability and life-cycle costs you want.

A great reliability strategy describes in detail how to ensure high reliability for your operating assets. Plant reliability can only be improved in one of two ways: (1) by using redundancy so that another unit takes over when the duty unit fails (see parallel arrangements in Chapter 1) or (2) by making each equipment in the operation supremely reliable so it is failure-free during service. Reliability solutions involve applying the three Series Reliability Properties and building in parallel arrangements. The Series Reliability Properties and parallel arrangements are foundational concepts for reducing the risks to all operating equipment and work tasks. With them, you can create the reliability you want by embedding in your engineering, procurement, supply chain, operating, and maintenance processes those best practices and right methods that are sure to deliver it.

Apply Series Reliability Property 1

The reliability of a series system is no more reliable than its least reliable component.

Unreliable equipment is known as a “bad actor.” They cause a lot of production troubles. Series Reliability Property 1 advises you to fix your bad actors or else they’ll stop your business from performing at its best and generating high operating profits. To get high equipment reliability, you need to ensure that every critical part of the equipment is highly reliable. Figure 11.1 is a top-level process map for a centrifugal pump-set when it is in operation. This item of equipment will be used as an example for developing a plan to make effective reliability improvements.

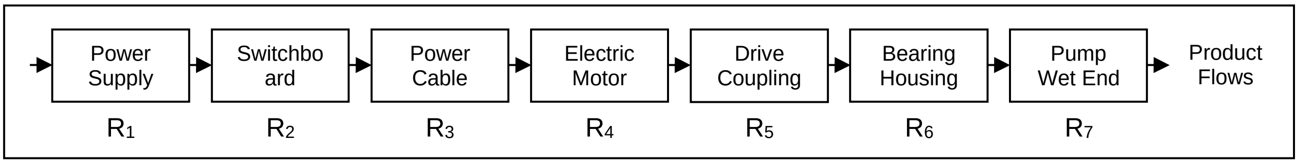


Figure 11.1—A Centrifugal Pump-Set Process Map

Series Reliability Property 1 requires you to identify whether the reliability of the least reliable items needs improvement. For the pump-set example, a minimum series reliability of 0.9999 is expected from the equipment—that is, there is a chance of one failure in 10,000 opportunities. In a continuously operating process plant that runs the pump 10 times a day, 10,000 opportunities represent 1,000 days without a failure—about three years of service. To get that level of reliability from the pump-set system, each item depicted in the process map needs greater individual reliability. We can estimate the scale of the individual item reliabilities required by using Formula 1.2 and assuming the first four electrical items in the process have equal reliability and that the three mechanical items have 10 times less reliability. Industrial mechanical equipment is less reliable than electrical equipment, with mechanical equipment typically incurring 10 times more failures in the same period than electrical equipment.[1]

$$R_{\text{Pump-set}} = R_1 \text{ x } R_2 \text{ x } R_3 \text{ x } R_4 \text{ x } R_5 \text{ x } R_6 \text{ x } R_7 = 0.9999$$

$$R_{\text{Pump-set}} = 0.9999971^4 \text{ x } 0.999971^3 = 0.9999$$

A pump-set reliability of 0.9999 requires an individual electrical item reliability of 0.9999971—about three failures in every 1,000,000 opportunities for failure—and a mechanical item reliability 0.999971—three failures every 100,000 opportunities. Each electrical item must have only one failure every 100 years and each mechanical item one failure every 10 years in order for the pump-set to have only one failure in three years.

One hundred years of failure-free electrical system operation is a daunting requirement. Such reliable electrical equipment cannot yet be made with guaranteed certainty of success using the technologies now available. With good maintenance, it is not impossible for electrical transformers, switchboards, and cables to remain in operation for 50 to 100 years, although failure rates for their components will rise as they age in service. Already it is clear that predictive and preventive maintenance will be needed for parts that degrade during the service life of the system. Some equipment, such as the electric motor and transformer tap changer will require total overhaul several times during the decades ahead. Replacement with new parts will be necessary for many of the electrical items at least once, and in some cases twice, during the next 100 years.

Mechanical items in the equipment will need to be replaced several times to get a century of failure-free service from the pump-set. One failure in 10 years is a challenging but not impossible goal for most mechanical parts in non-abrasive or corrosive services. The most unreliable machinery component is the mechanical seal in the pump. These seal types can experience variable and unsteady operating conditions that cause them to fail sooner than once in 10 years—including cavitation, pump vibration, pump frame distortion, water hammer, shaft misalignment, torque overload, poor assembly on installation, corrosion, wear and impact, and chemical decomposition of elastomeric items. To get higher reliability for the pump-set system, the reliability of the mechanical items must be raised. Series Reliability Property 1 advises you to work on new ways to make the least reliable mechanical components much more reliable. The mechanical items in the pump-set require better solutions to prevent degradation and stress in the components' materials of construction to achieve higher reliability. This is where the process map helps identify more reliable options than those currently in place.

Localized reliability improvement of individual process steps or equipment parts is vital when the improved reliability delivers a strong return on investment. These improvements can include use of better-engineered designs, using parts that are more robust, better installation practices, better operating practices, better maintenance strategies, and even complete equipment replacement with a more reliable item. The economics of the situation will drive which choices you make—higher costs and losses justify spending more money to prevent the problem. It is sensible to do a life-cycle costing model to understand the effects of TDAF costs, replacements, and capital expenditures on the future of the operation.

Figure 11.2 shows quality assurance tasks and precision activities added in parallel to the mechanical items. When done correctly, they greatly increase component lifetimes. Adding the life-cycle requirements of using engineering quality specifications to remove modes of failure, equipment installed with precision procedures to prevent deformation, shafts correctly aligned to precision standards, and the pump-set precision operated to minimize component stress and degradation will produce long-lived assemblies and a failure-free pump-set during its working life. These practices are learned skills and techniques that prevent stresses and errors from being introduced, and their use lifts equipment reliability. Paralleling precision skills with high work accuracy and defect removal raises the reliability of each mechanical item. The process map makes it easy to see where to add parallel life-cycle tasks to improve operating equipment reliability.

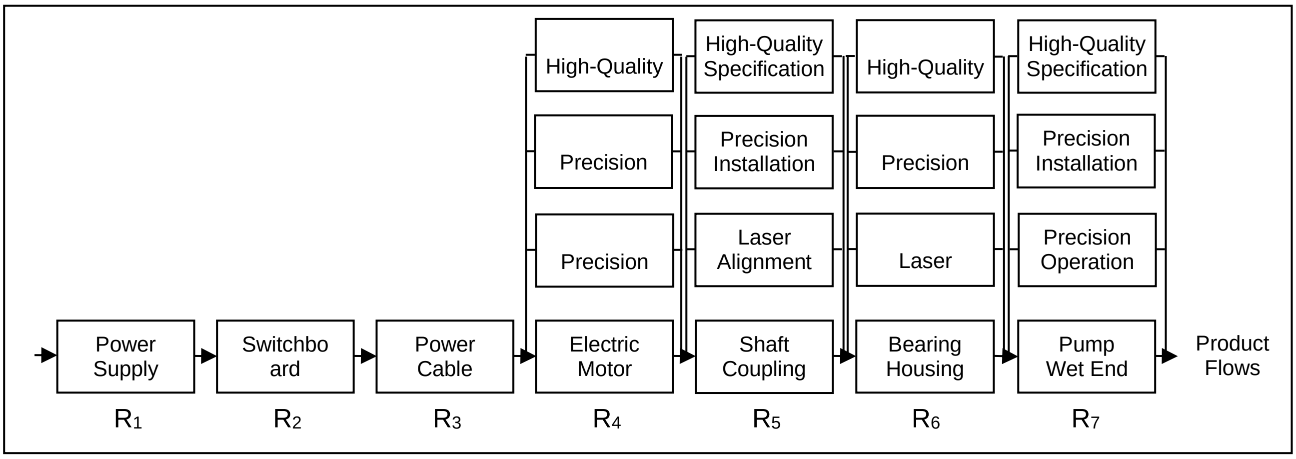


Figure 11.2—Centrifugal Pump-Set Reliability Improved by Parallel Tasks

Very few operations will use the same equipment for 100 years. Practically speaking, most businesses will build another plant in 30 to 50 years or modernize equipment when productivity degrades too severely and continue operation with brand-new assets. The most progressive companies will continually upgrade their equipment with the latest model when the current equipment has repaid its investment or when new equipment becomes available with a sufficiently high return on investment to justify a change out. This strategy ensures they will never have "old" plant in use, thereby guaranteeing high reliability. It is an effective way to constantly gain the benefits and higher profits for their company of reliability improvement from the equipment manufacturer's technological and engineering innovations. Nonetheless, while equipment is in a location, you want failure-free service for its entire working life, regardless of how long that life will be.

Apply Series Reliability Property 2

Add "k" items into a series system of items, and the probability of failure of all items in the series must fall by an equal proportion to maintain original system reliability.

The requirement here is to simplify your processes by combining steps and removing steps so that there are fewer opportunities for things to go wrong. Series Reliability Property 2 gets you to remove unnecessary components from the system or redesign the system so that a lesser number of items are used. By reducing components or steps, the system becomes more reliable because there are fewer possibilities for failure. Figure 11.3 asks what would happen if we removed the drive coupling from the centrifugal pump-set. Is there technology available to eliminate the drive coupling?

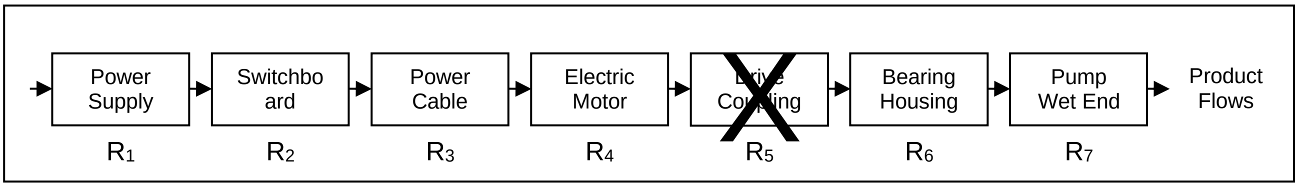


Figure 11.3—Centrifugal Pump-Set Reliability Improved by Removing Drive Coupling

Figure 11.4 shows two such technologies: canned motor pumps and magnetic drive pumps. Both pump types do not have a drive coupling.

Figure 11.4—Canned Motor Pump Magnetic Drive Pump

With the drive coupling removed, the system reliability (if the other items maintain their individual reliability) is calculated as follows:

$$R_{\text{Pump-set}} = R_1 \times R_2 \times R_3 \times R_4 \times R_6 \times R_7 = 0.9999$$

$$R_{\text{Pump-set}} = 0.9999971^4 \times 0.999956^2 = 0.9999$$

Removing the drive coupling allows less reliable items to be used while still achieving system reliability—the mechanical assemblies can have more than four failures per 100,000 opportunities. To confirm the effect of simplifying the system, the bearing housing is also removed. This means the pump wet end is directly mounted on the electric motor shaft. The system reliability then becomes,

$$R_{Pump\text{-}set} = R_1 \times R_2 \times R_3 \times R_4 \times R_7 = 0.9999$$

$$R_{Pump\text{-}set} = 0.9999971^4 \times 0.999912 = 0.9999$$

The wet end can fail nine times per 100,000 opportunities, and the system reliability is unchanged, at one failure in three years. In simplifying your system, you can reduce your capital costs with poorer-quality equipment and still get the required system reliability. But every breakdown will cause large TDAF costs. Even a planned corrective repair causes lost production and adds maintenance costs. By using equipment that suffers nine failures in the time that high-quality equipment has three failures the operating and maintenance costs rise substantially and continually recur. If instead you get more reliable equipment, thereby eliminating six failures, you will make significantly more operating profit year after year. This is how having a corporate policy to use high-quality equipment and making economic replacement of assets before they "age" makes fortunes for industrial operations.

Apply Series Reliability Property 3

An equal rise in the reliability of all items in a series causes a much larger proportionate rise in system reliability.

System-wide reliability improvements return far more profit than step improvements. Using Series Reliability Property 3 is an improvement choice that delivers astounding operating profits. Figure 11.5 shows the introduction of a company-wide policy to limit operating loads to 90% of an item's design duty. Another option is to "oversize equipment" and get the next-higher duty model so that its components operate at below design duty. Any additional capital cost to get the heavier duty model will be more than repaid through a higher return on investment from the greater productivity and lower maintenance costs you will get throughout its life.

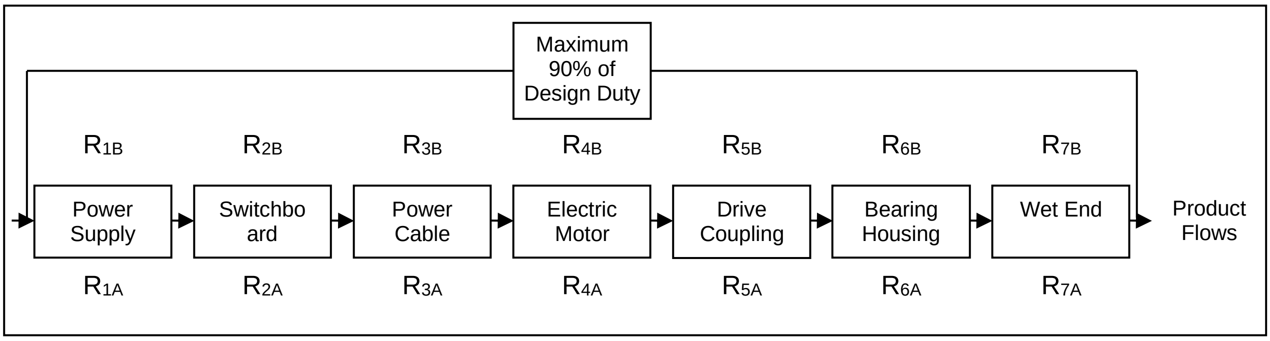


Figure 11.5—Pump-Set System Reliability Improved by a System-Wide Policy Decision

A business policy to run equipment at 90% of design duty is a system-wide decision that will cause stress reductions in all production equipment. It is an especially valuable strategy if your operating plant is of low quality design, made of weak materials, or poorly installed or maintained. In high fatigue situations, reducing fluctuating loads by 10% can increase parts' fatigue life up to 10 times.[2] Running at no more than 90% of design duty load can mean nine fewer failures during the service life. The choice to run equipment at 10% below design duty ensures that all parts throughout the entire operation get higher reliability. With one asset management policy decision, you stop equipment failures everywhere in a company and convert fortunes in TDAF cost losses into new operating profits.

Wherever possible, apply Series Reliability Property 3. It will bring the greatest benefits and amazing return on investment. But do not neglect the other two Series Reliability Properties. Apply Series Reliability Property 2 during design by using the DOCTOR (Design and Operations Cost Totally Optimized Risk; see Chapter 7) to get project managers to create robust, highly profitable business processes. Use Series Reliability Property 1 with your maintenance engineers, plant operators, and maintenance technicians to constantly make local reliability improvements to your “bad actors.”

Current Maintenance Strategy Selection Methods Do Not Prevent Failure

Maintenance strategies and activities can be chosen by using top-down or a bottom-up methodologies. Top-down strategy selection is based on equipment failure history. Maintenance records are reviewed to identify which plant assets fail and what range of causes produce the failures. Strategies are then selected to reduce equipment failure rates. The bottom-up approach identifies causes of equipment failures and then selects maintenance strategies and practices to maximize equipment reliability. Depending on the risk from the event and the certainty of failure detection, you might choose predictive maintenance, preventive maintenance, breakdown maintenance, or failure-finding tests. The better methodologies also include cost–benefit analysis to make sound economic decisions about the best mix of maintenance strategies to use to maximize operating profit.

The standard maintenance strategy selection methods currently used in industry do not prevent failures. They are designed to find and stop disastrous events. They promote failure by letting defects become serious problems before you act to prevent a breakdown. If you only look at your machines for problems to fix, then problems are what you will always get. Although top-down and bottom-up methods let you arrive as some sort of maintenance strategy, they cannot maximize reliability because they need failures to fix. They cannot minimize maintenance costs because they generate maintenance. Their limitations allow preventable failure causes to remain in your equipment until they become failures.

Developing a Highly Successful Equipment Risk Prevention Plan

The Plant Wellness Way recognizes that there is a dependency hierarchy of risk that extends from the operating stresses and local environment affecting a component's microstructure, such as healthy lubricant, correct lubricant film thickness, proper interference fit between mating parts, trueness of component shape, fineness of surface finish, subsurface stress levels, adequate load distribution, and so on, through to a catastrophic failure of the plant.[3] Every equipment failure can be traced back to what was done to its components' materials of construction during their lifetimes. Figure 11.6 shows these dependency links between an initial Physics of Failure mechanism through to the component, subassembly, assembly, parent asset, operating process, and, finally, business system levels. The state of health at each level of the hierarchy immediately causes risks at that level which can become problems in those levels above it. Ultimately, the reliability of every physical asset, and the subsequent risks they cause to a business, depends on how well you eliminate and prevent the causes of Physics of Failure mechanisms throughout its parts' life cycles.

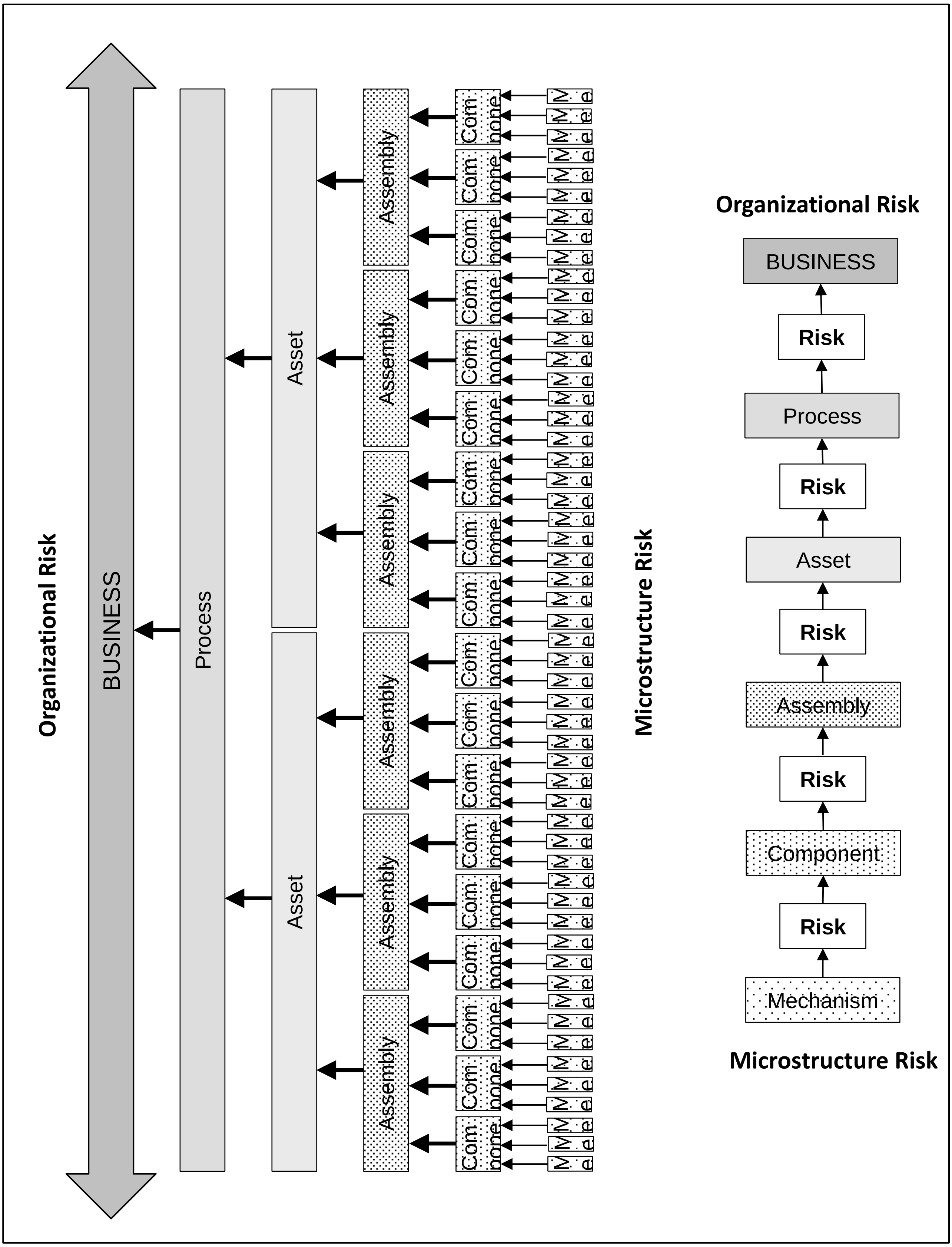


Figure 11.6—Hierarchy of Risk from Component to Organization

Current maintenance strategies look at the asset and assembly levels of the dependency hierarchy for problems. This makes maintenance ineffective at preventing failures because it allows the effect of microstructure failure mechanisms to become so severe as to be detectable in the behaviour of the parent asset. So long as failure mechanisms are present in equipment, they trigger the risk of failure. Only when there is no risk at the Physics of Failure mechanism level of the dependency hierarchy can you ensure an asset has maximum chance of exceptionally long lifetime reliability resulting in the least risk of operating failure.

Getting high equipment reliability is within the power of every business. Reliability is malleable by choice of policy and quality of practice used at each level of the dependency hierarchy. At mechanism level, set demanding quality standards for equipment parts to get outstanding reliability during operation. At component level, use precision to deliver long service lives to parts and apply the highest-quality operating and maintenance practices. At assembly level, use more robust, durable materials for components so they take greater stresses and don't degrade. At the asset level, replace assets early with the newest models rather than wait too long and get numerous failures and lower productivity. Be willing to pay for higher quality equipment so your company can make fortunes from fewer failures. For the process level, have right knowledge everywhere and only used the right practices, insuring they are done rightly. These requirements need to be included into corporate thinking when you make engineering, asset management, operational, or maintenance decisions. The people that undertake new business initiatives and whose who select new capital assets or replacement equipment only have one chance to take the best business option—after that, everyone must live with the choice for years to come.

The most beneficial life-cycle strategies are those that eliminate Physics of Failure mechanisms to reduce the total risk that a part carries during operation. The lower down the dependency hierarchy that good decisions are made, and precision quality controls are installed the more comprehensive is the risk control strategy. In the Plant Wellness Way, the technique used to select the right engineering design, manufacture, supply chain, maintenance, and operating requirements throughout the dependency hierarchy is called Physics of Failure Reliability Strategy Analysis. The technique follows the Stress-to-Process Asset Management Model (see Chapter 6), starting with the risks to component microstructure and works up the hierarchy to specify the correct strategy, knowledge, skills, and practices required in the business and life cycle processes used to provide component reliability.

Each mechanism cause of a critical part’s failure is identified and addressed one by one until the part’s lifetime risk control plan is complete. The risk control plan covers all that will be done during the life cycle to remove or significantly reduce operating risk. It lists the mix of design, manufacture, supply chain, operations, and maintenance activities to lower the risk of microstructure destruction and deliver high equipment reliability. Figure 11.7 shows where Physics of Failure Reliability Strategy Analysis is used in the process of choosing operating risk reduction actions. Mitigation and prevention actions will fall to the maintenance and operations groups, and design improvements will go to the engineering group. Design changes are carried out by a professional discipline engineer or a competent technical person who understands the equipment’s purpose and construction.

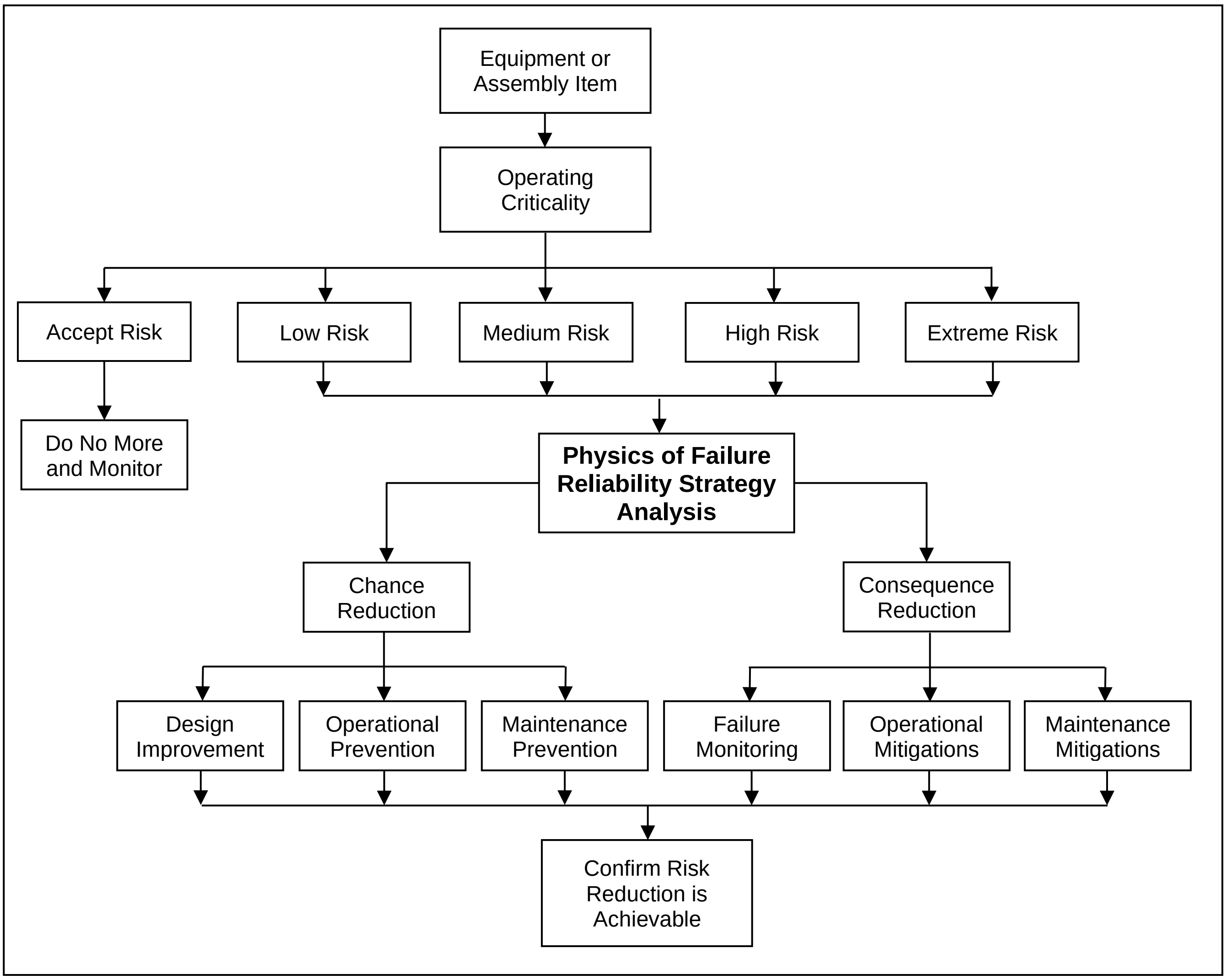


Figure 11.7—Reliability Strategy Selection Chart

Plant and equipment reliability is only improved if parts do not fail. By doing Physics of Failure Reliability Strategy Analysis at the component and mechanism levels, you identify the engineering, manufacturing, operational, and maintenance issues that must be addressed at each level of the dependency hierarchy for maximum asset reliability. The choices available to prevent component failure and subsequent equipment breakdown are as follows:

- Keep total stress well inside the elastic zone everywhere in the microstructure
- Minimize intended fluctuating and cyclic microstructure stresses
- Eliminate unintended fluctuating and cyclic microstructure stresses

- Establish and permanently sustain healthy microstructure contact environments
- Remove microstructure failure causes from throughout the life cycle
- Monitor for the causes of microstructure failure and remove the causes
- Monitor for the onset of microstructure damage and correct the issues
- Replace microstructures before failure
- Change the part's design to prevent microstructure overstress or degradation
- Change the processes impacting the microstructure to prevent overstress or degradation

If you want outstandingly reliable plant and machinery, you cannot be maintaining and repairing them. You need equipment with parts that do not fail. That requires engineering designs, manufacturing methods, installation techniques, operating practices and maintenance tasks in which component failure is not initiated. You need a reliability-creation paradigm and not a failure-focused maintenance paradigm that finds and fixes problems. Figure 11.8 highlights the difference between a failure-focused perspective and a machinery health–focused view. In failure-focused maintenance, you fix machinery problems as you find them. In wellness-focused maintenance, you create and sustain machine health so that there are no problems. To get wonderfully reliable plant and equipment, continually deliver the conditions that cause their health and well-being.

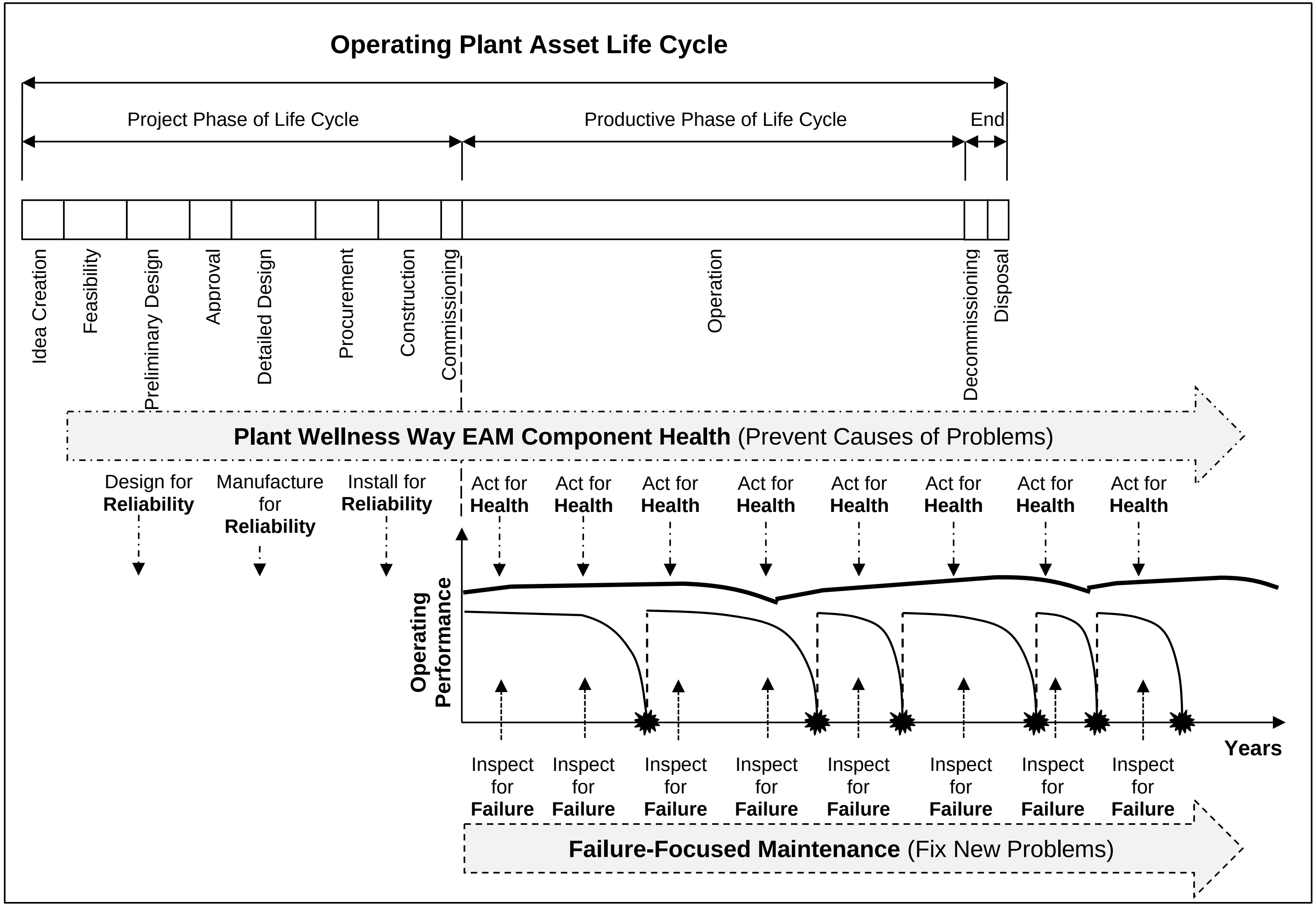


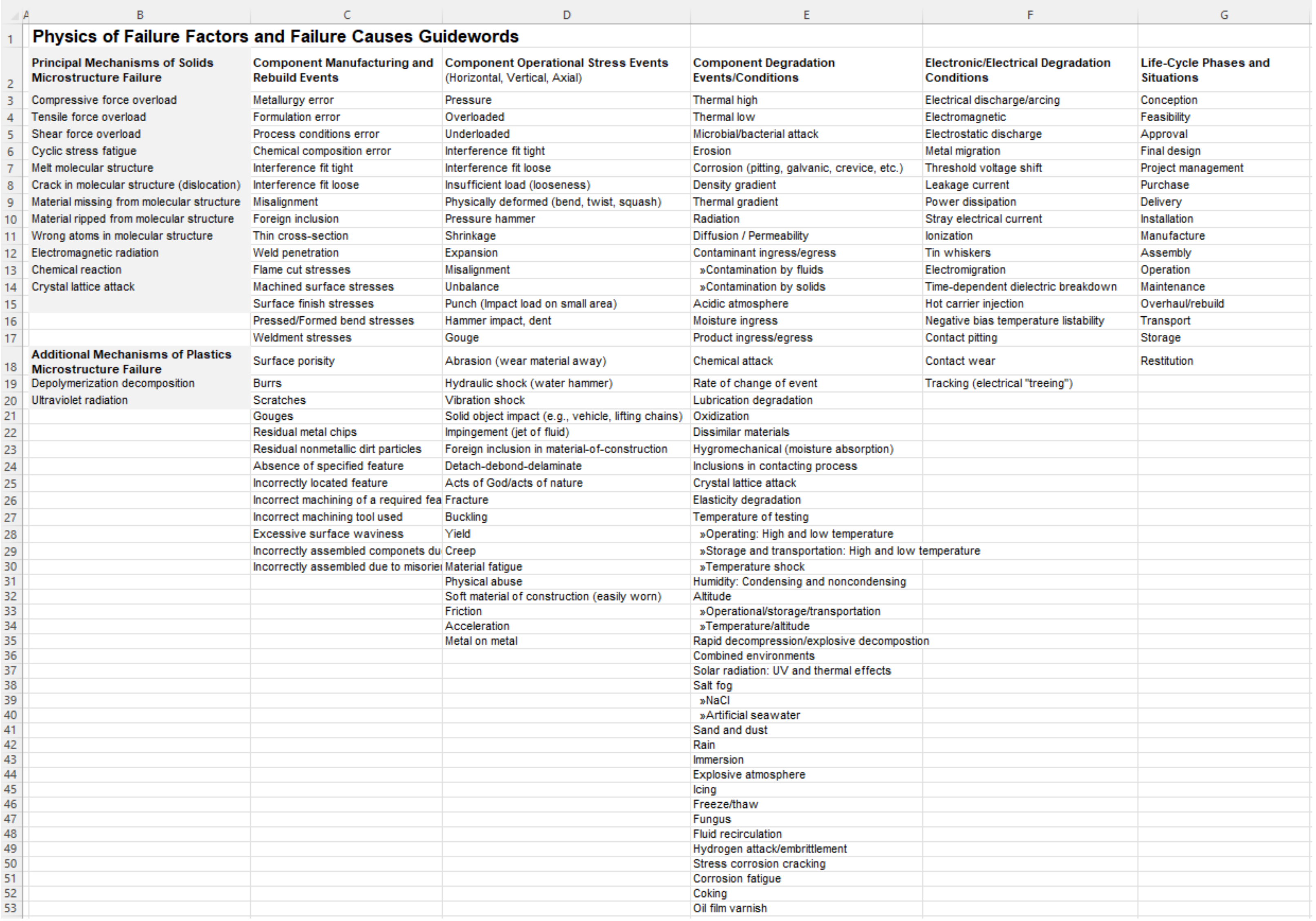
Figure 11.8—Failure-Focused versus Wellness-Focused Reliability Strategies

Physics of Failure Mechanisms and Their Failure Causes

There are just two ways that physical matter can be parted: (1) materials of construction fail when microstructures are destroyed by physical means, or (2) the atomic bonds disintegrate. The principal ways to destroy atomic bonds and microstructures are listed in the left-hand column of Table 11.2. These are called the Physics of Failure factors.

The event and condition columns in Table 11.2 record known causes of atomic bond breakage and microstructure destruction. Collectively they are called the Physic of Failure cause mechanisms. You can add new triggers of material-of-construction failure to the list as they are identified in your operation. The table is a repository for corporate knowledge of what causes equipment failures. A comprehensive Physics of Failure Factors and Failure Cause Guidewords list is in the spreadsheet accompanying this book.

To prevent material-of-construction failure, we need to ensure that the situations and events that can cause atomic structures to fail do not arise. The elimination of “the cause of the cause” of failure is a powerful concept for creating reliability because it lets you identify, deliver, and sustain the conditions needed for long-lasting microstructure health. Whereas other asset management methodologies focus on identifying failures, the Plant Wellness Way focuses on producing the conditions needed for outstandingly long material-of-construction lifetimes.



	B	C	D	E	F	G
1	**Physics of Failure Factors and Failure Causes Guidewords**					
2	**Principal Mechanisms of Solids Microstructure Failure**	**Component Manufacturing and Rebuild Events**	**Component Operational Stress Events** (Horizontal, Vertical, Axial)	**Component Degradation Events/Conditions**	**Electronic/Electrical Degradation Conditions**	**Life-Cycle Phases and Situations**
3	Compressive force overload	Metallurgy error	Pressure	Thermal high	Electrical discharge/arcing	Conception
4	Tensile force overload	Formulation error	Overloaded	Thermal low	Electromagnetic	Feasibility
5	Shear force overload	Process conditions error	Underloaded	Microbial/bacterial attack	Electrostatic discharge	Approval
6	Cyclic stress fatigue	Chemical composition error	Interference fit tight	Erosion	Metal migration	Final design
7	Melt molecular structure	Interference fit tight	Interference fit loose	Corrosion (pitting, galvanic, crevice, etc.)	Threshold voltage shift	Project management
8	Crack in molecular structure (dislocation)	Interference fit loose	Insufficient load (looseness)	Density gradient	Leakage current	Purchase
9	Material missing from molecular structure	Misalignment	Physically deformed (bend, twist, squash)	Thermal gradient	Power dissipation	Delivery
10	Material ripped from molecular structure	Foreign inclusion	Pressure hammer	Radiation	Stray electrical current	Installation
11	Wrong atoms in molecular structure	Thin cross-section	Shrinkage	Diffusion / Permeability	Ionization	Manufacture
12	Electromagnetic radiation	Weld penetration	Expansion	Contaminant ingress/egress	Tin whiskers	Assembly
13	Chemical reaction	Flame cut stresses	Misalignment	»Contamination by fluids	Electromigration	Operation
14	Crystal lattice attack	Machined surface stresses	Unbalance	»Contamination by solids	Time-dependent dielectric breakdown	Maintenance
15		Surface finish stresses	Punch (Impact load on small area)	Acidic atmosphere	Hot carrier injection	Overhaul/rebuild
16		Pressed/Formed bend stresses	Hammer impact, dent	Moisture ingress	Negative bias temperature listability	Transport
17		Weldment stresses	Gouge	Product ingress/egress	Contact pitting	Storage
18	**Additional Mechanisms of Plastics Microstructure Failure**	Surface porisity	Abrasion (wear material away)	Chemical attack	Contact wear	Restitution
19	Depolymerization decomposition	Burrs	Hydraulic shock (water hammer)	Rate of change of event	Tracking (electrical "treeing")	
20	Ultraviolet radiation	Scratches	Vibration shock	Lubrication degradation		
21		Gouges	Solid object impact (e.g., vehicle, lifting chains)	Oxidization		
22		Residual metal chips	Impingement (jet of fluid)	Dissimilar materials		
23		Residual nonmetallic dirt particles	Foreign inclusion in material-of-construction	Hygromechanical (moisture absorption)		
24		Absence of specified feature	Detach-debond-delaminate	Inclusions in contacting process		
25		Incorrectly located feature	Acts of God/acts of nature	Crystal lattice attack		
26		Incorrect machining of a required fea	Fracture	Elasticity degradation		
27		Incorrect machining tool used	Buckling	Temperature of testing		
28		Excessive surface waviness	Yield	»Operating: High and low temperature		
29		Incorrectly assembled componets du	Creep	»Storage and transportation: High and low temperature		
30		Incorrectly assembled due to misorie	Material fatigue	»Temperature shock		
31			Physical abuse	Humidity: Condensing and noncondensing		
32			Soft material of construction (easily worn)	Altitude		
33			Friction	»Operational/storage/transportation		
34			Acceleration	»Temperature/altitude		
35			Metal on metal	Rapid decompression/explosive decompostion		
36				Combined environments		
37				Solar radiation: UV and thermal effects		
38				Salt fog		
39				»NaCl		
40				»Artificial seawater		
41				Sand and dust		
42				Rain		
43				Immersion		
44				Explosive atmosphere		
45				Icing		
46				Freeze/thaw		
47				Fungus		
48				Fluid recirculation		
49				Hydrogen attack/embrittlement		
50				Stress corrosion cracking		
51				Corrosion fatigue		
52				Coking		
53				Oil film varnish		

[Table 11.2—Physics of Failure Factors and Failure Causes Guidewords]

Physics of Failure Factor Analysis for Reliability Strategy Selection

Identifying health-focused reliability strategies requires strategy selection methods that get you away from equipment failure-spotting and toward lifetime health-creation. The Physics of Failure Factors Analysis (POFFA) is such a technique. It is part of a suite of investigative techniques making up the Physics of Failure Reliability Strategy Analysis methodology. It identifies all the ways in which a component can physically fail and then lets you select the most effective life-cycle strategies for maximizing its reliability. It is a scientifically based, holistic, and cost-effective methodology for life-cycle profit maximization by proactively ensuring components have lifelong health and wellness.

The POFFA approach analyses failures at the microstructure and atomic levels. The technique identifies how many ways the microstructure of a machine component can be physically destroyed. Once all microstructure failure mechanisms are listed, you then identify all of the causes of each mechanism during the part's lifetime. With the causes known, you place defect elimination and failure prevention activities throughout the life cycle to proactively prevent each cause.

In POFFA, you don't use failure modes. Using failure modes installs unreliability into equipment by design. Instead, the analysis puts you in the time *before* failures arise so that by design you can prevent the situations that cause a part's microstructure to fail. You give components' materials of construction operating longevity. POFFA identifies all the causes of atomic structure and microstructure destruction that a part can suffer and guides you to select and use those practices that create and sustain health and minimize stress. You do not address failure—you eliminate it. You determine the conditions needed for exceptional component reliability and establish reliability creation causes throughout the life cycle to produce outstanding long equipment operating lifetimes.

POFFA provides a list of issues to address to get maximum parts reliability. It is the investigative phase of a Physics of Failure Reliability Strategy Analysis that leads you to choose the strategies and practices to use across the life cycle to prevent microstructure failure and thus deliver the most reliable parts and equipment for your operation.

Doing a Physics of Failure Factors Analysis

Physics of Failure Factors Analysis is a highly effective way to scrutinize an equipment part in detail. Every part can analyse down to its microstructure. You use it like an "intellectual microscope" to examine a component at any location. You "point" the microscope at the region of structure you want to interrogate. For that location, you identify all the principal mechanisms that could destroy the microstructure. In Figure 11.9, the intellectual microscope is focused on the rolling element of the electric motor bearing. It could have been pointed at other parts of the bearing—the inner ring, outer ring, retaining cage, or even the lubricant between the surfaces.

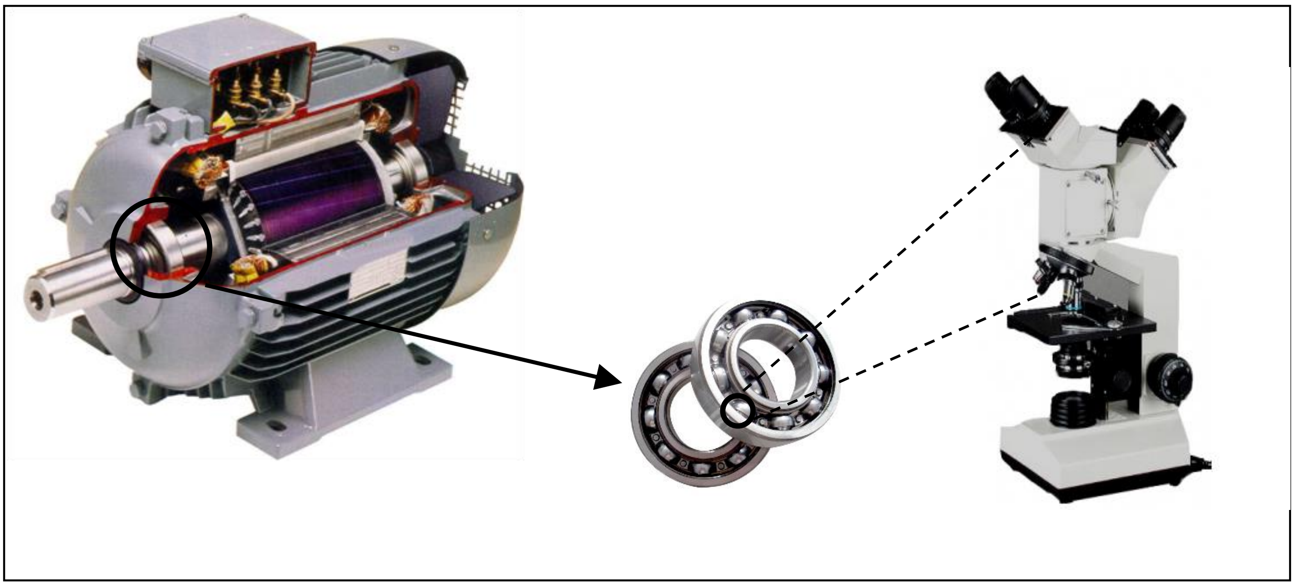
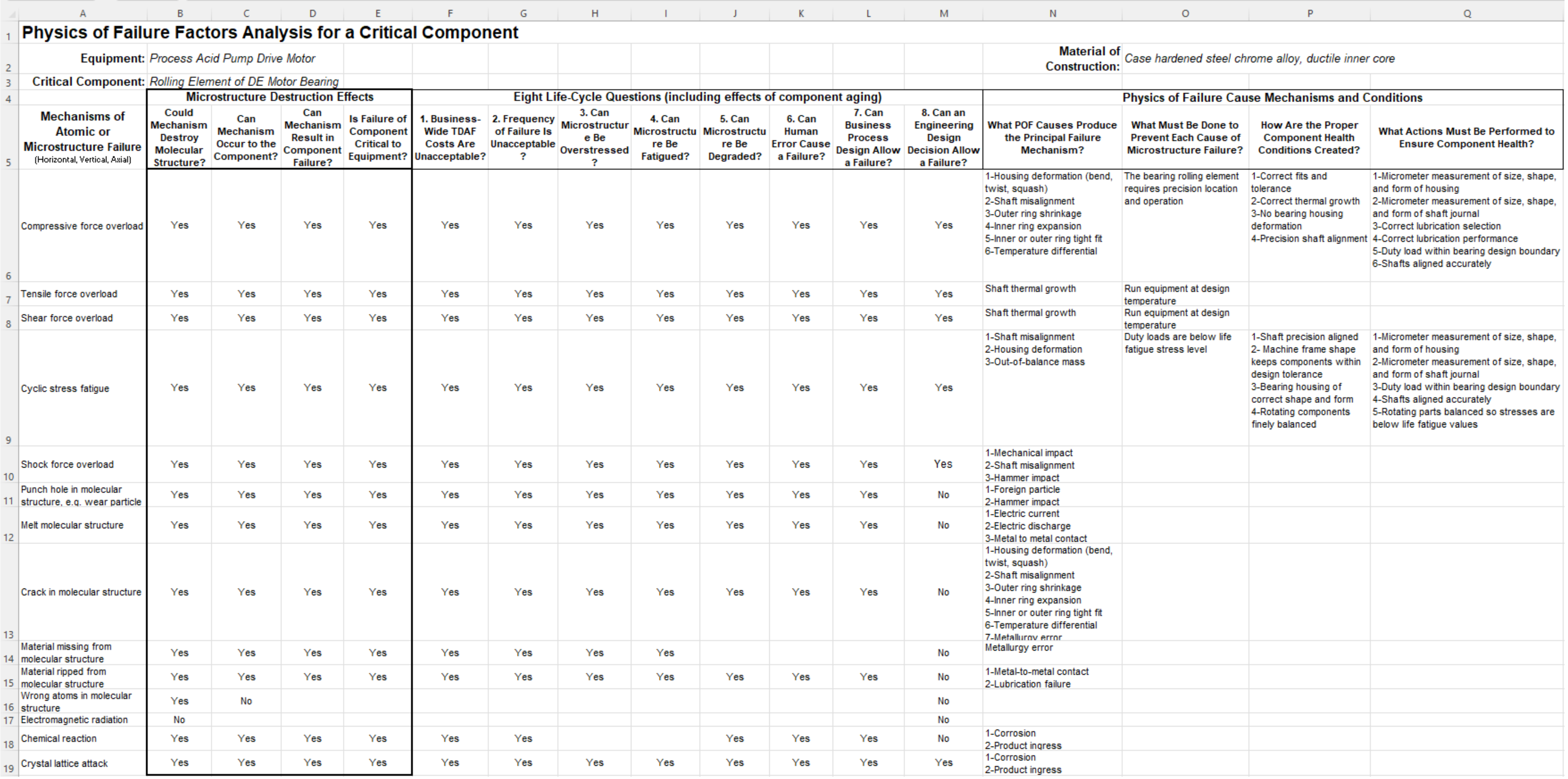


Figure 11.9—Analysing an AC Motor Deep Groove Ball Bearing

POFFA is performed on all critical components by a person knowledgeable in the design and use of the component and its parent equipment. An experienced discipline maintenance, electrical, electronic, mechanical or structural engineer, or industrial engineer; a discipline design engineer; or a career-long serving electrical or mechanical maintenance discipline supervisor will have the level of engineering and equipment knowledge needed to do the analysis. If there is no one with such expertise and experience available, a team containing the necessary range of knowledge and know-how is assembled. Once the analysis is completed by the appointed person or team, a second competent person or team in the same discipline must be "paralleled" to do a review of the findings for accuracy and completeness.

The analysis starts with a spreadsheet in which you list the complete set of "Principal Mechanisms of Solids Atomic or Microstructure Failure" factors for the part being analysed. In the example POFFA in Table 11.3 for a rolling element in a ball bearing, each principal material-of-construction failure has a series of questions about its risk to the part's microstructure. The question choices are restricted to yes or no answers to identify whether a risk truly exists. When the answer to a microstructure destruction effect question is no, the factor is no longer considered. When the answer to a question is yes, the factor remains valid, and the next question is asked. If the failure factor turns out to be a real issue, it is necessary to identify each of its failure mechanisms and all their causes so that effective strategies and controls can be established during the component's life cycle.



Physics of Failure Factors Analysis for a Critical Component

Equipment: *Process Acid Pump Drive Motor*

Critical Component: *Rolling Element of DE Motor Bearing*

Material of Construction: *Case hardened steel chrome alloy, ductile inner core*

	Microstructure Destruction Effects				Eight Life-Cycle Questions (including effects of component aging)								Physics of Failure Cause Mechanisms and Conditions			
Mechanisms of Atomic or Microstructure Failure (Horizontal, Vertical, Axial)	**Could Mechanism Destroy Molecular Structure?**	**Can Mechanism Occur to the Component?**	**Can Mechanism Result in Component Failure?**	**Is Failure of Component Critical to Equipment?**	**1. Business-Wide TDAF Costs Are Unacceptable?**	**2. Frequency of Failure Is Unacceptable ?**	**3. Can Microstructure Be Overstressed ?**	**4. Can Microstructure Be Fatigued?**	**5. Can Microstructure Be Degraded?**	**6. Can Human Error Cause a Failure?**	**7. Can Business Process Design Allow a Failure?**	**8. Can an Engineering Design Decision Allow a Failure?**	**What POF Causes Produce the Principal Failure Mechanism?**	**What Must Be Done to Prevent Each Cause of Microstructure Failure?**	**How Are the Proper Component Health Conditions Created?**	**What Actions Must Be Performed to Ensure Component Health?**
Compressive force overload	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1-Housing deformation (bend, twist, squash) 2-Shaft misalignment 3-Outer ring shrinkage 4-Inner ring expansion 5-Inner or outer ring tight fit 6-Temperature differential	The bearing rolling element requires precision location and operation	1-Correct fits and tolerance 2-Correct thermal growth 3-No bearing housing deformation 4-Precision shaft alignment	1-Micrometer measurement of size, shape, and form of housing 2-Micrometer measurement of size, shape, and form of shaft journal 3-Correct lubrication selection 4-Correct lubrication performance 5-Duty load within bearing design boundary 6-Shafts aligned accurately
Tensile force overload	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Shaft thermal growth	Run equipment at design temperature		
Shear force overload	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Shaft thermal growth	Run equipment at design temperature		
Cyclic stress fatigue	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1-Shaft misalignment 2-Housing deformation 3-Out-of-balance mass	Duty loads are below life fatigue stress level	1-Shaft precision aligned 2- Machine frame shape keeps components within design tolerance 3-Bearing housing of correct shape and form 4-Rotating components finely balanced	1-Micrometer measurement of size, shape, and form of housing 2-Micrometer measurement of size, shape, and form of shaft journal 3-Duty load within bearing design boundary 4-Shafts aligned accurately 5-Rotating parts balanced so stresses are below life fatigue values
Shock force overload	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1-Mechanical impact 2-Shaft misalignment 3-Hammer impact			
Punch hole in molecular structure, e.g. wear particle	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	1-Foreign particle 2-Hammer impact			
Melt molecular structure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	1-Electric current 2-Electric discharge 3-Metal to metal contact			
Crack in molecular structure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	1-Housing deformation (bend, twist, squash) 2-Shaft misalignment 3-Outer ring shrinkage 4-Inner ring expansion 5-Inner or outer ring tight fit 6-Temperature differential 7-Metallurgy error			
Material missing from molecular structure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				No	Metallurgy error			
Material ripped from molecular structure	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	1-Metal-to-metal contact 2-Lubrication failure			
Wrong atoms in molecular structure	Yes	No										No				
Electromagnetic radiation	No											No				
Chemical reaction	Yes	Yes	Yes	Yes	Yes	Yes			Yes	Yes	Yes	No	1-Corrosion 2-Product ingress			
Crystal lattice attack	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1-Corrosion 2-Product ingress			

Table 11.3—POFFA for Rolling Element in Deep Groove Ball Bearing

Eight Life-Cycle Questions to Answer

Your business is built from people, processes, and plant interacting together in some coordinated way to produce a product or service for paying customers. Plant and equipment risks prevent companies from being world-class operations by continually causing breakdowns, waste, and losses. You use the eight life-cycle questions to identify the risks to a critical component and where the causes and defects come from during its lifetime. It is a simple and quick way to find your future troubles.

Economic Justification

The answers to the economic questions determine whether a full analysis is required for a subassembly or part. Where equipment TDAF costs, including opportunity costs are low and the event frequency is low, so that the risk falls into the “Accept” level of the risk matrix, the default choice is to adopt a run-to-failure strategy and rectify the damage in a timely manner. The two exceptions are if maiming or death of people, or the destruction of the environment can occur. Even when the consequential costs of such events are affordable, they cannot be allowed to occur. If the economics or the safety or the environmentally consequences of the situation are unacceptable, then the analysis continues.

1. Is the total business wide TDAF cost consequence of a failure acceptable?
2. If failure is acceptable, how frequently can it occur before it becomes unacceptable?

Physics of Failure Causes of Parts Failure

These questions highlight the many causes and combinations of causes of an equipment part's failure. There are hundreds, maybe thousands, of ways that can combine to create risks inside your machines. The best protection against equipment failure is to eliminate all possible causes and paths of parts breaking.

3. Can the microstructure be overstressed?
4. Can the microstructure be fatigued?
5. Can the microstructure be degraded?

You factor component age into the consideration through the growing risks that ongoing usage causes your operation. Equipment parts accumulate stresses in their microstructure and "age," resulting in decreased strength. Parts that are in service for a long time suffer more environmental degradation of their surfaces. Consequently, the frequency of repairs and associated maintenance costs rise, and the equipment becomes progressively unsafe to use. When reviewing old assets, compensate for the effects of degradation and stress by increasing the frequency of failure of old components by a reasoned proportion based on the asset's time in service and how carefully the asset has been used and maintained during its operating life. The maintenance work history is evidence of past repair frequency; for wear-out parts you need to increase the failure rate to compensate for an increasingly fatigued asset; for randomly failing parts reflect the effect on reliability from the asset management culture present in the organization—a culture that is not yet world class will only get worse and older assets will suffer higher rates of stress induced random failures. If you are fortunate to have kept good component failure data, then reliability engineering analysis can be done to quantify the effects of age and abuse to give you a more certain consideration of the rising risk with the time that assets are in use.

Human error and weak business process design are the major categories in equipment failure. For whole-life protection, the mistakes attributable to people and process design must be prevented. It is necessary to learn where in the life cycle are the best locations to include useful error-proofing strategies.

6. Can human error cause a critical part to fail?
7. Can business processes allow a critical part to fail?
8. Can a design decision allow a critical part to fail?

Developing a Physics of Failure Based Reliability Strategy

For each principal Physics of Failure factor identified, list all the cause mechanisms of atomic or microstructure destruction noted in the event and condition columns that can produce the factor during a part's lifetime. You seek all possible lifetime causes of a component's material-of-construction failure so that they can be eliminated in all phases of the life cycle. Some cause mechanisms will arise many times in the life cycle. For example, whenever a part is installed, be it during original equipment manufacturing, scheduled overhaul or breakdown maintenance repair, the same bad installation practices producing the same mechanisms can exist at all three times. Whether you do anything about a mechanism and what you do depends on the size of the risk to the business.

The Physics of Failure Factors Analysis makes you think through what you must do to keep component microstructure healthy. You are not after the root cause of failure. A failure can result from dozens of root causes, many of which may never be identified. You do not focus on rectifying a problem—instead, the focus is on not having the problem in the first place. The answers to the eight life-cycle questions will generate engineering, manufacturing, supply chain, maintenance, and operational actions to stop a microstructure failure mechanism by designing ways to prevent the causes of those situations in every phase of the life cycle. For each way that a part loses integrity, you introduce suitable means to prevent it. This approach lets you design asset management, operational, and maintenance processes and activities that drive out risks and increase equipment reliability to get failure-free service.

Once you have identified the ways your parts can be destroyed, you need to prevent those causes from arising. This is when you set your asset reliability strategy and select your plans to make your machines and equipment highly reliable. The POFFA outcomes feed the Physics of Failure Reliability Strategy Analysis, in which you choose the ideal reliability tactics and actions for each part.[4]

In a POFFA, you use the Stress-to-Process Model to recognize how your equipment parts' microstructures can be failed. You work up from the bottom of the risk dependency hierarchy to eliminate failure at all levels in an asset. Consequently, you design the right processes and build an organization that can produce the world class reliability needed for endless Operational Excellence.

FOOTNOTES

1. David Sherwin, “Introduction to the Uses and Methods of Reliability Engineering with Particular Reference to Enterprise Asset Management and Maintenance,” presentation, Perth, Western Australia, 2007.

2. Robert C. Juvinall, *Engineering Considerations of Stress, Strain, and Strength* (New York: McGraw-Hill, 1967).

3. Paul B. Price, Reliability Consultant and Condition Monitoring Specialist, United Kingdom, 2014, email correspondence

4. An alternative way to use the Physics of Failure Factors to identify how component microstructures fail and arrive at viable solutions is the Deformation/Degradation Analysis introduced in the Appendix.