Effect of Material Properties on Reliability

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Table of Contents

Introduction

By way of explanation, CEFO is a convenient memory device intended to help individuals recall the four major categories of deterioration that cause failures resulting in poor reliability.

It is helpful to keep in mind that these terms represent physical processes found in nature. They are most commonly called Failure Mechanisms by those involved in analyzing and improving reliability. On the other hand, the same physical processes are called Deterioration Mechanisms when used by those involved in analysis and assurance of the integrity of stationary equipment like pressure retaining equipment.

The principal difference is that the criterion used to measure reliability performance is the frequency at which failures occur. On the other hand, the objective of managing the integrity of pressure retaining equipment is prevention of failures by limiting the amount of deterioration.

The thought exercise described above is intended to guide the reader to the conclusion that detailed knowledge of forms of deterioration is a key factor in both improving reliability and in the effort to completely avoid failures. If there are no failures, the MTBF is infinite.

While loss of functionality (as is key to reliability performance) is frequently less dramatic than the loss of integrity (as is key to pressure retaining equipment failure), they both find their cause in the same major forms of deterioration. Pressure equipment engineers perform their function of avoiding catastrophic equipment explosions and releases by maintaining a detailed understanding of the status of forms of deterioration in equipment for which they are responsible. If desired, the same could be true (at least for critical equipment items) for the engineers responsible for other kinds of equipment (including pumps, compressors, turbines, and a host of other equipment).

As an example, the presence of concentration cell corrosion can prevent a switch from powering a circuit. The same form of corrosion when active in a pressure retaining system may lead to an explosion or release. While the results of one failure can be far more dramatic than the other, the same techniques can be applied to avoid both.

In any case, the objective of both reliability and integrity engineering is to avoid adverse effects of the forms of deterioration that are present by:

1. Identifying the form(s) of deterioration.
2. Understanding the rate at which the deterioration is advancing.
3. Understanding the deterioration allowance (or amount of deterioration that can be allowed before a failure is likely to occur).
4. Knowing how and when to trigger the corrective action so as to prevent a failure.
5. Understanding the most effective and efficient way to restore the deterioration allowance to make the asset “good as new”.

In some instances, restoring the deterioration allowance is accomplished by simply adding weld metal to the deteriorated areas so as to re-establish the “as new” conditions. In other instances, the easiest and least expensive way to achieve “as new” conditions is to replace the deteriorated component with a new one. This approach is more common in reliability management because components often cannot be restored to the same tolerances as new.

Now, let’s step through another thought exercise by asking and answering the questions, “What if reliability engineers wanted to behave more like pressure equipment engineers who ensure the integrity of pressure retaining equipment by avoiding failures?” and “What would they have to do?”

First, they would need to “get inside” of the devices they maintain to thoroughly understand all of the forms of deterioration that are or may-be present through the entire life cycle of the devices for which they are responsible. They then need to create a strategy for each device component that allows them to respond to deterioration long before failure is possible.

This approach would make the measurement of Mean Time Between Failure obsolete because there would be no failures. There would only be deterioration and methods to reduce or eliminate deterioration and strategies for restoring the effects of deterioration while an adequate amount of deterioration allowance still exists.

Clearly, this approach is not new. Engineers have used this approach in many situations, but not all. It would not be economically feasible to use in all situations but understanding the concepts behind the approach can allow it to be used for critical situations.

If this strategy was chosen to form the basis for life cycle management during the entire life of critical assets, it would be possible to clearly define the roles and expectations for participants at each point in the life of assets.

So, as we move forward through this discussion in which we hope to more clearly understand the effects of material properties on reliability and useful life, it is important to be reminded that there are two kinds of material properties, the properties needed to support the needed functionality of a device and the properties needed to support the reliability and useful life of a device.

In this discussion, we will assume that for a specific material to be selected when creating a device, it must have the requisite properties to support the functionality. The job of selecting the materials with the proper characteristics for functionality is always complete when the design is complete.

Herein, we will focus only on the material properties associated with deterioration that ultimately determines the reliability and useful life of a device. Those forms of deterioration are Corrosion, Erosion, Fatigue and Overload. Unlike the material properties associated with functionality that are instantly apparent when a device is first placed in service, some of the characteristics associated with deterioration become apparent only later in life and it is important to recognize those characteristics and take the steps needed to avoid their becoming problematic.

As a final point in this introduction, depending on where you look, you will find there are several classifications of engineering materials. A common classification includes:

- Metals
- Polymers

- Ceramics
- Composites

For purposes of this course, we will focus primarily on metals. Metals enjoy the broadest and most common use in applications where general requirements for integrity, reliability and long life are primary concerns. While the other classes of engineering materials are important, it is more typical they will be specifically selected because of their suitability to the specific requirements of an application. That is less likely to be the case with metals. They are frequently used because of their general characteristics and, as a result, are more likely to suffer from a variety of forms of deterioration that can affect integrity, reliability, and useful life span. In many applications, a nearly perfect choice of a metal will perform generally very well but specifically poorly.

The following sections of this course describe the forms of deterioration that affect reliability and then, using that information, will identify roles and create expectations at each stage in the life of an asset to manage that asset's reliability and useful life.

Section One – CEFO in detail

This section is intended to add detail to the categories of deterioration and how one might combat them. In this course, we assume that each device has been designed in a way that allows it to perform its intended function to the fullest when new. Therefore, the conventional forms of engineering design analysis have been completed in a comprehensive manner. While the completion of that effort will produce a fully functional device, it might produce a device with less than adequate reliability or a less than desired useful life.

In this course, we are hoping to identify the steps that would be needed to ensure a much greater reliability and an indefinite life. The difference in effort required to achieve that goal would exist in the way deterioration is handled during each and every step of the lifecycle. Here, we hope to avoid failures by addressing forms of deterioration in a way that does not allow failures or permanent degradation to occur.

In addition to the need to address forms of deterioration in major elements of an asset, it is necessary to consider deterioration, both initially and as the asset ages, within much smaller and less visible components. For instance, it is seldom that it is the engine block that fails. Instead, poor reliability is caused by corrosion or buildup of resistance caused by oxidation on electrical and electronic components. Troublesome minor components have caused far more breakdowns and early demise of vehicles than the failure of any major component.

The following paragraphs focus on the deterioration mechanisms and how they are addressed without being triggered by failure.

1. *Corrosion*

   While the generic term corrosion can be useful in categorizing a wide variety of natural processes, avoiding the deterioration caused by "corrosion" often requires more accurate determination of the precise form of corrosion that is present. Let's describe a few forms of corrosion

- Uniform corrosion – Uniform corrosion is the most frequently recognized form of corrosion because it is the most apparent. It is commonly found on ferrous metals and alloys that are not protected by coatings. When observed, it uniformly covers an entire surface of the affected asset.
    - Control of uniform corrosion is most commonly achieved through a coatings program or simple cleaning of films of surface corrosion. One secret to achieving uniform corrosion control without failure is preventing deterioration to coating systems instead of the metal itself so that the metal surfaces are never exposed to the corrosion mechanism. Another is a routine cleaning program that will remove corrosion products before they cause failures.
    - Clearly, owners of those assets will never again during the life of the asset have the same opportunity to perform metal preparation as would have been possible during manufacture or construction. As a result, it is best to install a coating system viewed as being "permanent" at the point of origination and instructions how to maintain that coating system be provided by the manufacturer to the owner.
    - A common failure mode (component-condition) involving uniform corrosion that frequently produces reliability related failures is the production of films and corrosion products on electrical contacts and switches. In a recent situation, a home heating was unable to start because the thermostat contacts or electrical switches providing power were unable to make contact. After working them several times the surface film removed and the system was able to start.

- Galvanic corrosion – Galvanic corrosion is the result of a more active metal being in contact with a less active metal in the presence of an electrolyte. Negative ions flow from the material acting the as anode to the material acting as the cathode via a path through the electrolyte. A battery functions using this same galvanic action.
    - The most effective way to prevent galvanic corrosion is by installing a nonmetallic coupling to prevent the flow of negative ions. This practice is common in plumbing and required by plumbing codes. While a galvanic coupling may not survive the same life as a simple metal coupler, it is much easier to replace than all the metal components that would otherwise deteriorate.
    - Once a system is designed and constructed, the geometry is set, and it is no longer simple and easy to accommodate the installation of a nonmetallic component, so designers and builders need to install the nonmetallic device at the point of origination.

  - The build-up of a high resistance film on battery terminals is physical evidence of galvanic corrosion at work. The result of this build-up can be reduced voltage output which will prevent vehicles from starting and lights from shining at their full intensity.

- Crevice or concentration cell corrosion – Crevice or concentration cell corrosion is a highly localized deterioration to a metal adjacent to a crack or crevice between adjacent surfaces. Good design practice requires that joints forming a crevice be avoided to prevent the concentration of oxygen concentration, chloride concentration or increased pH. Any configuration that causes concentration by forming a quiescent zone that is not adequately flushed by flow can cause this kind of corrosion.
  - The best time to prevent crevice or concentration cell corrosion is at the time an asset is designed and built. If bolted or riveted joints are used when first constructed, they are likely to be used throughout the life of an asset. As a result, the asset will always experience crevice or concentration cell corrosion.
  - It is preferable to replace bolted or riveted joints with welded joints to avoid cracks and crevices. If it is necessary to provide bolted joints at certain points for future disassembly then those joints should be designed in a way that avoids tight crevices and allows points of disassembly to be flushed by natural flow of fluids.
  - Crevice corrosion is common in older plumbing systems where black iron fittings, fittings made of dissimilar metals or previous galvanized fittings that have lost their zinc coating are connected to equipment or complete systems that are much more robust. This ultimately causes seepage or leaks. Of more dramatic failures of complete plumbing systems.

- Pitting corrosion – Pitting is a form of corrosion typically confined to small or limited areas. Pitting corrosion is the result of deterioration being focused in small areas where surrounding areas are left substantially undamaged. Pits can be narrow and deep and can result in through-wall penetrations.
  - As with the need for the protection schemes described above, the susceptibility to pitting corrosion needs to be recognized during the design process and addressed during construction. Then, once in service, the owner will need to perform routine inspections to identify pitting and repair damaged areas when pits are found.
  - Pitting was particularly memorable because, when performing Reliability Centered Analysis on an asset, it was found that the tool used to detect the presence in heat exchanger tubes was intended to measure uniform thinning. While the reported measurements might contain some “noise” caused by the uneven surface, it would not specifically identify the presence of pits.

- Stress corrosion cracking – Stress Corrosion Cracking (SCC) refers to deterioration that results when a metal is simultaneously exposed to a corrosive media and tensile stress.
    - SCC is a form of deterioration that is determined by actions taken during the design and material selection. Clearly, the presence of corrosive media and tensile stresses are most frequently identified as a part of the initial design requirements. As a result, the original material selection should have been based on those requirements.
    - While the material should have been selected specifically to avoid SCC based on known requirements, that does not mean that the asset will always be exempt from all kinds of deterioration for the entire life. For instance, if an asset is exposed to tensile stress, it might be exposed to over-stress. If exposed to corrosive media, it might also be exposed to elevated concentrations of that media or possibly a different kind of corrosive media. The point this discussion is leading to is that, if an update is required at some point, it must be completed using material that fulfills the actual demands of the most extreme service and the rationale for selection accurately recorded. It is not uncommon for owners to “forget” the reason certain more expensive materials have used. Then after being replaced with less expensive but also not adequately protective material, a pattern of failures returns.
    - SCC is a relatively common problem around chemical plants in which concentrated acids might be found. Since elevated stress is always a possibility, the required combination of environment and stress can frequently occur.

- Erosion assisted corrosion – Erosion corrosion is the form of accelerated deterioration that occurs when a protective oxide coating forms on the surface of a metal, then the oxide coating is removed by erosion. The erosion can result from an abrasive material being held in a flowing material passing over the metal surface. Erosion corrosion is accelerated by the repeated formation of the surface film followed by erosion that removes it. The more frequently the film forming-scouring process occurs, the faster the deterioration will occur.
    - Erosion corrosion is produced by two distinct deterioration steps. As a result, it is possible to deal with erosion corrosion using a material or configuration that is not susceptible to either or both. For example, a heavy wall can be made of an expensive alloy that is both strong enough to handle the stress and is inert to the source of corrosion. Or, alternatively, it is possible to select a composite material that is designed to perform both functions using materials with different capabilities. For instance, an inexpensive base metal can be used to provide the required strength and it

can be covered with a cladding of exotic metal to protect the base metal from being corroded.

- Selective leaching – Selective corrosion or leaching is a form of corrosion in which the more susceptible metal in an alloy (that has been deposited in grain boundaries during formation) is selectively removed by corrosion. When the framework is gone, the base material is weakened and porous.
    - A way of thinking about this form or deterioration is to consider a structure in which the frame members simply disappear over time. Had an architect or builder chose framing materials that behaved in that manner, it would have been an unforgivable error. Using a material susceptible to selective leaching in an environment in which selective leaching is possible is a critical mistake.
    - Viewing this form of deterioration from the standpoint of the owner, if the composition of the process fluids being handled were to change so dramatically that selective leaching is possible, the mistake would be as significant as was the mistake made by the designer above. It is therefore necessary for owners to understand this possibility and make arrangements to avoid it from happening.
    - When alloys of zinc or aluminum (for example) are used, and process changes are envisioned or lack of control exists, it is important to include timely microscopic analysis of coupons as a part of the on-going inspection program**.**
    - A useful example of this form of deterioration can be found in the condensers (shell and tube heat exchangers) in marine service. If admiralty brass tubes are used and seawater is mistakenly substituted for coolant, the chloride in the seawater can leach out the zinc leaving weakened and leaking tubes.

- Others – there are a variety of other forms of corrosion. While some can be identified using only the naked eye, others require the use of microscopic or metallographic inspection along with a complete and continual understanding of the environment in which the material is functioning.

2. *Erosion*

Erosion is the form of deterioration produced when a surface is exposed to an abrasive material moving across the surface at the velocity required to abrade the surface. The rate of erosion depends on the hardness of the damaged surface, the hardness of the abrasive material and the velocity of the abrasive material relative to the damaged surface.

Unfortunately, at times erosion can occur in those places where you have taken steps to avoid other forms of deterioration. For example, in pump or engine bearings, oil is pumped to create a hydrodynamic boundary layer that will prevent bearing surfaces from rubbing. If the oil filter experiences break-through, abrasive material can flow with the oil and, instead of protecting the bearing surfaces, erosion will abrade and damage the bearing surfaces.

An example of serious erosion was a case in which the air intake for the plant air and instrument air compressor was positioned close to the sandblast (abrasive) yard. In this case, the capacity of compressors was increasingly reduced because of erosion of the compressor valves and piston rings. When the current capacity of the compressed air system failed to keep up with demand, the plant management simply added another compressor in the row until there was more than a half-dozen rental compressors on site. When the root cause was identified and the position of the air intake was moved and the permanent compressor was rebuilt (to replace the damaged valves and rings), all of the rental compressors could be returned to the rental company.

Erosion can often be identified by gradually decreasing performance. The cause of erosion can be identified by the presence of abrasive in a lubricant or product stream. The kind of abrasive materials found can point to the source of the abrasive. Many of the cases of erosion result from a change in the flowing fluid(s). In the case of the compressor described above, the problem could also have been prevented by installing an inlet filter that would plug if having to deal with more abrasive material than the machine could endure. A simple pressure differential gauge across the inlet filter would point to the situation that would lead to deterioration or failure if not immediately corrected.

It is important to keep in mind that installing a pressure differential gauge across the inlet filter is not something that is typically within the scope of work done by maintenance personnel. It needs to be installed with part of the initial project or completed using a capital project once in operation.

3. *Fatigue*

Fatigue is a natural process in which the external fibers of a component are exposed to cyclical stresses regularly reversing from tension to compression to tension to compression and so on. The degree of cyclical stress being caused by system loading must be greater than the fatigue limit of the material in order to cause a failure. Components can operate below the fatigue limit without failure for an infinite number of cycles. While appearing immune to fatigue, large rather robust components can be capable of billions of cycles before finally experiencing a fatigue failure.

After a specific number of cyclic transitions, the outer surface fibers exposed to highest stress levels will initiate cracks that can quickly propagate and lead to catastrophic failure. Once past the fatigue limit of the material, the time at which cracking will occur will depend only on the stress level, the number of cycles and the properties of the material. If operating below the fatigue limit, even an infinite number of cycles will not form fatigue cracks. If above the fatigue limit, failure can be avoided any time before failure occurs by reducing the stress below the fatigue limit or by preventing the addition of more cycles.

Fatigue failures are frequently found in pump, compressor or turbine shafts turning at high speeds. If spinning components like impellers, couplings or complete rotating assemblies are not adequately balanced or aligned, the imbalance or misalignment can easily produce stresses greater than the fatigue limit. While the shafts might last for billions of cycles, that number of cycles can accumulate quickly. A pump continually operating at 3600 r.p.m. will accumulate 1,892,160,000 or almost 2-billion fatigue cycles per year.

Manufacturers need to understand the behavior and performance of the equipment they produce, and alignment and balance standards should be provided in the equipment manuals when their equipment is sold. There are just two ways this kind of problem is avoided. First, the requirements can be provided in the manual and owners expected to follow those requirements to ensure warranty coverage. Second, owners can conform to installation standards used on all the rotating equipment. Unfortunately, this approach leads to waste when overly strict requirements are applied to equipment that do not require those elevated standards.

Over time, maintainers may start to believe that more stringent installation are not required for some of the equipment they maintain. This happens when some of the components fail quicker than the required number of fatigue cycles can accumulate. This, they will never experience a fatigue failure.

When that happens, it will not be clear where stringent installation requirements are necessary and where they are not. This is likely to lead to stringent requirements being eliminated where needed and failures allowed to occur.

The best approach is for design engineers to identify instances in which tight balance and alignment standards must be followed and then provide that information to owners using a technique that will make the requirements permanently available. For instance, name tags, labels or durable thumb drives containing this information can be affixed to the equipment.

In one impressive example, two moderate sized, slow turning compressors were used in a chemical plant. The redundant arrangement allowed one to operate and the other acted as a spare. The practice in the plant was to switch back and forth between the two (so, while ready for use, they were both worn to the same degree and likely to fail at nearly the same time). The two were maintained in the same manner so neither of the two-hundred- and fifty-pound couplings were balanced, and neither were properly aligned.

Despite the fact that the operating speed was only 400 r.p.m., the required number of fatigue cycles was reached after nearly thirty years. When the first compressor failed, it was thought that the shaft was made from the wrong material and that the crack propagated from a one by one-half inch keyway. When the second of the two failed approximately four months later, an adequate root cause analysis was completed, and it was determined that the cause was fatigue. The four-inch diameter shaft cracked in a manner that appeared nearly as clean as if had been cut with a saw. The shaft was replaced with the same material that had lasted thirty years and the coupling was balanced, and the compressor and motor was aligned. In addition, the other compressor was balanced and aligned as it should have been.

4. *Overload*

When I think of deterioration caused by overload, I always picture of a greatly overweight fully grown man riding on a child's tricycle. This image provides a vision of a device being used in a manner other than what it was designed to perform.

When an asset in this manner the device will be loaded well beyond the elastic limit of its materials and permanent deformation will be created. This picture in my mind does not add the detail of a child first riding the tricycle at a time the applied load was within the tricycle's design limits. The mental picture also does not extend to that person continuing to ride the tricycle over the course of his life as his weight increased until the applied load is no longer within the design limits of the trike.

Had I done so, I would have envisioned the plastic deformation gradually increasing with the added load until it reached the point where material thinning caused by deformation made the metal too thin to support the load, then it would fail.

While overload is possibly the simplest form of deterioration to envision, it may be the most difficult to understand how anyone would allow it to occur. The design load limit should be obvious and exceeding that limit seems to be dumb. Building elevators and gathering areas have maximum loading clearly marked. Cranes and lifts are marked with maximum loads. While maximum loading is not as apparent for other assets, the maximum loads for vehicles, trailers and other assets intended to handle varying loads can be found with licenses and in operating manuals.

But the concept of simple ignorance is often naive. A device can be used to handle acceptable loads when first applied, then loads can absent mindedly creep up until they exceed design capacity. As in the example of the tricycle rider, it is always the same tricycle and the same rider. Why wouldn't it always work?

Try to think of examples in which applied loads are absent-mindedly allowed to exceed design limits:

- Elevated pipes intended to handle light hydrocarbons are hydrotested using water that far exceeds the normal or design load.
- Pressure vessels intended to capture gasses are fully loaded with water for testing.
- Construction intended for handling dry materials are used to handle materials that are wet.
- An office building designed for supporting a small density of occupants and furniture is converted into a warehouse.
- A pumping system intended for pumping hydrocarbons is used to pump water.
- The list goes on.

Most of us have seen situations in which a pick-up truck is overloaded but still driving down a highway at high speeds. That situation is probably the result of incremental increase. If a single load has never been applied that immediately breaks the springs, it is likely that loads have caused the springs to sag when loaded, but they seem to rebound when the load is removed.

Unfortunately, the springs may rebound to a significant percentage of their original height, but not quite the full height. The seemingly successful practice of overloading will then continue on an increasingly frequent and increasingly overloaded basis.

This practice does not only happen for individually owned pick-up trucks, it happens with equipment owned by construction companies, with elevators in buildings, with floors and stairs in warehouses and a variety of other situations.

Section Two – The Various Characteristics of Deterioration

When thinking about forms of deterioration that causes poor reliability and reduced lifespan, our minds tend to focus on the forms of deterioration that are very apparent and are associated with circumstances that occur when equipment is actively being used.

Doing so can prevent us from identifying a significant portion of deterioration mechanisms that happens when an asset is idle. Hoping to broaden our perspective, this section will provide some thoughts on the various dimensions that can be used to characterize forms of deterioration.

- While our minds tend to envision obvious or **apparent** forms of deterioration, there are many forms that remain **hidden** until discovered by either proactive inspection or failure and reactive repair. Some forms of deterioration will become apparent once the device is disassembled. Others will not. Some failures become apparent only through testing.

- Again, while our minds tend to focus on forms of deterioration that occur when an equipment item is **active**, there are other forms that occur when equipment is **inactive or dormant**. As a result, we tend to believe that a devices susceptibility to deterioration ends when it is changed from a dynamic state to a static state or simply turned off. We need to open our minds to deterioration mechanisms that are the result of natural processes that we are not aware are going on around us.

- We frequently tend to focus our attentions on deterioration that produces some sensible signals or **symptoms** that suggest the possibility of impending failure but there are others that are **imperceptible** or obscured before failure. Many of nature's processes happen very quietly.

For instance:

- If a chain drive on a bicycle remains **apparent**, deterioration is obvious and the products of deterioration on the chain and sprocket serves as a reminder that cleaning and lubrication is needed. On the other hand, if that same chain drive is placed in complete protective guard, that reminder does not exist and unless the guard is regularly removed, and the chain cleaned and lubricated it will wear until it breaks. This is not meant to suggest that guards are unnecessary. It is meant as a reminder that the effort needed to assure routine inspection and lubrication must be triggered by some other form of reminder than seeing the actual chain.

- While hour-meters tend to provide a reminder that anti-friction (ball or roller) bearings must be lubricated when machines are being regularly operated, hour-meters do not provide a reminder when equipment is sitting idle. Frequently equipment containing anti-friction bearings are left with the weight of the rotating element being supported by a single spot on the bearing surface when idle. This happens when rotating equipment is sitting idle in a warehouse or installed on projects for long periods before startup. This practice will cause that spot on the bearing surface to become harder than surrounding bearing surfaces. Once started the softer material surrounding the hard spot will recede compared to the hard spot causing vibrations and further wear. This process called brinelling, can be avoided by rotating the equipment shaft by a partial turn each week. That will cause bearings to rest on a different spot and avoid localized hardening.

- Much of the attention focused on rotating equipment deterioration is associated with those forms of deterioration that produce changes in the sound or the level of vibrations. These symptoms are apparent and easily measured. On the other hand, mounting fatigue cycles are silent and produce no measurable symptoms until the required number of fatigue cycles is reached, a crack forms, and the component fails. Here, the required number of fatigue cycles expected before failure must be determined (by testing or experience), a safe margin of error estimated and subtracted from the number of cycles at failure (to produce the safe number of fatigue cycles), the number of fatigue cycles must be counted whenever the equipment is active and, finally, the component experiencing fatigue must be removed and replaced when reaching the safe maximum number of fatigue cycles. Looking for a crack and hoping to intervene before failure is an unreasonable expectation. Crack formation, propagation, and dramatic failure all happen too quickly to avoid when initiated.

The examples provided above are only a small portion of the kinds of deterioration mechanisms that must be anticipated to avoid extensive deterioration and ultimate failures resulting in poor reliability and shortened life of assets. It is important to understand the forms of deterioration and their causes that are specific to the industry where you work or for whom you are designing equipment.

Here the concern should be for “susceptibility” rather than “certainty”. For instance, uncoated metals that are exposed to weathering are almost certain to experience deterioration. On the other hand, equipment containing dissimilar metals, crevices, and are accessible by atmospheric moisture are susceptible to various forms of deterioration so efforts should be made to monitor and avoid that deterioration.

Section Three – A short list of circumstances that can lead to deterioration

The following is not intended to be comprehensive or exhaustive. It is intended to provide some examples of circumstances that have led to failures that have adversely affected reliability in the past. Each industry, equipment type, and degree of sensitivity by design engineers will produce varying amounts of deterioration, levels of reliability, and length of useful life.

- Hidden or obscure batteries – Increasingly microprocessor-based systems contain batteries that are neither obvious or easy to access or replace. Occasionally these batteries can last for several years, but upon failure result in unexpected forms of failure. If not renewed in a timely manner systems may require re-cycling the system or re-initiation on a regular basis. These steps halt the function being performed.

- Sources of debris, abrasive, or harmful materials – Occasionally, systems safely contain the materials in one location that become the source of its demise when released to other locations. For instance, a catalyst held safely in one location can become an abrasive when introduced in other locations. The same is true of a variety of aggressive liquids.

- Poor electrical connectors – The frequency and importance of electrical connectors has increased with the growth of electronics and computer-controlled equipment. While these systems operate at low voltages and can therefore be less robust, the lower voltages are also more susceptible to reduction or interruption by small amounts of corrosion.

- Poor electrical switches – The same is true of electrical switches. Low voltages allow for use of devices that are less robust but that also makes them more likely to fail.

- Corrosion circuits – With an increasing number of circuits carrying low voltage to provide power or control systems, more voltage is running around in equipment forming natural corrosion circuits. In addition, the drive to decrease weight to improve fuel economy results in lighter and thinner materials being used in a variety of applications. The differences in metallic materials combined with natural corrosion circuits can produce unexpected deterioration and failures.

- Lubricant deterioration – Unless properly protected and changed at proper intervals, lubricants can deteriorate from oxidation and introduction of debris or water. Rather than providing protection, lubricants can become the source of deterioration. It is often useful to replace filler caps with breathers that remove moisture.

- Manual cable connections – Less frequently but still present are situations in which positions are set by mechanical cables. These cables typically have numerous metal-to-metal wearing points and a termination provided by a bent cable end connected through a hole in the device being positioned by the cable. These metal-to-metal surfaces are subject to erosion if not lubricated.

- Blades, files, and brushes – Devices that are dependent on sharp edges or abrasive surfaces are particularly susceptible to corrosion and erosion. While this deterioration effects the device itself, it also produces debris that can adversely affect surrounding devices.

- Chains and gears – As with the last category, these devices contain shapes that seem designed to capture and hold moisture and debris, and produce accelerated corrosion and deterioration that affect surrounding components.

- Valve operators – Valve operators and similar devices have several characteristics that can produce deterioration. First, they transfer heat and mirror the temperature of the device to which they are attached, either extremely hot or extremely cold. Their workings are protected by covers that often traps debris. They have gear teeth and other elements that produce concentration cell corrosion. If inexpensive clay-based grease is used, the clay will dry out leaving the oil to drain and the mechanisms to go without lubrication.

- Springs and supports – Springs and other kinds of supports are intended to carry loads and accept various movements. As a result, they can be subject to overload and to fatigue. It is important to ensure they are not overloaded (e.g. piping systems being filled with water for hydrotesting instead of light hydrocarbon as designed) or exposed to greater movement than intended (e.g. more frequent or more intense temperature changes).

- Filters and dryers – If filters and dryers are allowed to remain filled longer than expected they may be subject to internal corrosion or break-thru. Either case can adversely affect downstream equipment.

- Drive belts – Drive belts are typically covered by protective guards. If so, they can deteriorate to the point of failure without being discovered. Sight glasses or routine inspections must be provided to ensure that deterioration can be found and failures avoided.

- Links between warm-moist gases and sub-dewpoint surfaces – While most common in humid areas of the country, like the gulf coast, humid conditions can exist anywhere. When gaseous moisture that has entered comes in contact with a surface below the dew point, condensation will occur. This liquid can then serve as an electrolyte to connect dissimilar metals and concentration cells or crevices to produce corrosion that can continue unnoticed until a failure occurs.

- Idle spare equipment – Spare equipment is commonly used only upon the failure of the primary equipment item and that is often only upon an emergency when immediate start-up is required. Equipment is designed to take care of itself while in operation, not when idle. For instance, an idle pump can have liquid build up in the volute or stuffing box causing corrosion. It is important to identify activities needed to protect idle equipment and ensure it is ready to start when needed. Don't forget the driver or the transfer switch if one exists.

- Unstable supports for dynamic equipment – If a dynamic equipment is mounted on an unstable support (e.g. skid mounted, mounted on an elevated structure, mounted on mobile equipment, portable equipment, transitory or reparable equipment) make certain that the movements of the mounting location do not produce misalignment or synchronous amplitudes that can harm the equipment.

- Connections in complex systems – Frequently connections in complex systems are created using other than bolted or welded methods. These connections can be electrical connectors held only by tension. While the connections may appear to work when new or when disconnected and re-made from time to time, they may be troublesome, subject to loosening, wear, or concentration cell corrosion.

- Unequal deterioration rate in combined systems – Occasionally, there is a single major form of deterioration that is accepted and used to determine the timing of overhaul or renewal. In this case, it is commonly decided that other forms of deterioration will be addressed during the time set aside to the major deterioration. If so, it is important that minor forms of deterioration are identified and, if they conclude prior to the major maintenance event, they are addressed at the appropriate times.

- Etc.

One last point – In addition to deterioration mechanisms leading to failures in devices and equipment, functional failures can be caused by inadequate coding in firmware or control programs. Since this is not a material related cause of poor reliability (it is a coding issue), it is not addressed herein.

For the sake of completeness, many of those issues can be solved by recycling the system (by shutting it down and re-starting it). Unfortunately, if the device is being asked to perform a function for which recycling is not acceptable (and programs not coded), this situation will produce a failure. In this case, manufacturer engineers should be asked to correct the problem.

Section Four – Life Cycle Steps and Key Activities

The following phases or steps occur during the life cycle of a plant or individual equipment. Each step must provide certain specific activities for understanding and addressing important forms of deterioration. If not addressed, it is likely the reliability and/or useful life will suffer. As a result, it is important to both understand the important results from each phase and the activities of specific individuals in performing those roles. It is also critically important that areas of accountability be communicated, accepted, and monitored to ensure accomplishment.

For example, while Design For Reliability is experiencing increasing acceptance during the design phase, activities that continue to understand and deal with new or changing forms of deterioration as assets age are not equally common. For instance, an owner may acknowledge the presence of uniform corrosion when installing a new asset but fails to identify or address the presence of erosion, fatigue, overload, or forms of corrosion other than that initially identified as the asset traverses later phases of its lifecycle.

The objective is to maintain vigilance to other forms of deterioration that may adversely affect reliability or useful life for the entire lifecycle of an asset.

1. *Pre-Design / Development Phase*

    a. In the initial conceptual stage of a new facility or asset, it is important for the individuals who identify and approve the requirement for the new assets to also identify and communicate new expectations pertaining to reliability and useful life, particularly if those characteristics are new or different from past experiences. Say, if the new asset is expected to function far differently than similar assets that currently exist, the initiators need to say so and clearly quantify the extent of the difference.

       An example of this was when a major railroad wanted the manufacturers to build on the work they had successfully accomplished internally. The railroad had decreased the road failure rate from 4 FLY (failures per locomotive year) to 2 FLY and they wished for new locomotives to be built to deliver 1 FLY performance. Locomotive manufacturers viewed this as a dramatic change that would result in a doubling of current pricing. Ultimately, this concept would require a change in paradigms by many of the participants in the discussion. This example is consistent with the change in paradigms that happens when manufacturers are forced to pay the entire Cost of Quality for the defects they produce.

    b. Individuals who create the conceptual requirements (or their lieutenants) should communicate with key participants at each stage of the development process to ensure they fulfill the parts of their role that will produce the desired results pertaining to reliability and useful life. For instance, if the person overseeing the commissioning/start-up/initial operation is expected to identify and report issues that suggest the new asset will not function or perform as intended, they must be clearly instructed to report such issues and how to suggest ways to overcome shortcomings.

c. Contractual descriptions for the functions described above should be built into role descriptions and performance requirements. If those individuals simply get the new asset running and fail to take steps that will identify likely sources of deterioration, reliability requirements, or useful life issues, their job is not complete.

2. *Design / Development Phase*

   a. On-going oversight must be performed by someone who understands both the objectives for improved reliability and useful life and what is required to achieve them.
   b. New design practices including Design For Reliability and Reliability Block Diagram methods and increased accelerated testing using final material selections and product configuration are part of the design requirements that must be completed.
   c. System for recording and communicating current and possible eventual forms of deterioration to the future owner must be provided. This includes known requirements for inspection, repair, and timely renewal. Such systems may include digital data files that are permanently attached to equipment items.

3. *Manufacturing / Construction Phase*

   a. Protective schemes applied during manufacturing and construction must be assembled including:
      i. Rotating roller bearings during dormant periods when in storage and between installation and start-up.
      ii. Monitoring equipment for deterioration that occurred before delivery or installation and start-up. Make arrangements to have all items returned to the expected new conditions.
      iii. Overlapping early commissioning steps with construction whenever possible. Performing operation and testing activities as early as possible to ensure equipment is fully functional and able to perform to anticipated requirements while time is still available to address shortcomings.
   b. Apparent sources of deterioration created during construction must be managed, including:
      i. Keeping equipment storage locations clean, dry, and accessible for inspection.
      ii. Regularly inspecting for deterioration that may have been caused by accidental or intentional activities during construction.

1. Look for damage to coating systems and make repairs.
2. Inspect on arrival for damage that may have been produced by transportation accidents or failure to provide adequate protection.
3. Particularly for those items that will experience long periods of being dormant during normal operation, look for forms of deterioration that occur when dormant and make arrangements for protection.

4. *Commissioning / Start Up / Initial Operation Phase*

a. Preventive measures applied during commissioning and start-up include:
    i. Observing required break-in periods at no or partial loading during initial operation.
    ii. Understand where break-in lubricants are being used and schedule early oil replacements including filter and breather changes.
    iii. Observe where high vapor pressure materials are needed and used in crank cases and oil sumps to avoid ingress of moisture and humidity. See they are removed and replaced with proper lubricants before operation.
    iv. Be sure that all exposed machined surfaces are properly protected between manufacture and commissioning.
b. Verification of components and conditions.
    i. When projects or equipment contain electrical connections, make sure they are properly made and protected. (Use in-plant personnel to familiarize them with new systems.)
    ii. The same goes for physical connections.
    iii. For all essential equipment, establish baseline conditions for later comparisons. For example, measure delivered voltage from power supplies, electrical circuits, current draw for motors, and horsepower requirements for major electrical loads. Use this information in the future to determine deterioration.
c. Verification of **component** functionality
    i. Exercise each component through its entire range of functionality.
    ii. Determine how each component is expected to behave after anticipated forms of deterioration have occurred and record in troubleshooting section of operating manuals.
d. Verification of system functionality
    i. Exercise each system through its entire range of functionality.
    ii. Determine how each system is expected to behave after anticipated forms of deterioration have occurred and record in troubleshooting section of operating manuals.
e. Verification of asset functionality

   i. Exercise the complete asset through its entire range of functionality.
   ii. Determine how the complete system is expected to behave after anticipated forms of deterioration have occurred and record in troubleshooting section of operating manuals.

5. *Normal Operations*

   a. Be sensitive to changing conditions. Monitor behaviors as they relate to anticipated deterioration and record similarities and differences.
   b. Identify unexpected changes in operating conditions then identify any new forms of deterioration and record the relationship along with corrective actions in the troubleshooting section of the operating manual.
   c. Update program of predictive and preventive maintenance to include newly identified forms of deterioration.

6. *Routine Maintenance*

   a. Routine maintenance should include activities to assure cleanliness, tightness, freshness of lubricants and other operating fluids as well as calibration and adjustments.
   b. As a part of Precision Maintenance as applied to Routine Maintenance, disassembly and assembly procedures should include requirements to gather "as-found" and "as-left" conditions of critical tolerances, fits and clearance of equipment as well as performing calculations needed to determine required "deterioration allowance" restoration needed to ensure the desired lifespan between maintenance or replacement intervals.

7. *Overhaul Maintenance / Restoration*

   a. When Precision Maintenance is applied to major overhauls, it is necessary to record "as-left" conditions of critical tolerance, fits, and clearances upon assembly and "as-found" conditions upon disassembly. Differences between "as-left" and "as-found" conditions will identify the amount of deterioration that has taken place. Dividing by the time in service between those measurements will identify the "deterioration rate".
   b. Multiplying the "deterioration rate" by the length of time in the desired run will identify the required deterioration allowance. If it is impossible to achieve the desired run-length using the maximum deterioration allowance (for the current

material). It will be necessary to replace the current material with one that is less susceptible to the current form of deterioration.

8. *Renewal*

   a. When an asset or equipment item has reached the time for complete renewal, it is necessary to identify the complete objectives of renewal including new functionality as well as any new requirements for reliability and useful life of the renewed asset.
   b. When significant changes are being made, perform all the steps used during the initial design.
   c. When renewing any component, equipment item, or complete asset, it is important to avoid situations where you may fail to identify "used-up" life when performing the renewal. (For example, there was a situation in which older locomotives were being renewed. When the overhead fans that are part of the dynamic braking system were renewed, the existing blades were welded onto new hubs. The useful life of these fans was determined by the fatigue life of the blades and the old blades had already exhausted 90% of their fatigue life. As a result, new fans required new blades.)

9. *Transfer of Ownership*

   a. As a part of "Due Diligence" performed to identify the fair price and true value for an asset, it is important to understand the forms of on-going deterioration and their current status. While the short-cut approach commonly used is based on the frequency of major maintenance and its cost, there may be on-going deterioration that is not adequately addressed using that technique. It is important to take long enough when performing Due Diligence to quantify significant forms of deterioration that may not be adequately addressed using short-cut techniques.
   b. Even more important than unaddressed forms of deterioration are issues that will affect asset availability and therefore income producing capability of assets. Understanding all the issues affecting reliability and remaining useful life or identifying any limitations that prevent an accurate estimate of those characteristics is critical.

10. *End of Useful Life*

    a. The true end of life or just the end of life for you?

        i. Many factories operate on such a tight profit margin that a key difference occurs when the assets have been fully depreciated. While that condition affects the current owner, a future owner may be able to re-start the depreciation schedule. That financial effect can breathe new life into many assets. Unfortunately, a new financial life does not ensure a new reliability of useful life. In fact, if the purchaser is not careful, the transfer of assets can reduce reliability or useful life. The purchaser needs to be certain to transfer the organizational knowledge of the facility and all the other elements needed to continue prior operations including the knowledge that assures reliability and useful life.

b. Paying the lifecycle value forward.
    i. In addition to the buyer, the seller has a part to play in properly transferring the true value of any asset. For instance, if there is deterioration that went undiscovered during due diligence and the human assets or files needed to transfer the needed information has not been passed, the seller owes it to the buyer, the surrounding community, and the remaining employees to inform the buyer of those limitations. Doing other would seem to be unprofessional and unethical.

Fortunately, of unfortunately, many old refineries and other plants never die, they are just sold to other companies. This practice allows the new owner to re-start the process of depreciating the asset value as a tax write-off. That favorable economic device often gives new life to old assets.

If the former owner or owners re-invested the value of annual depreciation into the asset, that amount would have gone a long way to reverse the various forms of deterioration occurring during each year in the life of an asset.

But many owners use the value of depreciation only to reduce taxes and thus improve returns. This approach ignores on-going deterioration.

In addition, private equity investors may take actions that further reduce needed assets like marketable spare parts inventories.

Further, the lay-offs and separation of individuals comprising the knowledge bank reduces understanding of hidden forms of deterioration recorded only in the memories of individuals. It is frequently impossible to reassemble the human knowledge bank once it is gone.

While attempts may have been made to store required knowledge in CMMS, ERM or other systems, those systems still require a human knowledge bank to extract and interpret the information they hold.

Section Five – Conclusion

In a sense, managing the reliability and useful life of systems and components is more of an art than a science. Clearly, it is important to understand the science associated with material deterioration, but that understand is only useful to a point. That point is where the science ends and the art begins.

Keep in mind:

1. No one has the benefit of unlimited resources, so it requires judgement to balance the application of resources.
2. No one has perfect timing. You are either ahead of the deterioration schedule (and wasting money) or behind it (and allowing failures to occur).
3. No one has the intuitive ability to sense things he or she cannot see.

The clock is always ticking, and the schedule is not the same for all the horses in the race. When performing Design For Reliability using Concurrent Engineering, the efforts are never really concurrent. The conclusion for DFR occurs after the finish of the functional design and the start to purchase material and components. It is often impossible to determine the reliability of components until sometime after they are selected, delivered, and tested in the environment where they will be used. It is impossible to complete the Reliability Block Diagram analysis until after the individual components has been selected and their reliability and forms of deterioration and deterioration rate verified.

That difference in timing means that there will always be at least some portion of the components that do not fully meet reliability requirements.

The world is not perfect and never will be. The objective is to do as well as possible and hope your insights are not myopic.

As an example, consider the story of the World War II bombers. Early in the war, when it was found that far too many bombers were being lost to bullets and flak, a decision was made to begin adding armor to the areas where holes were found in the fuselage of returning planes. When the survival rate did not improve, the strategy was reconsidered.

It was decided that armor was being added to the wrong places. When planes returned with damage, it meant those damaged areas were survivable. As a result, it was the areas where damage was not being found on returning planes that could not be survived.

The process of adding armor was moved to other areas that were vulnerable, and there were no signs of damage on returning planes. The survival rate improved.

You should hope that your insight is better than that of those who first determined the locations where armor should be added to bombers. Initially, the added armor did nothing but added weight, reduced the bomb load, and decreased the fuel efficiency of the planes. The net effect was more negative than positive. The revised approach may have cost bomb load and fuel efficiency but did so while saving planes and crews.

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