Failure Modes and Failure Mechanisms

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By

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Introduction

The business of making systems reliable is one that, despite its popularity and importance, seems somewhat nebulous and technically unclear to many people. There are numerous examples in which a significant event resulting in the loss of an asset has occurred and the cause is chalked up to “bad luck”.

On one occasion, a famous photographer was asked if he really thought photography was a form of art or more a matter of luck. He responded that it may just be a matter of luck, but wasn’t it amazing how some people had all the luck. Reliability seems to be much the same. Individuals who spend time and resources focusing on achieving good reliability seem to have more success that those who do not.

One topic that people who spend time and resources focused on reliability tend to understand is how deterioration leads to failures. Again, those individuals who focus very little on reliability tend to see deterioration leading to failure as something that is beyond their control.

In a way, the control of deterioration is what reliability is all about. While there appears to be an infinite number of forms of deterioration and an infinite number of sources, there is really a relatively small number. By understanding the sources and forms of deterioration, it is possible to determine the forms of prevention needed to improve the reliability of your assets.

This course is intended to provide the student with a relatively simple yet comprehensive description of the how deterioration leads to failures and how forms or prevention can reduce the deterioration and improve reliability. Those in the “reliability business” use specific terms to describe the causes of deterioration and the specific conditions associated with failure. While it is most important to intuitively understand what causes deterioration, how deterioration progresses to the point of failure and how various forms of prevention work, it is also important to gain an understanding of the terminology. Much of the information used in developing a complete understanding of specific instances of deterioration leading to failures is assembled and structured using the terminology accepted within the industry. As a result, it is useful to both understand how things work in nature and how they are described in an engineering sense.

From Cause to Failure

There are a series of steps that lead to the failure of an engineered device. I find it important to focus on failures of engineered devices because engineered devices depend on specific properties of components. The forms of deterioration we will discuss are mechanisms found in nature that adversely affect those specific properties.

The steps are:

- Cause
- Lack of protection against a Failure Mechanism (or lack of prevention)
- Failure Mechanism at work
- Measurable Deterioration
- Defect – Potential For Failure (deterioration to the point the device is unable to handle the intended load)
- Failure Mode
- Failure

While it may seem that I am drawing distinction between steps that are only subtly different, the student will find that there is value in these distinctions when it comes to understanding how human intervention can be made to occur at the right times to prevent failures.

The **cause** is a distinct activity that led to the required prevention not being applied. It is important to distinguish the cause from the actual activity where prevention was not applied because the choice that resulted in the act may be separated from the act. For instance, if a corporate officer chose not to fund the company's paint program, that choice may result in lots of instances where corrosion occurred. In this case, the cause would be the senior manager's decision, not the painter who failed to apply the paint.

In identifying the cause, it is important to keep the following steps in mind. The first is the lack of prevention and the second is the Failure Mechanism at work. In a situation where the corporate officer described in the above example acted in a discriminating manner and removed funds for painting in only those situations that were cosmetics or for appearance and allowed for painting to be applied to those places where the coating was needed for prevention, he would not be the cause of the failure.

On the other hand, if the choice was indiscriminate and led to the end of all painting (both cosmetic and preventive), the choice of the senior manager would be the cause.

In contrast, if the senior manager directed that cosmetic painting be stopped and preventive painting be continued but someone below him in the organization chose not to apply paint in an instance where it was needed for prevention, the cause is elsewhere in the organization.

While the differences may seem subtle, it is important to determine the true cause if a solution is to be identified. Gaining added approval from a senior manager will do little to correct the problem if approval already exists. Also, telling individuals further down in the organization to perform additional preventive painting will do little good if the senior manager has said, No!

The next step is **lack of prevention against a Failure Mechanism**. For mechanical devices, there are four Failure Mechanisms: corrosion, erosion, fatigue and overload.

While those Failure mechanisms exists many places in nature, they may or may not be present in the specific working environment of an asset. For instance, if a metal device is located in the wet, humid environment of the U.S Gulf Coast, it is likely that the device is exposed to corrosion associated with the effects resulting from atmospheric moisture. Conversely, if the asset is used in a dry desert locale, it will likely not experience that form of corrosion. If components or a device are exposed to the constant cycling of compressive stresses then tensile stresses above the fatigue limit of the materials used to construct the devices, they will experience fatigue. If not exposed to cyclic stresses, they will not experience fatigue.

If components are exposed to those failure mechanisms due to atmospheric moisture or due to vibration or bending, then some form of prevention must be applied. If prevention is not applied, the associated Failure Mechanism will be free to proceed.

The next step is the **Failure Mechanism at work**. It is important to distinguish between the lack of prevention allowing the Failure Mechanism to start and the lack of awareness that allows it to continue. For example:

- Corrosion produces signs of deterioration and metal oxides or rust.
- Erosion typically produces some form of debris resulting from thinning. In the case of an internally lubricated device, the deteriorated material will be apparent during oil analysis.
- While the cracks that result from fatigue are not apparent until a significant number of cycles are complete, the presence of fatigue causing stresses might be made apparent from vibration or displacement (bending) of components.
- Overload also frequently has some physical signs of its presence. Sagging or bending for supporting elements, overheating of load-bearing elements or accelerated deterioration of loaded components are signs that a component is overloaded.

If operators and maintainers are not sensitive to the signs that a Failure Mechanism is at work, the deterioration will be allowed to proceed unabated.

The next step in the process is **measurable deterioration**. While deterioration is included above as one of the means for identifying a Failure Mode at work, it is also one of the tools useful in identifying a P-F interval.

The P-F interval for a specific form of failure is the time between when the "potential for failure" exists and when the failure occurs. The "potential for failure" is a characteristic that should be distinguished from any other step in this series. The Potential for Failure exists only when a component is no longer able to sustain the burden that might occur within the range of reasonable possibilities.

For instance, a component might be exposed to corrosion for a long time and it might experience significant metal loss. But if this component is still able to sustain the maximum burden it might see, there is no potential for failure. Using the same example, suppose that a component has experienced a significant amount of deterioration and the normal range of loading is greater than the component will bear. But, in this case, assume some form of control is installed to limit loading to less than the capability of the deteriorated component, then the potential for failure has been eliminated.

Again, it is important to separate the presence of measurable deterioration from other steps in this series of steps because; it provides another opportunity for human intervention. If the capabilities of the deteriorated component are determined and the operating environment is modified in response to that deterioration, then the potential for failure can be managed. On the other hand, if the measurable deterioration is not acknowledged and managed, the potential for failure will be present.

The next step is the **presence of a defect and the potential for failure**. Assume that all the opportunities for early intervention described above have been missed and a failure causing defect exists in some component. In other words, the potential for failure is present. The following are a few examples:

- A load bearing component has corroded to the point it no longer has the capability of supporting the maximum normal loading.
- A load bearing component has eroded to the point it no longer has the capability of supporting the maximum normal loading.
- A load bearing component has operated above the fatigue limit for a long enough period of time (and fatigue cycles) that it is possible a crack can form at any time (or might have already began to form but is still not apparent).

- A load bearing component that has not been designed to support the normal loading to which it is exposed, has experienced loading beyond its capabilities for enough time to damage or reduce its load bearing capabilities.

In any of these cases, failure can happen at any time. The potential for failure exists. An important point to consider is that while the potential for failure exists, the failure has yet to occur. There is always some amount of time, sometimes small and sometimes significant, that exists between when the potential for failure exists and when a failure occurs. While there is no guarantee how long this opportunity will be, there is still an opportunity to intervene and prevent failure.

External corrosion produces rust or other forms of corrosion products. These corrosion products have more than ten-times the volume of the metal from which they were produced. With an attentive eye, it is difficult to miss the signs of external corrosion. Forms of overload are frequently apparent from the symptoms associated with a component operating beyond its capacity. While finding a fatigue crack between formation and failure may entail an element of luck, timely observations of elements exposed to fatigue can find and prevent failures. The amount of vibration or bending sufficient to cause loading above the fatigue limit should be apparent. In these cases, the individuals who have frequent opportunities for observations must also be provided with the knowledge of specifically what to look for.

The next steps are the **presence of the Failure Mode and occurrence of the Failure**. Clearly, the Failure Mode is linked directly to the Failure Mechanism. If the terms used to describe the Failure Mode are meaningful, it will be possible to identify that linkage.

There are two important factors to consider when choosing the terminology used to describe the Failure Modes your equipment is experiencing:

1. You will need a clear link to the Failure mechanism to identify the cause of the deterioration
2. You will need to clearly quantify the number of instances caused by each distinct Failure Mode and Failure Mechanism so you will know where to invest scarce resources.

This course will provide more information about the linkage between Failure mechanism and Failure Mode later.

To conclude this discussion, it is important to highlight the point that prevention or intervention depends on a clear knowledge of how things deteriorate and what ultimately causes them to fail.

A clear understanding of the steps leading to failure assists the owner in:

- Performing root cause analysis
- Identifying opportunities for intervention
- Identifying the effective forms of prevention

If you know those things, you can either prevent the deterioration or intervene before the deterioration results in a failure. Lacking that knowledge, you are dependent on the kindness of Mother Nature in choosing not to unleash one of her Failure Mechanisms against your assets.

Failure Mechanisms

Much of engineering school has to do with learning how things work in nature. Statics and Dynamics help us understand the forces acting on elements of any system. Strength of Materials provides an understanding of the loading that elements can withstand based on system geometry and cross-sectional area. Courses in Metallurgy and Corrosion show how certain characteristics are determined and how deterioration might occur. There is an array of similar courses associated with other kinds of systems that describe analogous characteristics for those systems. While the essence of understanding Failure Mechanisms is held in those courses, the information is typically not portrayed in a manner that allows the student to directly tie what has been learned to the subject of reliability.

It is also not possible for a typical reliability engineer to spend the time needed to apply basic science to each and every application where a failure might occur in each and every system. As a result, there is value in characterizing the factors that can adversely affect reliability in more easily understood and applied format. Using those generic characterizations, it is then possible to apply generic forms of prevention that help to widely eliminate deterioration. A typical example is a plant-wide painting program. When properly applied a plant-wide painting program will eliminate deterioration due to corrosion in a vast array of situations, far more than if they had they been handled on a one-at-a-time basis.

For mechanical components within systems, there are four Failure Mechanisms. They are:

1. Corrosion
2. Erosion
3. Fatigue
4. Overload

Clearly, there are a number of kinds of corrosion and each of them can cause the deterioration needed to result in a Failure Mode and a Failure. Also, erosion results from a number of causes. The same is true of fatigue and overload. The benefit of the form of generic characterization that groups similar Failure Mechanisms together is that it provides reassurance that the number of Failure Mechanisms is not infinite. There is a starting point and there is a relatively simple way to quickly focus attention on a limited number of sources for deterioration. There is no need to throw up your hands and say, “there are too many possibilities”. The number of Failure Mechanisms is small enough that all but a few can be prevented by following “good practice” in design, assembly and maintenance.

For instance, here are a few “good practices” that can be applied during design, assembly and maintenance that will provide prevention for a number of typical Failure mechanisms:

1. Keep metals isolated from others that are more or less chemically active. Avoid creating corrosion cells.
2. Provide protection where forms of erosion are possible.
3. Where movement of vibration can be present, be careful to avoid situations that might allow rubbing. Use non-metallic grommets to shield electrical conductors passing through holes in bulkheads.
4. Where movement of vibration can be present, provide supports or bracing that will limit movement and prevent fatigue.
5. In situations where the protection afforded by enclosures depends on seals that deteriorate with age or wear, be sure that those seals are properly maintained.
6. Provide capacity or capabilities in systems for loading at worst-case conditions. When providing a safety factor in the design, the safety factor should not be provided only to handle unusual but expected loadings. All expected loadings should be handled within normal design tolerances and the safety factor should go beyond those limits.
7. When producing a “fleet” or a number of items using the same design, construct one or more “rabbit” units using the same manufacturing processes that are intended to be used on all the units to follow. Closely review the completed “rabbit” units to identify any shortcomings that exist within the assembly process. Test the “rabbit” units using extreme conditions that the units may experience during actual use. If leaks, vibrations, rubbing or any number of undesired effects are noticed, correct the problem on the “rabbit” and alter the manufacturing process to address the problems.
8. Maintain the systems of prevention rather than deterioration to the asset. When a form of needed prevention is no longer effective and deterioration to the asset must be maintained, the likelihood of failure and costs of maintenance will increase dramatically.

Applying What Was Learned In Engineering School

One might ask what distinguishes an individual with an engineering education from non-engineers when it comes to understanding issues related to reliability. While few schools typically focus directly on laws of nature as they relate to Failure Mechanisms, they do focus on them as they relate to characteristics needed to provide functionality. As an example, courses in Statics and Dynamics are useful in identifying the forces that exist in systems. The information provided in Strength of Materials and Metallurgy courses help students understand the stresses, strains and the allowable limits of specific materials.

While those courses do not directly address Failure Mechanisms or how the resulting deterioration cause failures, they do provide students with an intuitive understanding of how things work and what causes them to stop working. Said another way, the capabilities provided by a sound engineering design are the same characteristics that are lost when deterioration is allowed to proceed.

As another example, courses in Mechanical Engineering Design or Boundary Layer Theory will provide students with an understanding of the film thickness provided by lubricants in sleeve bearings during operation. While that education may not directly address the Failure Mechanisms associated with systems of that kind, it will provide the student with an intuitive understanding of why a specific lubricant viscosity is required (to maintain an adequate film thickness) or the maximum size of a particle of debris that can be present without resulting in erosion (damaging the bearing surfaces).

The point being made in this section of the course is that if a student is finding it difficult to understand Failure Mechanisms, he should be reminded to revisit the things he learned in engineering school. When component or systems start breaking down, it is because the assumptions made during their design are no longer holding true. Elements are stressed beyond their capabilities. Element capacity has been reduced due to corrosion, erosion or other forms of deterioration. Cracks due to fatigue have reduced the effective cross section of a component.

Another possibility is that critical issues were not considered during the design. Many designers tend to focus only on how they see things functioning. Those who have written computer programs understand the trap of focusing on how you want things to work rather than thinking solely about what the instructions are saying and how the computer will process the instructions. The computer has no way of knowing what the programmer intended. It only knows what the instructions say.

The same is true of all designs. Nature does not respond to what the designer intends. Nature responds to what exists. If there is a way for leakage to occur, it will occur. If there is a way for rubbing or erosion to occur, it will occur. If there is a way for a corrosion cell to form, it will form.

As a result, a “rock solid” design not only takes into account everything the designer learned in school, it also takes into account information that was inferred but not directly stated in those engineering courses. For instance, the strength of a component has to continue to exist after the cross section has been deteriorated by corrosion. The current a wire is capable of carrying must be capable of the loading even after the cross section of the wire has been reduced by erosion or corrosion. If you are not preventing deterioration then the design has to provide for operation in a deteriorated state.

Deterioration

The result of the active presence of a Failure Mechanism is deterioration. When corrosion is present and active, the cross-sectional area of a component will be reduced because some portion of the outer surface of the component is being converted to a corrosion product, like iron oxide or rust. The physical characteristic of the material to which the component has been transformed no longer contains the load bearing capability of the original material. In fact, the converted material may be so weak that it washes or is worn away.

While this description of deterioration may seem overly detailed and cumbersome, it does describe the process and result of deterioration in a way that helps one to understand. All Failure Modes have a similar impact of reducing some characteristic important to the engineered application of the component in question. The details contained in this definition are important because it helps us understand the objective of prevention. Prevention is a method of protecting the characteristics important to the engineered application. Effective prevention not only eliminates the visible products or deterioration like rust or debris resulting from erosion, it also eliminates the presence of changes that are not so apparent.

An example of deterioration that is not so apparent is a process like de-zincification or de-alloying of metals. In the case of certain alloys, the performance in certain applications is dependent upon the presence of certain alloying materials in specific concentrations. Loss of those alloys as the result of a failure mechanism that exists in nature will reduce the ability of the alloy to perform its intended function. Unlike the forms of deterioration that are apparent to the naked eye and readily measurable, some forms of deterioration are only measurable on a microscopic or analytical basis.

Despite the fact that these forms of deterioration are somewhat invisible, it is the responsibility or the designer to be aware of causes that might exist in the operating environment and it is the responsibility of the reliability engineer to introduce some form of prevention or timely replacement.

Deterioration Rate

While the presence or absence of deterioration is frequently easy to identify, the factors that determine the rate of deterioration is often more difficult to quantify. A good example is uniform corrosion. A simple approach at quantifying the rate of corrosion is one based on measuring the thickness of the material being corroded on a regular basis and then dividing the difference in metal thickness (metal loss) by the time between measurements. This is called the corrosion rate.

Once the corrosion rate has been determined, it is possible to identify the time at which the component will fail based on the thickness of the corrosion allowance. (Corrosion Allowance divided by Corrosion Rate equals Time to Failure).

But that assumes a constant Corrosion Rate both across time and across the entire surface being corroded. If a corroded surface is also exposed to some form of erosion and the corrosion products are regularly being carried away, the rate of deterioration will be much higher. If there are specific areas that tend to concentrate the corrosion, the uniform corrosion may not actually be uniform. In each of these situations, it is possible that localized deterioration is much higher than expected so failure can come much sooner than expected.

Since the objective is always to prevent failure, it is necessary not only to understand the form of deterioration but also the deterioration rate. Effective prevention is timely prevention. I like to use the saying: Once the cat is out of the bag, you need to think about how to deal with a mad cat and not a bag. In other words, once the Failure Mechanism has been present and deterioration has been occurring for an extended period of time, the solution no longer is based on a fully capable component. The solution and future forms of prevention must consider the deteriorated state of the asset.

While it is always preferable to introduce prevention before deterioration occurs, that is not always possible. When a new Failure Mechanism is discovered only after some period of deterioration, the available alternatives are more limited. For instance, it is not possible to paint a rusty pipe without first removing all the corrosion product and re-establishing a metal surface.

When Failure is Possible

The possibility of failure often exists long before the failure actually occurs. A good example of this involves a system of piping and pressure vessels that is experiencing corrosion. Assume that the operation of this system causes the internal pressure to fluctuate widely. While the pressure retaining capabilities of the system needs to be designed to withstand the maximum pressure, that pressure may occur very infrequently.

As a result, as the system corrodes and the wall thickness is reduced beyond the design thickness, the system is capable of retaining the current operating pressure but not the maximum pressure. This situation can go on for quite some time until either the operating pressure is increased above the capability of the corroded system or until the deterioration is discovered and corrected.

There are a variety of analogous situations in physical systems where the current reduced robustness is capable of current loading but not maximum loading.

- A component that has experienced some amount of fatigue may quickly fail when the load is moderately increased.
- Electric circuits that have frequently been stressed beyond normal operating limits may fail on the next occasion when the full service factor is needed.
- When a system has been deteriorated by one Failure Mechanism (say corrosion), it may fail very quickly when exposed to another Failure Mechanism (say overload).

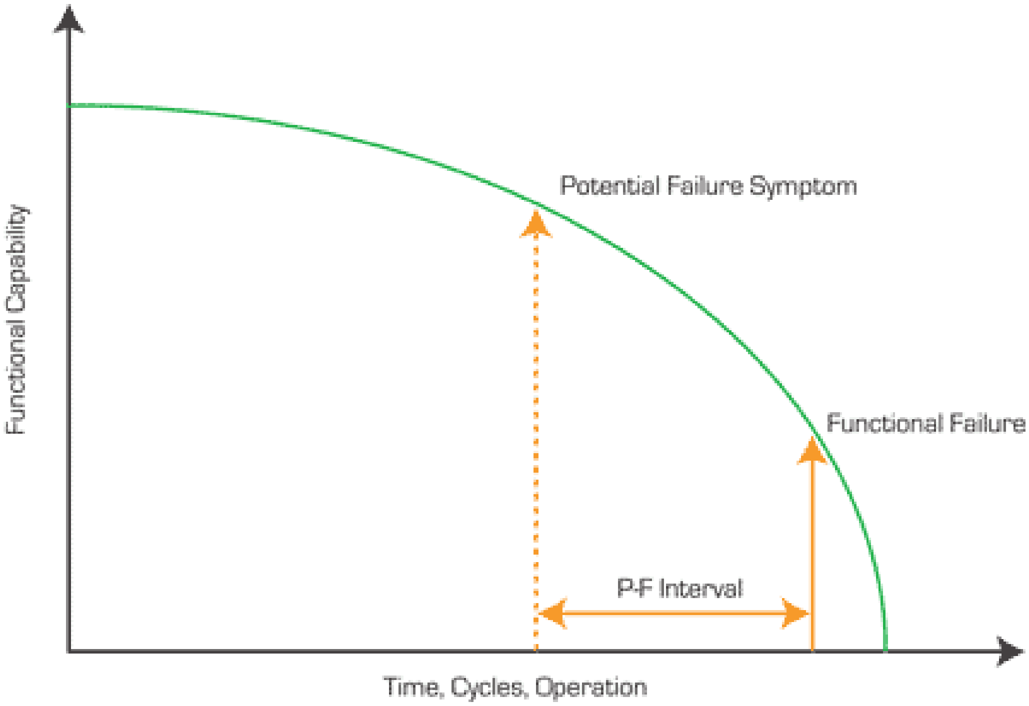
The point of this discussion is that the end point of deterioration might not be the time it reaches the design limits of a component. The normal operation of a component might be well less than the design limits and therefore might survive much longer. This difference creates an opportunity to avoid failure for those who maintain a high level of awareness and responsiveness.

P-F Interval

One of the models frequently used to characterize the path to failure is the P-F Interval. In this model, P stands for the potential for failure and F stands for the Failure itself.

The P-F Interval, as with many of the other concepts in the subject of reliability, includes some elements that can have a variety of definitions. As with those other hazy concepts, the most important thing is that you define how you choose to use the term and how the term will be applied in your analysis.

The graphic shown below provides a way to envision the P-F interval. It shows a decrease in the Functional Capacity of an asset as the number of cycle or age increases.



As suggested above, there are several possible interpretations for the time at which the "potential for failure" first appears. For instance:

1. There was some potential for failure when prevention was omitted and the system was left open for corrosion.
2. The potential for failure became more certain when the corrosion actually began.
3. The potential for failure or likelihood of failure increased dramatically when the thickness of the pressure retaining boundary was less than the thickness required for the maximum possible pressure.

A person making a case for adding money to a budget for a painting program might take the first position.

A person making a case for saving money by not performing a painting program might take the second position.

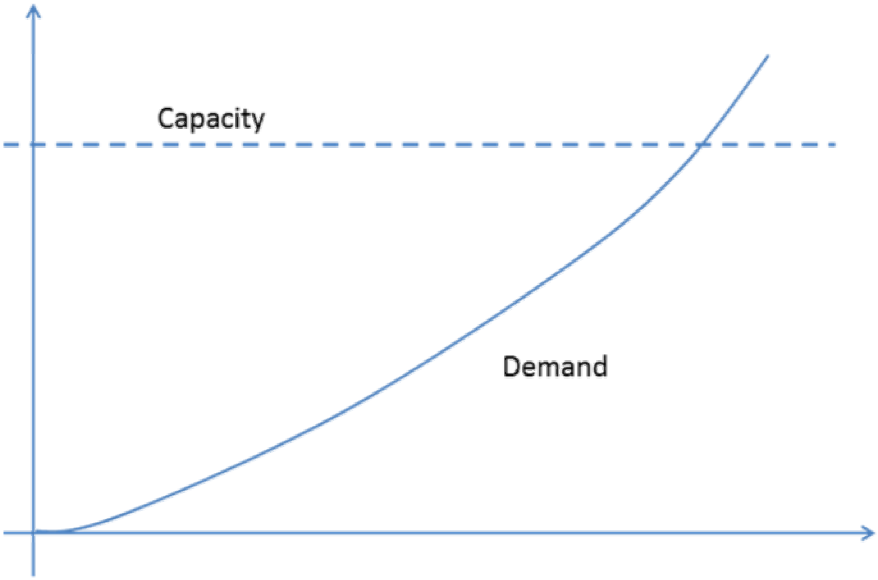
A person trying to justify having not performed a painting program and having allowed corrosion to occur might take the third position.

In this discussion as with many other situations, the exact time at which the potential for failure might begin to exist is more a question of organizational effectiveness that it is physics or engineering. If an organization can quickly find corrosion and respond, there is very little potential for failure independent of the amount of prevention.

On the other hand, most organizations are neither sensitive enough to find corrosion or responsive enough to correct the problem in a timely manner before deterioration leads to failure. In those cases, potential for failure equates to the point in time that prevention is omitted.

When Demand Crosses Capacity

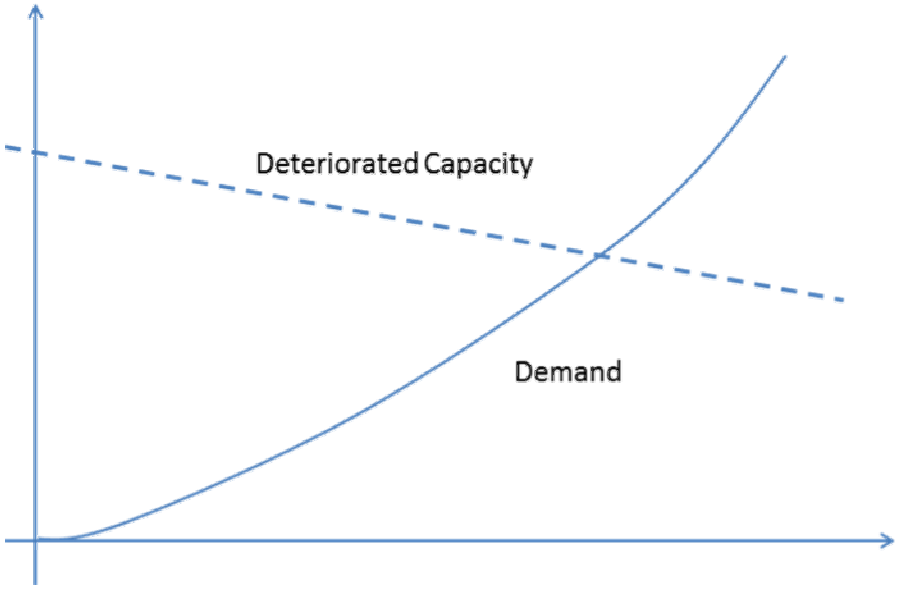
In business, when demand for your product passes the capacity of your capital assets, things are good. That is the point in time that all your investments are hard at work and you are achieving the envisioned return on investment.



In some ways, the reliability business is much the same. When a system is being operated in a way that takes advantage of all the capacity that was designed into the asset, the spending on robustness is justified. That situation shows that designers were not overly conservative in their design. Their design choices were good ones.

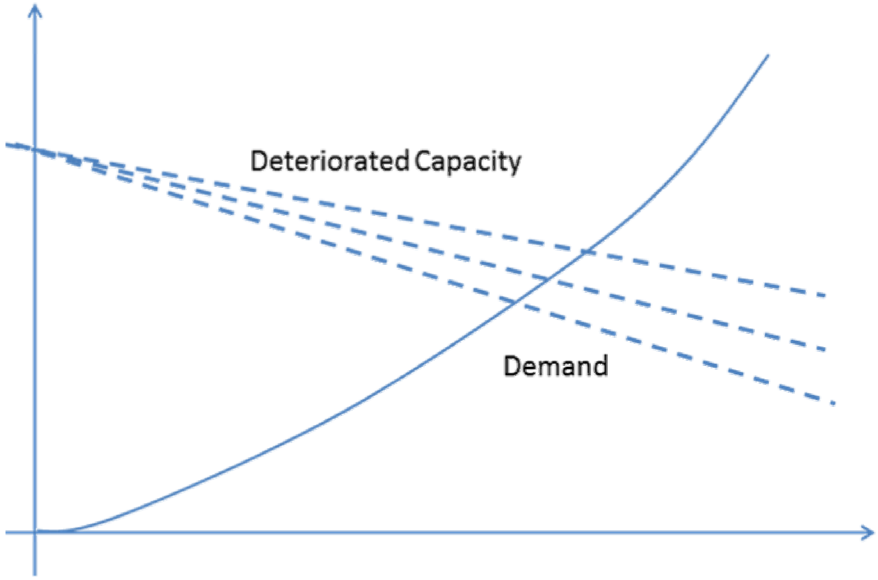
Unfortunately, when deterioration occurs, a system is no longer capable of coping with the same demand. Either the normal loading or the loading at peak conditions is greater than the capability of the system to withstand the loading.

The graphic provided above portrays a situation when the capacity has been maintained. The graphic below portrays a situation where deterioration has occurred and the capacity has declined over time.



In the second case, the deteriorated capabilities of the system are able to support only a much lower demand. This demand might be an operating pressure. It might be some other form of loading, like electrical current. In any situation, failure will occur at the point where the demand line crosses the system capacity line.

Unfortunately, the capacity of a deteriorated system does not function with the same level of clarity or accuracy as did the original system. In this situation, failure can occur over a range of demand loadings.



Since there are no exact tables showing the precise characteristics of a deteriorated material, only nature will determine the exact point at which failure will occur. Failure Mechanisms and the deterioration they produce are uncertain.

Luck versus Prevention

The points being made in the last few sections of this course are that:

1. Deterioration Rate is uncertain.
2. Lacking prevention, finding deterioration prior to failure is uncertain.
3. The point at which the potential for failure exists is uncertain.
4. The point at which the demand line will cross the line describing the deteriorated capacity is uncertain.
5. The only thing that is certain is using effective prevention to protect the original capabilities of a system right from the start and continuously thereafter.

With the amount of uncertainty that exists when one chooses not to protect the original engineered capabilities of a system, the only alternative to prevention is luck. When one chooses to ignore steps leading to certainty, he is choosing to rely on luck.

In fact, luck is actually an exercise in statistics. Each time a chance is taken, the individual exposes his assets to a statistical likelihood of failure. Like flipping a coin, while the statistical likelihood may not play out in the short-term, it will always play out in the long term. In other words, if an individual makes ten choices that result in a 1% likelihood of a catastrophic event, it is possible that no untoward event will immediately occur. If a company has ten individuals making similar choices, the chances are much higher that a catastrophic event will occur.

For those who are skeptical, an experiment might be useful. Flip a coin ten times and record the results. It is possible in such a small sample that the results may be uneven. There might even be instances where a significant string of either heads or tails occur sequentially. Now flip the coin 100 times and simply record the number of each result. The likelihood is that the final statistics will be close to 50/50. Now have ten of your friends each flip a coin ten times and add the results. Again, the likelihood is that the final statistics will be close to 50/50.

The point being made is that while it may be possible to avoid the impact of statistics for some period of time; in the long run, the statistical likelihood of failure will prove itself.

The decisions to take steps that prevent Failure Mechanisms from causing deterioration are choices that avoid such risk taking. The opposite is also true.

Linking Failure Mode to Failure Mechanism

The terminology you choose to use for describing your Failure Modes will, in a large way, determine your ability to prevent them from happening again in the future. This is an important fact to understand so I will say it in another way. If you are not very careful in describing the Failure Modes that disable your equipment, it is unlikely you will be able to eliminate the cause and prevent future failures.

This is an important issue to thoroughly understand, so we will discuss a few examples:

- Say, for instance, you choose to refer to a specific Failure Mode as an Electrical Ground or even more directly as a ground in a specific circuit or wire, your choice of terminology will determine your ability to respond to this specific failure. Further, if you are dealing with a large population of similar devices, your terminology will severely impact your ability to address the presence of a chronic issue by properly quantifying the number of times a specific Failure Mode has occurred.

  First, the ground only exists while the circuit is energized. Once power is removed to allow troubleshooting, the ground no longer exists.

  Second, there are a variety of ways a ground could exist. The grounded wire or portion of the electrical circuit could be severed and in contact with a grounding surface. In this case, a wire could have been cut or it could have corroded or it might have failed due to fatigue.

  It is also possible that the insulation protecting the electrical circuit might have deteriorated and allowed the circuit to have come in contact with a grounded surface. In this case, the insulator might have failed due to abrasion or exposure to UV damage or overheat or chemical attack.

  It is also possible that some unprotected part of the circuit like the area next to the connectors might have come in contact with a liquid electrolyte that is creating an electrical connection between that surface and a grounded surface.

  All of the various ways that failure occurred as described above would require a different form of prevention:

  - A severed wire may require some form of strain relief or protection from abrasion.
  - Damaged insulation may require the selection of a different kind of insulator or it may need some form of shielding.
  - Grounding due to the presence of a liquid electrolyte might require that seals on the electrical enclosure be maintained on a more regular basis.

Simply using the term, "Circuit – Grounded" (or words to that effect) will not help identify either an individual or a chronic problem. It is important to name the damaged component or sub-component and the specific condition best describing its failed state. By doing so, it is possible to identify the Failure Mechanism that produced the deterioration and then create an effective form of prevention. It is also possible to determine the number of instances of one form of failure as compared to all others. Using only the description "grounded" might lead to upgrading the insulation. This solution would be only 50% effective if half of the failures were the result of an un-insulated connector.

- As another example, let's discuss a leaking mechanical seal. As with the case above, the leak will only exist while the seal is exposed to the pressurized liquid. It may even leak only when the pump is rotating. In any case, when the pump is shutdown and de-pressured, the leak no longer exists.

  The leak may be the result of a number of causes:

  - The seal might contain a piece of debris holding the seal faces apart.
  - The seal might be worn-out.
  - The spring or springs holding the seal faces together might have weakened.
  - A secondary seal between the stationery portion of the seal and the stuffing box might have failed.
  - Distortion on the pump case caused by pipe strain or a soft foot might be mis-aligning the seal faces resulting in leakage.
  - The material used in the seal might be inappropriate for the substance being pumped resulting in corrosion.

Independent of the actual cause, it is necessary to know the condition of the failed component or subcomponent to create a link with the actual Failure Mechanism. The Failure Mode description should take the form "Component – Condition". Individuals who perform repairs need to be educated to create repair records that identify Failure Modes in those terms. If they are unable to discriminate, it might be necessary to create tables of choices from which they can select.

Once the Failure Mode is known, it is important to identify the specific Failure Mechanism that produced the deterioration leading to the failure. For mechanical components, the Failure Mechanisms are limited to the following choices:

1. Corrosion
2. Erosion
3. Fatigue

4. Overload

For electrical or electronic components, the list is somewhat longer. First, most electrical components have some mechanical characteristics so they can fail in the same ways that mechanical components fail. On top of the mechanical Failure mechanisms, there are a variety of Failure Mechanisms specific to electrical or electronic components. They include the following:

- Overload – Supply Transient
- Overload – Load Stall
- Electrical Equivalent of Fatigue
- Insulation Breakdown – Heat
- Insulation Breakdown – Chemical Attack
- Insulation Breakdown – UV Damage

Clearly, a component can deteriorate to the point of failure as the result of corrosion or erosion or overload. Similarly, fatigue can produce a crack that will expand to produce separation. Unfortunately, the solution to these different Failure Mechanisms is not a “one size fits all” situation. Each Failure Mechanism requires a different form of prevention.

Linking Failure Mechanism to Prevention

Your ability to select the appropriate form of prevention will depend on understanding which of the Failure Mechanisms are active. Further, it will require both an understanding of the working environment and an analysis of the Failure Mode to identify the Failure Mechanism.

For instance:

- The presence of moisture in some form in the environment and the presence of corrosion products at the site of the failure would lead to the conclusion that the Failure Mechanism is corrosion.
- The presence of vibration or significant movement of components during operation along with a relatively clean break and tell-tale benchmarks lead to the conclusion that the Failure Mechanism was fatigue.
- When measurement of the operating current shows occasions of loading greater than the allowable capacity of a component, along with overheated or charred components, points to electrical overload as the Failure Mechanism.

These few examples provide useful patterns for identifying:

1. The Failure Mode in the form Component – Condition

2. Investigation of the critical characteristics of the working environment

These examples are needed to understand the Failure Mechanism that is at work producing deterioration. Once the precise Failure Mechanism is known, it is then possible to identify the form of prevention required to slow or stop the Failure Mechanism, prevent deterioration and prevent failures.

For instance:

- In the first case above, efforts to avoid entry of moisture into an enclosure or protection of chemically active surfaces from contact with moisture will prevent corrosion.
- In the second case, installation of supports that prevent movement, proper balancing or alignment can eliminate the movement leading to fatigue.
- In the third case, installation of components rated for the highest expected current will prevent overload conditions.

Lacking the resources or ability to eliminate the presence of the Failure Mechanisms, another way to prevent failures is to allow deterioration to progress at a known rate but to intervene before failure can occur. In any of the three cases described above, it would be possible to conduct regular inspections and to replace deteriorated components when they are approaching the state they can no longer perform their intended purpose. The weaknesses with this approach are:

1. Replacement of deteriorated components is typically far more expensive than prevention.
2. Knowing exactly when to intervene is frequently more of an art than a science. If planned intervention is too late, the failure will occur.

A useful example of the value of maintaining the form of prevention rather than the actual asset is painting. When a painting program is ignored, several undesired effects occur:

- Appearance is degraded.
- The surface being protected is exposed to corrosion.
- As the surface continues to corrode, base metal is lost.
- When base metal is lost, the risk of a leak increases.
- A leak can result in an injury or a costly environmental event.
- The ultimate repair will require replacement of the deteriorated base metal.
- If the surface has been damaged, the surface integrity will need to be re-established by abrasive blasting and replacement of the primer.

While the painting example is the simplest and easiest to understand, most other systems have analogous secondary costs that are added when the basic form of prevention is not maintained.

Comprehensive Examples of Failure Modes and Failure Mechanisms

As an example of a situation in which a number of Failure Mechanisms are present, we will discuss a Boiler Feedwater Pump.

While this example is frequently viewed as a fairly simple pumping application, all of the four forms of mechanical Failure Mechanisms typically exist in the working environment for this kind of equipment.

Corrosion – In and of itself, water is not very corrosive. On the other hand, boiler feedwater for large continuous operations is typically treated using processes that involve both acid and caustic. If control of the treatment process is lost, it is possible for the feedwater to become corrosive.

Erosion – While boiler feedwater is seldom contaminated with debris that can directly cause corrosion, it is not unusual for BFW pumps to be damaged by erosion. A relatively common problem is that the Net Positive Suction Head (NPSH) is not kept above the minimum required. Boiler feedwater is typically very hot and when the suction pressure gets too low, cavitation will occur. When cavitation occurs, small bubbles will form in the pump suction. The small bubbles will have much the same effect as solid debris and will result in erosion of pump components in the flow path. If cavitation is not closely managed, the pump impeller can be damaged to the point that the pump is no longer able to produce the required discharge pressure.

Fatigue – Fatigue is one of the most common Failure Mechanisms affecting any form of rotating equipment. The speed of rotating components will result in a significant number of fatigue cycles being quickly accumulated, if there is any problem that places the rotating element under stress. Common situations that can place the rotating element under stress include:

- The pump shaft can be misaligned with the shaft from the driver.
- The coupling or some other rotating element can be improperly balanced.
- The inlet and outlet piping can be installed in a manner that places stress on those connections and transmits the stress to the pump case.
- The supports can be connected to the base or foundation in a way that either transmits stresses to the case or allows the case to move while in operation.

Any of the situations described above can create stresses in a pump that result in fatigue once the shaft begins to rotate.

Overload – Overload is most frequently identified in other components of the pumping system than the pump itself. It is possible that either the rating of the coupling or the power available from the driver is less than that required when the pump is operating at full load. In that case, either of those elements of the complete pumping system can deteriorate as a result of overload. A typical situation resulting in overload is when things change. For instance, if the viscosity of the fluid being handled or the discharge head is increased without appropriate changes being made to the pumping system, components will experience overload.

Obviously, each of the Failure Mechanisms described above can be avoided by taking the appropriate steps during design, operation, maintenance and through management of change.

Design – The selection of the pump characteristics, materials and associated components during the design must account for the requirements of the working environment. Just any pump will not adequately perform in a BFW pumping application. The capacity of the coupling and the driver needs have a large enough safety factor to ensure they are not overloaded during maximum operating conditions. The material of construction must take into account the range of normal operation of the treatment system. If there are other forms of protection against high or low pH, then vanilla metallurgy may be acceptable. Otherwise, the metallurgy must be capable of coping with operating extremes without deterioration.

Installation – The practices applied during installation of a pumping system will determine if several of the Failure mechanisms are allowed to exist. The following are installation practices that should be used:

- All rotating elements should be properly balanced.
- Pump and motor shafts should be properly aligned.
- Once the pumping system is installed and aligned, the piping should be checked for cold stress. (Does the piping spring away from the normal connections when disconnected?)
- Once the pumping system is installed and aligned, the supports should be checked for “soft foot”. (When loosened, do the support legs lift from the base?)

Appropriate installation practices need to be applied on initial application and each and every time the pump is maintained thereafter.

Operation – While the geometry of the liquid level in the suction drum is typically designed to adequately meet the needs of the pump's required NPSH, coping with this issue and preventing erosion resulting from cavitation is an operating issue. If an operator is not sensitive to maintaining the proper operating level and does not detect the sounds of cavitation, it is likely that the BFW system will spend some time operating with cavitation. While this may not occur all the time, ultimately deterioration will mount and result in inadequate operation.

Another issue (that is an issue of operator diligence) is the adequacy of BFW treatment. Even a properly designed system can have a wide range of operation and the resulting BFW pH can vary accordingly. To minimize variation and resulting corrosion, operators need to be vigilant.

Maintenance – As with any hot rotating equipment, the importance of lubrication cannot be over-emphasized. The level and condition of lubricants must be closely monitored and maintained.

When repairs or overhauls are completed, the original conditions must be restored. Maintainers must be sensitive to the required tolerance, fits and clearances to ensure they are properly restored. They must also ensure that replacement parts retain the same quality and dimensional characteristics as the original parts.

Management of Change - If operating conditions change, consideration must be given to the effects those changes might have on the current capabilities of the system. It is not unusual for changes that increase capacity to overload the capabilities of a system. While the system may be able to cope with changes on an instantaneous basis, the increased loading may result in increased deterioration and more frequent failures.

Lists of Failure Modes and Associated Failure Mechanisms

While it is beyond the scope of this course to provide a comprehensive list of Failure Modes and Failure Mechanisms, it will be useful to provide a few examples of the Failure Modes and Failure Mechanisms commonly experienced.

It is important to note that the Failure Mode descriptions have been chosen such that they can be easily sorted and processed by a computer database. Also, the descriptions of Failure Modes and Failure Mechanisms have been selected so they are closely linked and the appropriate form of prevention can be easily identified.

Failure Mode / Failure Mechanism Table		
Typical Component	Failure Mode	Failure Mechanism
Diaphram Pressure Sensor	Pressure Sensor - Annulus Plugged	Corrosion (Annulus filled with corrosion product)
Diaphram Pressure Sensor	Pressure Sensor - Diaphram Cracked	Fatigue (Operated longer than allowed fatigue cycles)
Diaphram Pressure Sensor	Pressure Sensor - No Signal	Erosion (Signal wire rubbing on hole through bulkhead)
Wire	Wire - Severed	Erosion (Power Supply wire rubbing on hole through bulkhead)
Wire	Wire - Severed	Corrosion (Power Supply wire exposed to water from leakage)
Temperature Sensor	Temperature Sensor - No Signal	Erosion (Signal wire rubbing on hole through bulkhead)
Temperature Sensor	Temperature Sensor - No Signal	Corrosion (Signal wire exposed to water from leakage)
Anti-Friction bearing	Shaft Bearing - Overheated	Overload (Loading on system greater than design)
Anti-Friction bearing	Shaft bearing - Worn	Erosion (Excessive debris in lubricant due to delayed renewal)
Oil	Oil - Low TBN	Overload (Oil used beyond its life)
Oil	Oil - High Metals	Overload (Bearing loading resulted in oil contamination with bearing metals)
Grease	Grease - Washed Away	Overload (Improper grease used for outdoor application)
Grease	Grease - Overheated	Overload (improper grease used for high temperature application)
Pump Impeller	Impeller - Deteriorated	Erosion (Uncontrolled cavitation)
Pump Impeller	Impeller - Deteriorated	Corrosion (Uncontrolled pH in product stream)

Conclusion

It is not unusual for people to make the subject of prevention more complicated than it has to be. As a result, it is not unusual for people to harbor beliefs that reliable assets have to be expensive and they have to be unusually complex. In fact, the opposite is true:

- Simplicity enhances reliability.
- Reliability leads to the lowest life-cycle cost.

Prevention is not “gold plating”. Prevention depends on understanding the Failure Mechanism that is at work. Determining the Failure Mechanism depends on understanding the Failure Mode that resulted in the specific failure being studied.

In many cases, relatively minor forms of prevention can eliminate deterioration and reduce failures. Selecting the proper materials, proper assembly, proper lubrication, coating systems and proper maintenance are simple forms of prevention.

While choosing to ignore prevention may not have the same flavor of other forms of risk taking like big business deals, the negative impact on a business can be much the same as buying an under-performing business. Investing in expensive assets then ignoring prevention is simply a form of unmanaged risk-taking.