Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 03
Surface Degradation: A Commercial Perspective

Hello and welcome to lecture 2A. This lecture is an extension of lecture 2. Before starting to explore deeper into surface engineering, corrosion, and associated degradation, it is beneficial to consider the commercial perspective. To elaborate, when we refer to the commercial perspective, several questions arise, mean deviation of actual surface from ideal surface. Generally, an ideal surface is smoother surface with rounded edges and smoother transition to minimize crack initiation, and features that are less susceptible to corrosion. So, we want something like an ideal surface.

It follows that if the surface is not ideal, it will undergo surface degradation to some extent. The next question that arises is whether there will be any noticeable changes in the product's performance. From this perspective, friction and wear carry severe economic implications, leading to substantial expenditures on replacement, maintenance, and productivity. Furthermore, when we consider condition monitoring, there is a requirement for a monitoring system and qualified workers with expertise in this area, which can incur significant costs.

So, if we at the beginning itself, we take all the informed decisions from the outset regarding viability of surface treatment is cost economic or not, then it will be always better. As per my knowledge, many industries like automotive, aerospace, electronics, and manufacturing, surface degradation plays a very important role to uphold the product quality requirement. Addressing surface degradation is vital for enhancing productivity, improving quality, and ensuring safety.

While some may argue against pursuing a perfect or ideal surface, there are instances where creating surface irregularities can improve the performance, but we will discuss those point in a separate lecture when we discuss about the design of the surfaces in future lectures.
For the time being, it is important to acknowledge that surface degradation is undesirable and deviation from the ideal surface prompt considerations of economic implications and penalties associated with such surface degradation.

So, to start this discussion, I have used the term "analysis of surface degradation" on the slide. A question arises: how do we analyze surface degradation? While we are familiar with failure analysis, in this context, we are just concentrating only on surface degradation. Once again, the primary causes of the surface degradation come into question: Is it due to design flaws? Is it due to materials or manufacturing processes? Hence understanding the main challenges and maintenance strategies are crucial, as every system will degrade over time.

So, what kind of maintenance and how are we trying to maintain those systems will be important. Will there be any environmental issues? Sometime, temperature and humidity increases, leading to corrosion environment, or pollution rises. Could these factors be major contributors to surface degradation? So, we need to examine whether the faults lie in the design, material, manufacturing, maintenance, or environmental factors, including changes in the environment. So, how do we identify the causes of surface degradation? We have several methods. Visual examination is an easier one, but it cannot detect faults smaller than $50\mu m$. So we will not be able to see the initiation of the fault.

For this purpose, we may need to employ destructive and non-destructive testing. We can go ahead with the number of experiments in the laboratory, gathering necessary data, processing those data, and doing interpretation of those data. Understanding the causes and analyzing them are very important. For that purpose, we require a logical systematic approach to find out causes of surface degradation. Once we understand the causes, we must take necessary steps to reduce the chances of degradation in the future.

This is important because often, when we develop a new process or product, we may not have complete knowledge initially. So, the system may fail, necessitating a closed feedback system to understand the failure reasons and continuously rectify them. So, product launch may require a number of experiments within the lab to analyze thoroughly before it is foolproof. This is the way many industries are working, and it emphasizes the need for a logical and systematic approach.

We should have a logical and systematic approach to understand each and everything about the surface issues and mitigate those issues, considering their cost effectiveness. Regarding a systematic approach, referring to the ASM handbook volume 11, they provide a systematic diagram called fishbone diagram. This diagram helps to evaluate the cost effectiveness. It helps analyzing operations, checking for overload or installation errors.

Look at the design aspect. Design aspect includes the material selection and kind of the shape configurations. Sometimes we assess the skills and knowledge of personnel involved. Decision on the maintenance strategies – whether regular maintenance, periodic maintenance or some sort of sensor-based maintenance is very important. Loose connections, particularly in nut and bolt connections, often lead to maintenance issues, emphasizing the importance of addressing such issues promptly.

So, we need to have a sort of strategy and write up for the operating person, indicating what we need to follow. Wherever we do not have this kind of document/knowledge, most of the failure happens most of the failure happens because of that. So, that is important. Again, I would say design is one aspect of manufacturing. I can do very good design, but if I am not able to manufacture well, I am not able to quantify those manufacturing defects, then there will be problem. So, that is why I say, what are the defects and sometimes the defect will occur again, like in a heat treatment process. So, these are the major items or whatever processes we are opting for. It may be a new process, but if we do not have a complete understanding, if the operator does not have a complete understanding, the failure will be there. If you club this with the arrows, then we will come up with some sort of failure mode. So, this is what a fishbone diagram is.

So, what I will say is the fishbone diagram, sometimes called a cause-and-effect diagram, sometimes an Ishikawa diagram, is basically a visual tool we use to identify and analyze the various source of problems and issues. It is a kind of brainstorming method we use to start thinking about the possibilities in a liberal way. So, I can say it is a kind of brainstorming method to find plausible reasons and factors contributing to the problem. Now, why the fishbone? The name comes from the fact that this diagram is shaped like a fish skeleton, with the problem and effect represented at the fish head, and various causes are the fishbones that branch from a main backbone. Each branch is related to certain category, such as manpower, method, machine, material, measurement and mother nature category. Sometimes people say it is a 6 M diagram. Manpower is number one, and then method, machine, material, measurement, and mother nature category. That is why we sometimes call it a 6 M diagram. Now, when we talk about manpower, what we intend to say is the main point resources, including factors like skills, training, and knowledge. Do we have all of this? Can a person operate effectively? Do we have some sort of automation system, or are some people well trained in those areas? Do we have sufficient knowledge to rectify whatever problems come up, whether it is at a micro level or even a very small level?

Now, when we say the process and procedure used to be followed in a system can be referred as a method, that is the second aspect after manpower. We say process equipment, like tools and technologies which we are using, can be named as a machine. Materials are raw material commodities or resources that have been utilized for the complete machine or system or subsystem, or the components can be named as a material. We also require quantification. That is why we use the word measurement of matrix, and we also sometimes add statistics. Because when we come to industry, statistics play a very important role. When we scale up the number of systems, naturally, statistics play a very important role because even a 1% failure can cause a major failure, maybe defaming the complete company. So, that is why we require statistics also to judge performance and quality. And as we say, we are in the environment, so, mother nature, environment may say whatever the external elements, such as humidity, temperature, whether there will be rain, or some sort of pollution, will be playing an important role. So, once we have all this knowledge, we can make a fishbone diagram and then we can start analyzing, we can brainstorm.

So, come to some conclusion based on that. Now, I will just take one example, like a mechanical failure. I say final failure is a mechanical failure. So, in the fishbone, the head is a mechanical failure. Then what we are mentioning in that is when a system, process, or component fails to perform as expected. Now, again many times people feel failure means breakage. One piece should be divided into 5 pieces, 10 pieces, or 15 pieces, but it is not that way. We say if the component is not able to perform as expected what it was supposed to do, like if I want some efficiency of 98%., and my system is giving 95% efficiency, for me, the system has failed, right?

So, this is what my laptop is not able to perform like i9 or i7, it is working like i5 or i3, the system is failed. So the failure is different, but the whatever intended function, whatever we were expecting from a components, subsystem, or system, it is not performing that, that means there is a failure. So, that is what we are saying, that is a system has failed. Now, because we are discussing mechanical failure, I say the mechanical failure might take the form of a structural collapse. So, there may be breaking, or there may be bending, or something like that. Another one I say, the non-functional machinery. Machines are not operating. And lastly, a very minor one, we say the one part, or parts maybe the whole machine is there working condition, but with a few parts are not performing well. So, that will also turn out to be like mechanical failure.

So, what we really need is to identify the root cause of the failure. It's crucial to pinpoint the exact reason for the failure, whether it's due to various faults within the system or other factors. We aim to detect the initiation of the failure itself to prevent significant losses for the company. Therefore, we must be vigilant in identifying potential faults such as cracks, fatigue, creep, or corrosion. It's important to note that while we often refer to a failure as stemming from a single cause, it may result from multiple factors occurring simultaneously or in tandem. This underscores the need to thoroughly examine mechanical failures. While a comprehensive fracture analysis and fractography will be discussed later, a simple yet effective method is to inspect wear debris. Mechanical systems typically produce debris that can provide valuable insights into the root cause of a failure. Wear debris can manifest as chips, flakes, particles, or even nano-sized dust particles. Although not always visible to the naked eye, specialized setups can analyze and diagnose these debris, enabling us to identify and address potential failures early on. Ultimately, ensuring the dependability of a system and its processes hinges on identifying failure modes, particularly by detecting initial signs such as cracks, fatigue, or corrosion.

And we can immediately find out the reasons, and then we give some sort of effect, also maybe say essential why it is happening and how do we correct it and then mitigate it will be important. So, fishpond diagram sometimes is very important however, there are a number of other methods also available which can be utilized to mitigate the failures on the to brainstorm the various causes of the failure and then identify the failure. So, various techniques are available we will be detailing those things in later lectures. It is essential for us to understand, to have complete knowledge. For that purpose, this kind of course is very, very important and we need to rigorously do all those things to save the cost or to make it overall economic. So, whether it's economical or not, or whatever suggestion I am going to make, we need to decide on that. So, I will attempt to provide you with sufficient knowledge.

So, that you can make a decision, and sometimes a situation may be favorable, while in another situation it may not be favorable. With knowledge, we can make these important decisions. Now, let's consider a couple of examples. I'll start with an example from my lab. We have a test gear setup where there's a dynamometer to load the gearbox motor driving the gearbox, along with a small gearbox containing a single-stage spur gear. The details of the spur gears are provided; we have a pinion with 27 teeth and a gear with 53 teeth, both with a pressure angle of 20 degrees. We've maintained the hardness at 30 plus or minus 2. Although we could use 60 hardness to reduce wear, we've chosen 30±2 to observe wear under load. The applied torque is 40 Newton meters, and we've operated this setup for 198 hours to monitor its performance. This setup demonstrates typical gear operation. We conduct regular maintenance, which involves collecting oil samples. These samples are collected after intervals of 10, 20, or 30 hours, depending on our analysis strategy.

Now, when we collect the oil sample and filter it, we obtain wear debris that needs analysis. You can observe particles of various sizes, such as this $10\mu m$ particle and another with plate formation and edges, indicating smaller particle sizes. Additionally, there's a larger flag-sized particle. We can use a scanning electron microscope (SEM) to examine these particles in detail. I'm also able to show the surface, which interestingly reveals debris like what's found in the oil sample. It's important to note that not all debris comes off the surface immediately during analysis; some may remain due to adhesion, abrasion, or embedment, or may still be in the process of wearing out or sustaining damage.

So, you can see here that surface degradation is linked to the presence of debris, which we can magnify and observe on the surface. This underscores the significance of wear analysis through oil samples. We can classify the wear as cutting wear if we observe long fibers or particles with a significant difference in dimensions, such as d_1 and d_2, with a large ratio of $\frac{d_2}{d_1}$.

Next, sliding wear is indicated by the presence of spherical particles, typically associated with fatigue or rolling motion. This method allows us to assess whether the surface is degrading. If we prefer not to open the surface or examine the gear itself directly, we can continue collecting oil samples to detect debris, such as debris 1, debris 2, and debris 3. Depending on the concentration of debris, we can determine which type of failure is likely to dominate and become the primary cause of failure. In other words, the process involves collecting wear debris and performing image analysis to understand the relationship between the particles removed from the surface and the wear surface itself, and how this impacts gearbox performance.

Maybe in a short span, when wear begins, it may not be immediately visible or noticeable by other methods. However, through debris analysis, we can uncover these issues and take immediate action. Another important aspect is investigating surface degradation in gears, which requires defining the complete tribological system. This system includes gears, bearings, and seals. Determining the appropriate oil sampling frequency, whether every 24 hours, 10 hours, or 5 hours, depends on the concentration of wear debris. Once we collect wear debris and remove oil, we can analyze it using microscopy, spectroscopy, or laminar analysis to identify the types of particles and potential failures and remedies. These aspects are interconnected. For instance, the presence of spherical or irregularly shaped particles larger than 10μm can be alarming, indicating significant wear. However, particles smaller than 10μm may not have as significant an impact. This understanding contributes to improving performance and longevity, potentially aligning with the bathtub curve concept studied in previous lectures.

So, this is what we need to consider. However, if the particle size exceeds 10 μm, which is quite significant, or goes beyond 100 μm, indicating larger particles, immediate action is necessary. The range from 10 μm to 100 μm depends on the number of particles present. If there are only a few particles, it may take longer for surface degradation to become noticeable, and occasional particles may not cause significant damage right away. Surface damage tends to occur intermittently rather than from a single particle.

Now, let's examine another example. In a study from 2006, researchers designed a small setup, as depicted here. It includes a gearbox, like the one discussed in a previous slide, and outlines how to collect samples. In this case, they developed an experimental setup to test medium carbon steel, although different types of steel could be used. Specifically, they focused on medium carbon steels, which are essential for centrifugal applications.

Now, the circle diameter for the input gear is around 40 mm, with a module of 20° pressure angle, as we discussed in the previous slide. They maintained the 20° pressure angle, which is more common compared to 14.5° and 22.5°, while the pitch circle diameter (PCD) of the output gear is 30 mm. Naturally, we can determine the gear ratio to be 4 to 3, indicating that the input is 4 and the output is 3. Looking at it from the output point of view, the face width of both gears is maintained at around 8 mm, ensuring that the transmission loads are not problematic. They also ensured a slight difference in hardness between the driving gear, with a higher hardness of 179 on the B scale, compared to the driven gear, which is 170. This minor variation in hardness will not have a significant impact. Additionally, they used different types of oils in this setup. They collected data under various operating conditions, including normal, overload, and cyclic load conditions. This involved changing the operating conditions by continuously increasing the load and frequency. The operating duration varied accordingly, with emphasis on the continuously increasing load mentioned here. Furthermore, they gradually increased the speed during testing.

So, the increase in speed is also significant because we're aiming to accelerate the wear rate to understand what's truly happening in this scenario. This step has been completed. When collecting oil samples, it's mentioned that they filter it using the filter gram method to collect the debris on microscopic slides. They discovered a very high concentration of air debris, indicating that during the acceleration of load and speed conditions, many particles or a high concentration of air particles were present. Upon observation under a microscope (not an SEM), they noted the presence of larger particles, as depicted by the big particle here and another one here, alongside smaller particles.

So, there are large particles present, as well as small particles. Now, what can be concluded from this figure? They could infer that although there are big particles, there are also small ones. However, from the figure, they could conclude that there is a lack of many fatigue particles; only a few particles exhibit fatigue features. Therefore, based on this, they concluded that there is no fatigue failure, even though they subjected the material to cyclic loading. It's not dominant in this case. It's worth noting that the test lasted only 70 hours, unlike the previous case I presented, which lasted 198 hours. Additionally, they observed a significant number of particles indicating severe sliding speed. However, they found only a few particles larger than 100 μm.

When the particles are fewer than 100 μm, it indicates surface degradation, particularly in the earlier stages. Through proactive measures in these initial stages, we can effectively minimize surface degradation. However, they conducted all this testing under overload conditions and higher speeds. Ultimately, they found that the initial surface, as shown in the photograph, exhibited significant sliding on the gear teeth. Pitting on the gear teeth was also visible. Despite the absence of fatigue failure, pitting mostly occurs due to fatigue failure. This suggests that sliding wear on the surface is causing more issues than the overall effectiveness of the gear tooth in sustaining the load continuously. Therefore, the root cause in this case is determined to be sliding wear rather than pitting wear. While both phenomena are observed, sliding wear is deemed to dominate over pitting wear in this case.

Let's explore a third example, aiming to provide a comprehensive understanding of surface degradation identification. By exploring more examples, we can offer insights into diagnosing issues and potentially developing new methods for surface degradation testing. In this case, the experiment was drawn from a reference published in 2007. They employed a stationary disc with a rotating ball. The ball, made of 5200 steel with a high hardness of 50 HRC, had a diameter of 8 mm. Conversely, the disc was composed of relatively softer 4340 steel, a medium carbon steel, with a hardness about one third that of the ball's diameter. Both the ball and the disc had a thickness of 8 mm.

Observations included surface roughness, which is crucial as it reflects deviations from the ideal surface. If surface roughness consistently increases, it suggests underlying issues. Furthermore, additional terminologies are introduced in this slide. The experiments were conducted at a temperature of 20°C and a relative humidity of 30 to 40%, ensuring conditions were not excessively humid to avoid corrosion issues. Two types of oil, SAE 40 and N 32, were used in the experiments, with no significant density difference between them.

However, the viscosity difference is significant; SAE 40 is thick oil while N32 is thin. At 100°C, the viscosity of N32 is nearly one third of that of SAE 40. Interestingly, N32 is more stable; its deterioration is less pronounced compared to SAE 40 with increasing temperature. Although flash point is mentioned, it's not relevant for our operating temperature of 20°C, but it's included for completeness. Pour point or flow point is also noted.

Moving on to the actual experiments, they focused on the contact area, specifically the track shown here, which was soaked in lubricant. Two different lubricants, SAE 40 and N32, were used, with each experiment conducted twice to ensure statistical reliability. Conducting multiple experiments is crucial to ensure consistent results. Some researchers even conduct experiments up to five times to ensure statistical significance.

They conducted Test 1 and Test 2, with Test 1 using lubricant one and Test 2 using lubricant two. They found that due to the higher viscosity of SAE40, severe wear occurred after long operation of 168 hours, while with the thinner N32 oil, severe wear occurred just after 72 hours.

Interestingly, instead of focusing solely on gear pairs or teeth as in previous cases, they performed wear debris particle analysis. They collected around 20 particles in each case and analyzed their average surface roughness, skewness, and kurtosis values. So, here they are not judging the surface they are judging the particles which have come out of the surface may be say and then the surface has been damaged and the particle have come out of that. So, that is what they were trying to analyze and then what they found in test one and two S_a value is more or less same while S_{sk} skewness value in this case in test one was on the severe side one on the positive side, 0.27 while in test two it is a very low but slightly negative. However, the S_{ku} kurtosis value also in this case is relatively less equal to 2.53 for test 1 and 2.34 for test 2.

Let me explain in a slightly different manner. We're discussing three statistical parameters: average roughness, skewness, and kurtosis. These parameters are derived from multiple measurements and analyzed statistically. Some researchers suggest that skewness and kurtosis values alone can indicate whether a machine is likely to fail. That's why we emphasize these two parameters—they're related to surface characteristics and are important statistical indicators.

Now, in this case, we can determine the skewness and kurtosis for almost all machines, including gearboxes. This allows us to assess the gearbox's condition under both normal and abnormal operating conditions, enabling trend analysis to yield results. Let's delve into kurtosis: it describes how smooth or jagged the surface is. A low value indicates normal, smooth operation, while an increase suggests potential issues with rotating parts or malfunctioning. In simpler terms, a higher kurtosis value indicates more surface peaks, signaling increasing surface roughness and potential degradation. This method provides a straightforward means of identifying surface degradation and assessing machinery health.

So, kurtosis plays a very important role from that perspective. Now, let's discuss the second term, skewness. Skewness indicates how much the data points deviate from the mean value. Positive skewness is often associated with positive connotations in other contexts, but in statistics, it signifies an uneven distribution with a tail pointing towards higher values. A positive skewness value suggests potential defects in the machine. Therefore, in this case, a positive skewness is undesirable. Ideally, the skewness value should either be 0 or negative to indicate a more balanced distribution and normal machine operation.

Now, that's why we displayed the previous slide in this lecture, showcasing how skewness increases towards the positive side, indicating a higher possibility of issues. Here's an interesting point: if someone were to say, "Skewness is sufficient; I'll only measure skewness," it's important to note that in a normal Gaussian distribution, skewness is 0, aligning with the mean value. However, the kurtosis value is 3. A kurtosis value of 3 or less may not pose significant issues, but exceeding this threshold could indicate a problem. That's why we emphasize the need for both parameters for a comprehensive analysis, and we may also incorporate additional parameters to enhance judgment and results.

One advantage of these statistical parameters and measurements is their compatibility with recent advancements in machine learning algorithms and artificial intelligence. By leveraging machine learning algorithms, we can conclude from surface features alone, measuring skewness, kurtosis, root mean square value, or average roughness, whether surface degradation is occurring. This integration is advantageous as it offers a cost-effective and efficient means of assessing surface conditions. By understanding the kurtosis and skewness values, we can determine whether surface degradation is progressing or if refinement is underway. Both values are crucial, and I also mentioned the significance of the root mean square value, particularly in assessing roughness, which often varies depending on the coating manufacturer.

So, it's crucial to connect average roughness with RMS, kurtosis, and skewness, as they hold significant importance. I've discussed various aspects of surface roughness, skewness, and kurtosis, referencing profiles extracted from my book published in 2016, "Fundamentals of Engineering Tribology with Applications." Figures 8.9 and 8.10 are directly from the book, maintaining their original figure numbers.

In Figures (a) to (d), positive skewness indicates a deviation we should avoid, while negative skewness may necessitate additional lubrication or surface design modifications. Ideally, surfaces should exhibit a skewness value of 0, indicating symmetry around the mean. Regarding kurtosis, most surfaces should have values lower than 3, as shown in the previous slides. Values exceeding 3 suggest surface issues that warrant attention and appropriate measures.

Understanding these surface features is crucial for product assessment and mitigation strategies. Implementing a feedback loop system ensures simultaneous evaluation of surface degradation and product performance. This entails continuous monitoring of system components to detect any signs of degradation. If degradation is detected, safety and economic considerations come into play, guiding decision-making processes. Conversely, if no degradation is observed, focus remains on functionality without the need for extensive economic or safety assessments.

If there's no failure, we proceed with the feedback loop. For instance, if we determine the design is flawless but encounter material issues or symbols suggesting a problem, we initiate feedback to the system, manufacturing, or installation stages. Each stage can incorporate a feedback system; it's not solely limited to design. This approach isn't exclusive to complete product development; it's integral during the product development phase. Internally, we conduct performance tests and continually refine the product. This iterative process ensures that before product launch, we achieve perfection in design, material selection, manufacturing, installation, and all related service parameters. Any minor faults detected prompt us to revisit the relevant disciplines or keywords for modifications.

So, that's why we emphasize the importance of leveraging insights from surface degradation analysis. Continuous monitoring allows us to detect surface degradation, which may not initially cause complete failure but can still impact functionality. For instance, if our target performance is 95% to 100%, achieving 97% may prompt us to seek ways to improve further, aiming for 99%. This necessitates revisiting the feedback loop to identify necessary corrections and enhancements in product design, manufacturing, installation, or services.

By integrating insights from surface degradation analysis into the feedback loop, we ensure ongoing adjustments and improvements to the product. This iterative process drives product evolution based on our analysis findings, underscoring the significance of surface degradation analysis. Once we've completed these adjustments, testing becomes imperative. Even if initial tests were conducted, ongoing testing is vital to validate product performance and identify any emerging failures or faults. Continuous testing and validation are essential to ensure product reliability and effectiveness.

Then, whatever corrections we make, whether it's changing materials, shapes, or sizes, we must ensure thorough testing to confirm performance. For instance, fine-tuning manufacturing processes, such as shifting from a 180-degrees to a 200-degrees operation, requires careful evaluation of the potential impact. It's essential to ensure that proposed design and process improvements effectively address all identified faults and flaws within the system. If they don't, further analysis is necessary; if they do, it's a positive outcome.

This underscores the need for a culture of continuous improvement, as depicted in the diagram. As we progress through the course, we should keep this principle in mind, continually seeking ways to enhance product functionality and approach system development systematically.

Additionally, many times, despite conducting extensive in-house testing, it's impossible to simulate every potential fault or scenario. Therefore, some companies offer warranty periods, acknowledging that they've achieved a certain level of accuracy but are committed to ongoing improvement. By providing warranties, they accept that a small percentage of products may experience issues initially, but they use this feedback to improve their processes and products. This approach not only facilitates continuous improvement but also increases customer satisfaction, as consumers appreciate the company's responsiveness and commitment to quality.

So, I bought an AC, but it's not functioning properly. I contacted the company, reported the issue with my AC, and they found that it's faulty. They then use this feedback to improve their processes, addressing any design or material faults discovered. This feedback loop is particularly beneficial for startups.

Now, let's discuss the final phase of this lecture: the economic analysis of controlling surface degradation. While we aim to control surface degradation, we must consider if it's advisable and if it will yield desired results. Continuously improving or minimizing surface degradation is essential, but we must make informed decisions regarding mitigation measures.

Deciding to allocate funds for surface degradation mitigation requires a logical approach, as depicted in this slide. Protective measures incur costs, and we need to assess the value of these measures in terms of cost savings and overall benefits. If the cost savings from reduced material degradation outweigh the cost of protective measures, it's a positive outcome. However, if the difference is negative, it may not be prudent to proceed with the mitigation measures.

This simple rule of thumb guides decision-making, although the full impact of protective measures may not be immediately apparent. It may take months or even years to fully evaluate the effectiveness of these measures.

So, I should calculate all these values in present value terms. This means accounting for the cost after 10 years and considering factors like interest rates or potential returns. Instead of using the first equation (Equation 1), I will opt for Equation 2. In Equation 2, I will determine the present value of the protective measure, which includes the present value of cost savings and the present value of the protective measures themselves. Whether it's annual measurements or maintenance, I need to consider these factors when making decisions today.

So, this value represents the cost and the amount of savings, and we use the term "annuity" in this context. But what exactly is an annuity? An annuity is a function of the number of years and the expected return rate per year, such as 10% or 20%. As the rate of return increases, the annuity decreases, which in turn affects the savings. If the multiplication factor is lower, the cost may exceed the savings, resulting in a negative value, indicating an unprofitable situation where measures to control material or surface degradation may not be feasible.

Now, let's discuss the question of the rate of return. In some cases, the assumed rate of return may be 0.05, 0.1, or 0.15. The resulting annuity varies accordingly, with higher rates leading to higher annuities. However, if the rate of return is very high, it may not be advisable to implement measures to prevent surface degradation, as it could be unprofitable. Conversely, if the rate of return is low, implementing such measures becomes more viable.

For new businesses, especially those with inherent risks, the pursuit of fast returns is often a priority. To mitigate this, governments often provide support to high-risk projects, including startups. These initiatives aim to encourage innovation by providing financial assistance and resources to new ventures. Incubation centers and similar institutions also play a crucial role in supporting startups by offering resources and guidance, facilitating the development of new technologies and processes without undue financial strain on the entrepreneurs.

Now, the question arises: what exactly do we mean by "saving"? Saving, in this context, is a probabilistic measure. We can't determine an exact value; instead, we express savings as probabilities. These probabilities represent the likelihood of failure in two scenarios: one where no preventive measures are taken, and another where preventive measures are implemented against surface degradation.

In my slide, I emphasize the probabilistic nature of this analysis. We discuss savings in terms of probabilities because it's not based on precise or deterministic numbers. We distinguish between the probability of failure without preventive measures and the probability of failure with protective measures, each associated with its respective costs. The cost of failure, in this case, refers to the expenses incurred upon failure.

To illustrate, let's consider an example where the cost of each failure is $10,000, and the likelihood of failure without protection is 0.3, while with protection, it drops to 0.1. The difference in probabilities multiplied by the cost yields the savings. In this case, it would be (0.3 - 0.1) * $100,000, resulting in savings of $20,000.

We assume that these probabilities are not time-dependent for simplicity in our analysis. This probabilistic approach allows us to better understand the potential savings associated with preventive measures against surface degradation.

Calculating the rate of material degradation is no simple task, primarily due to the limited information available regarding surface degradation types. Unless significant research has been conducted on a specific product, gathering relevant data remains a challenge. This underscores the critical importance of employing a feedback loop. Continuously collecting data allows us to develop mathematical or probabilistic models for better assessment.

Moreover, investments affected by material degradation may see diminishing returns as the required rate of return increases. As illustrated in the previous slide, an escalating rate (denoted as 'r') may lead to the decision of forgoing degradation mitigation, resulting in component failures—an outcome companies seek to avoid.

Consequently, many companies prioritize higher returns early on, often with governmental support to foster their growth and research efforts.

In essence, a comprehensive feedback loop, along with hands-on experience and knowledge, is indispensable. I emphasize the necessity of continuous learning, urging participation in lectures and engaging in exercises to broaden understanding. Armed with knowledge, informed decisions can be made in the future with greater confidence. With that, I thank you for your attention.