

Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 16
Environmental assisted surface deterioration - Part 1

Welcome to the thirteenth lecture of our course on corrosion, environmental degradation, and surface engineering. In this lecture, we delve into the critical topic of environmentally assisted surface deterioration. Throughout this course, our primary emphasis lies on understanding surface degradation and strategies for its prevention or mitigation. In this session, we aim to explore the concept of environmentally assisted degradation, deciphering its meaning and identifying the key factors that contribute to surface deterioration. Environmental factors encompass a spectrum ranging from water and humidity to temperature variations, spanning both high and low extremes. Join me as we unravel the complexities surrounding these influences on surface integrity.

Sunshine primarily consists of UV radiation, a form of ultraviolet radiation that significantly impacts surfaces, as we've discussed previously. Chemicals, ranging from acids to gases and other toxic substances, chemically interact with surfaces. Additionally, abrasive particles such as dust, sand, or debris prevalent in the environment contribute to surface degradation. While we've explored these factors individually, the reason for revisiting them in this new lecture lies in the heightened complexity they present compared to our previous discussions.

At times, we may ask, "What are the signs of degradation, particularly those caused by environmental factors?" We can demonstrate a specific type of bridge, allowing you to observe signs of discoloration and corrosion on its surface. So, what are the signs of degradation? One of the easiest signs to identify is erosion, or possibly a form of material removal. At times, we may use terms such as peeling, delamination, or cracking to describe surface discoloration, as exemplified in this photograph of a bridge. Now, the wind is responsible for all the degradation, acting as a medium to abrade the material. Naturally, there are particles in the air, and if these particles impinge on the surface again, they will erode it further.

Wind serves as a primary source of degradation, carrying moisture in the form of humidity, water vapor, rain, or fog, alongside temperature variations ranging from extreme highs to lows. This variability becomes crucial, especially for materials composed of bi-metal or tri-metal structures, where differences in expansion coefficients can significantly impact degradation rates. Similarly, UV radiation or sunlight, a pervasive degradation source, warrants separate discussion due to its interaction with mechanical stresses induced by high-velocity winds and particles impacting surfaces. Additionally, chemical interactions involving reactive gases, acids, or other substances play a significant role in surface degradation.

Another aspect to consider is the presence of uncontrollable environmental factors, which are significant as they are beyond our influence. Elements like rain, fluctuating sunshine affecting temperature, and other natural phenomena are beyond our control. Our task lies in studying and observing these factors to design systems or components that can withstand them effectively. This concept is often addressed in literature as atmospheric corrosion, a term synonymous with environmentally assisted surface degradation. Atmospheric corrosion occurs due to the presence of gases, particles, water vapor, and chemicals emitted from sources like automobiles,

factories, construction sites, and improper waste disposal. These factors, including rain and oily spills, pose significant threats to material surfaces and must be carefully considered in design and maintenance practices.

Materials can include metal, polymers, ceramics, and composites. The atmosphere, which contains various particles, water vapor, and gases from daily activities such as automobiles, factories, and construction sites, influences all types of materials, either directly or indirectly. At this critical juncture, the atmosphere manifests itself as water. Water plays a crucial role in atmospheric corrosion, even though its ppm level ranges from 100 ppm to 10,000 ppm. Therefore, the concentration of water can vary greatly, ranging from 1 to 100%. When water interacts with a metal surface, it can transport iron, encourage the creation of electrolytes, and cause localized corrosion events. The major issue arises when water vapor reacts with sulfur dioxide, or possibly nitrogen oxide, in air acids.

We are well aware that acids can deteriorate the surface, and occasionally we may even hear the term "acid rain." So I can say that most metals are prone to acidic corrosion. Acidic corrosion hasn't accelerated the deterioration of any structure, including the bridges I previously illustrated in my presentation. We observe significant deterioration in buildings, monuments, and ships, as well as in machines, vehicles, components, and systems exposed to the environment. The environment is a significant factor over which we have little control.

Therefore, it's imperative to conduct modeling or experiments while considering all factors, including cost-effectiveness. Creating a large structure may seem impressive, but if it's not economically viable, it won't be competitive in the market. Hence, providing cost-effective solutions is crucial. Regarding water-related issues, wind poses another challenge. The blowing wind can carry sand or dust particles that can damage the exteriors of off-road machines or vehicles. Additionally, the mechanical stresses induced by these windborne particles striking the surface can exacerbate degradation. Furthermore, the chemical interactions facilitated by the gases carried by the wind significantly contribute to surface degradation.

This could be the reason why many books refer to this lecture as "atmospheric corrosion." So I try to simply provide a justification. The next question arises: Is this something new that people haven't done before? No, it is not new. The ancient Greeks believed that the primary elements that degraded metals and alloys were water, air, earth, and fire. So it is not new as such.

Over years of study, water has consistently emerged as a primary catalyst for degradation, along with air and soil—especially sand—or temperature fluctuations, even akin to fire. Countless diagrams and resources online or in books depict systems that have succumbed to environmental corrosion or related factors. Consider, for instance, carbon steel tubes exhibiting extensive corrosion due to water exposure. We can interpret this as either a natural process or artificially simulate such conditions to understand and address necessary remedial measures.

Similarly, bronze statues, a frequent subject of observation, develop a natural patina—a layer of oxide—on their surfaces due to atmospheric gases and pollutants reacting with the bronze, brass, or copper. This layer, susceptible to erosion by windborne particles, gradually diminishes the material, leaving behind evident marks such as pits, grooves, and scratches. This phenomenon underscores the ongoing process of environmental-assisted corrosion.

And sometimes we also observe that in anything that has been dug into the sand, and the reason being that it is inside the surface, it can be a foundation. We say that some sort of structure, maybe some portion of the structure is under the foundation, that will also be subjected to corrosion or degradation. The reason being that the sand itself has a moisture nature, and it also has abrasive particles. And then if there is some sort of degradation happening on that way also, we have already studied something like a fretting, and there is a possibility of some

sort of degradation happening on that way also. High temperature, fire, and all we know is that because of the high temperature, the activity will naturally increase significantly, and this has been shown here, particularly the thermal insulation layer, and below that there is some sort of corrosive layer on the surface of a boiler or heat exchanger in this case. In summary, metals are susceptible to various types of corrosion when they come into contact with water. In an earlier lecture, we studied electrochemical corrosion, which occurs when water is present. It acts as an electrolyte, naturally dissolving metal ions and transferring electrons from one surface to another, thereby causing corrosion. Therefore, this flow leads to a certain level of conductivity. If dissolved oxygen, chloride, sulfate, or other ions are present, the rate of corrosion will naturally increase significantly.

In this context, water alone isn't the sole contributor to corrosion; the presence of dissolved oxygen, chlorides, sulfates, and other ions in the environment significantly accelerates corrosion rates. This cumulative effect amplifies the overall impact, especially when considering the influence of heat or temperature, which we've extensively studied. Heat facilitates chemical processes by providing the necessary energy, thereby expediting reactions and rendering gases and ions more soluble. Consequently, corrosion rates escalate, particularly in the presence of water, due to the heightened chemical activity spurred by elevated temperatures.

In this scenario, we can assert that an increase in humidity or temperature will undoubtedly accelerate corrosion, potentially leading to the formation of multiple oxide layers. Additionally, a wind may erode the oxide's surface. Therefore, naturally, the degradation will occur at a significantly faster pace compared to our previous design. Another point comes when it comes to industrial emissions from vehicle exhaust and maybe some sort of other pollutant that gets released into the environment or air. They really make a corrosive product or corrosive compounds, and then that really is what we think about, like sulfur oxide, sulfur dioxide, nitrogen dioxide, or chlorides, and these are the really corrosive products as such, and then they deteriorate the metals very fast compared to the environment without, maybe, a close environment where we have control over this kind of gas, but in the environment because vehicles are increasing exhaust gases, naturally this will also cause a more and more kind of deterioration of the metals. Another one, as I mentioned, is that metals are buried inside and within the sand itself, and there will be more and more corrosion because there is a void to water contain or soil has moisture contain, and there are abrasive particles, and then many times we use some sort of chemical in the soil for various purposes. So, there is a chemical, there is moisture, there is a temperature, and there are abrasive particles, all of which will naturally enhance the material degradation rate.

So, it's evident that the actions related to soil can vary considerably due to factors such as soil chemistry and pH levels, which can be further influenced by the presence of chloride, sulfate, or other chemicals. Therefore, when designing new structures or revisiting existing ones, it's imperative to consider these environmental factors to anticipate surface degradation and enhance longevity. By doing so, we can ensure the longevity and durability of the components.

To summarize these considerations, I'll illustrate them in a comprehensive diagram depicting the various factors affecting atmospheric corrosion. These factors include moisture content, considering the duration of surface wetness—whether it's exposed for minutes, hours, days, or months—and the nature of precipitation, whether in the form of liquid water, ice, or vapor. Such an approach enables a more holistic understanding of the corrosion process and facilitates informed decision-making in system design and maintenance.

Naturally, another one is the dust. Dust particles will have different sizes and different velocities, and they will affect temperature already. We have already covered this, but sometimes we also provide somewhere else for the protection we use about sheltering. So, there is also the possibility that velocity will vary from one place to another. That is why we say that whenever we are designing any system or any product, we need to really consider the various aspects of environmental factors, and this is why these environmental factors really will be

the important pollutant. You know pollution itself is a big domain, and many kinds of pollutants are possible. We also have another one: what is the initial exposure condition? Is there a protective layer or protective coating on the surface? If some sort of LED preventive measure has been taken, what will happen quite possibly? If those preventive measures, which we have taken, maybe the environment is degrading itself, and the surfaces actually are, then the degradation rate will enhance or increase significantly. So, these are the factors that we need to account for and consider. We can clearly state that the primary factor influencing atmospheric corrosion is the initial condition, specifically the presence of a protective layer, coating, or oxide layer. Naturally, we have already discussed in our course that when a metal surface is exposed to an open environment, an oxide layer forms on the surface, acting as a protective layer.

This layer serves as a protective barrier against corrosive substances. If this layer is compromised, becoming penetrable or less passive, it diminishes its effectiveness in inhibiting corrosion. Initially, corrosion may not occur at all, but factors such as excessive rain can strip away this protective layer, leading to a significant increase in subsequent corrosion rates.

As mentioned earlier, factors like wetness duration, precipitation (including rain, dew, or fog), dust particles, temperature, exposure conditions, sheltering, wind speed, pollutants, and others all play crucial roles. What's noteworthy is that these factors often interact synergistically rather than independently. Understanding these complex interactions is paramount as they collectively influence the corrosion process. Therefore, it's essential to have a clear comprehension of how these factors interact to anticipate their combined impact on products, emphasizing the significance of wetness duration, as previously highlighted.

The duration of wetness refers to how long a metal surface remains moist. If water is promptly removed, the brief exposure typically doesn't cause damage. However, prolonged dampness provides ample opportunity for moisture to react with the metal, hastening corrosion rates. Rain, condensation, and fog can trigger corrosion processes, even if no corrosion was initially present. This environmental exposure can initiate corrosion action. As corrosion sets in, the surface becomes contaminated, making it susceptible to erosion, especially in the presence of excess water. Consequently, the once resilient surface softens, increases in porosity, and experiences a significant reduction in erosion resistance.

Therefore, rainwater can erode that material. Sometimes this rainwater itself contains gases, and we use the word dissolved gases to mean contaminants that will naturally increase the corrosion rate. Now dust or airborne particles, which can be taken away by the air itself, sometimes settle on the metal surface and form some sort of thin layer, and we know the carbon suit is one of the most common examples of automobiles coming out and directly coming on the surface and forming a kind of barrier layer. Now what will happen if there is some sort of corrosion on a surface and this layer comes on stage on that surface? Therefore, we won't be able to observe the corrosion from a distance, but it will persist in a more significant way.

There won't be any evaporation or removal of water, leading to a significant increase in the duration of dampness or wetness. This prolonged exposure to moisture poses a major problem, as various factors interact to exacerbate corrosion. These factors can accelerate corrosion by extending moisture exposure, providing favorable conditions for electrochemical or corrosion cells to form. Consequently, surface degradation rates increase. Additionally, higher temperatures intensify the activity of corrosion agents. Temperature fluctuations, due to changes in thermal expansion coefficients, can lead to condensation of water vapor, further contributing to corrosion.

If I intend to design a surface exposed to environmental elements, I might consider providing shelter or encasing it in a protective box. This sheltering would mitigate exposure to environmental factors, leading to better corrosion control. By identifying systems sensitive to environmental conditions and implementing sheltering

solutions, we can effectively reduce overall corrosion. This approach limits exposure to rain, wind-borne contaminants, and subsequently helps regulate corrosion rates. In a larger system consisting of numerous components, understanding the specific sensitivities of each part allows for the creation of more durable products with extended service lives. Additionally, when discussing erosion, it's essential to note that wind velocity, acting as the carrier fluid, can influence corrosion by accelerating moisture evaporation.

Now here are the two factors I am trying to consider: if there is rain and then there is a wind, it is also quite possible that moisture can evaporate. In this scenario, the wind can be beneficial, but if it carries particles that are approaching the surface, it can have a significant impact. What will happen in this situation? It will make a pit. The water will flow into the pit and settle there. So again, it will make an electrochemical cell here, and that will increase the corrosion rate.

In a controlled environment, wind velocity that aids in moisture evaporation is beneficial. However, if wind carries particles that impact the surface, creating pits where moisture can accumulate and initiate electrochemical reactions, it becomes highly detrimental.

Furthermore, air pollutants such as sulfur dioxide, nitrogen dioxide, nitrogen oxide, carbon dioxide, and chlorides can exacerbate corrosion rates. These chemicals possess a greater affinity for surface interactions, leading to the formation of corrosive products like acids, thereby significantly accelerating corrosion rates.

To effectively address these diverse environmental challenges, it's essential to categorize environments based on factors like rural, urban, industrial, marine, or indoor settings. Tailoring solutions according to these categories ensures cost-effectiveness and optimal performance. What works best in one environment may not be suitable for another; for instance, a solution ideal for urban areas may not suffice for industrial settings, and vice versa. By studying and understanding the unique conditions of each environment, engineers and scientists can develop tailored solutions to mitigate corrosion risks effectively.

Therefore, classification is crucial as it enables scientists and engineers to assess potential corrosion risks accurately. This approach is particularly relevant in the context of atmospheric corrosion, where understanding the specific environmental factors at play is essential for devising effective corrosion mitigation strategies.

Again, I am referring to the potential corrosion risk specific to a given environment. Therefore, it is important to understand that the corrosion risk in an indoor environment differs from that in a rural, urban, or industrial setting. Additionally, the corrosion risk in a marine environment may be significantly different. What are the advantages of this classification? We assert that if we possess ample information or knowledge, we can utilize it as a tool to devise strategies for surface protection, thereby enhancing the longevity and resilience of our products. Therefore, when we revisit the topic of surface engineering, we will focus on the development of a machine or a case study, taking these points into account once again. If I try to explain it differently, we could say that the classification arises because of minimal human activity and relatively low levels of air pollution in rural areas.

So here the contaminations are lesser, and then human activities are also lesser, which means a lesser population, and moreover, whatever the environment, which mostly consists of soils influenced by vegetation, and some sort of limited industrial activity, we do not call the industrial activities at the village level. So naturally, we consider those aspects. Only the new thing will come, maybe from one village to another; there may be a possibility of some sort of local geographic change; or maybe somewhere there will be more agriculture activities and somewhere less agriculture activities. So we consider those aspects, or rather, if we are making machines for agricultural purposes, we naturally need to think in those directions. These considerations are crucial when we

approach the environment from a rural perspective and design our products accordingly. Now, turning to urban areas, we see that human activities have increased due to population growth. This leads to an increase in the disposal of human waste and other resources without proper management. Consequently, pollutants increase, along with the number of vehicles and construction sites, compared to rural areas.

Overall, it will increase the atmospheric corrosion rate compared to what we have experienced in rural areas. Therefore, we can conclude that the atmosphere, especially in urban areas, has a higher concentration of sulfur dioxide than in rural areas. Therefore, the atmosphere in urban areas is more likely to contain high concentrations of sulfur dioxide and nitrogen oxide, as well as particulate matter, or PM, which we frequently use. Additionally, the volatile nature of DOCs may outweigh that of organic matter in this scenario. Therefore, these pollutants, when combined with moisture, can intensify the rate of corrosion, regardless of the circumstances. Therefore, when designing for an urban area, I tend to take a more conservative approach, assuming that increased environmental factors will lead to an increase in corrosion severity.

So we need to consider those things. Coming to the industry, we say naturally industry in environment it has a many corrosive the gases vapors particles, and then what will happen even there is a possibility of acid like a sulphuric acid vapor there is a possibility maybe the minor PPM level, but it still we need to consider those aspects even HCL or maybe hydrochloric acid or chlorides and various metal oxides also will be there. Therefore, the presence of this corrosive agent, coupled with high humidity levels and temperature fluctuations, naturally accelerates the corrosion of materials exposed to such environments. In the case of the marine site, the presence of salt is a contributing factor. So we can say that the presence of salt-laden air and a high level of humidity primarily affect the atmospheric corrosion rate, basically the marine environment or even the coastal environment, whatever the vehicles or whatever we are designing near the coastal area. Naturally, we need to account for those kinds of things, and then even the sea water, which may say sea vapor as such nearby, may have a number of dissolved ions; it may also have some sort of chloride; and we know very well that if the industry is really discarding their water directly into the sea, the contamination level will increase, the salinity level will increase, and then what we say is that the overall corrosion rate will increase. From a CBOD perspective, rural areas are relatively easier to manage, urban areas slightly more challenging, industrial areas slightly more challenging, and marine areas significantly more challenging.

Therefore, we must take into account various factors, such as the type of environment, the types of contaminants present, and the level of pollution, so that we can tailor our design accordingly. However, if this is not feasible, we must approach everything from a universal perspective. This will ensure a clear and straightforward diagnosis: an analysis of something failing in an urban area will naturally differ from an analysis of something failing in an industry, an analysis of something failing in a marine environment will differ, and the root cause of failure will also differ. The delivery of this introductory lecture on environmentally assisted surface degradation underscores the critical importance of understanding this environment. We aim to provide an overview of this type of environment. Now many times we feel the indoor environment is safe, but it is not always there. The reason being that there is a possibility that we are using some sort of cleaning agent in our everyday lives or indoor environment. Those agents also leave some gases in the in the environment, and those gases will create a substrate of chemical composition that will deactivate the systems and affect corrosion. So we can say the indoor environment is also polluted, and then we need to really consider those aspects as well.

From this perspective, I believe that the environment encompasses solar radiation, various contaminants, water vapor or humidity, gases, high temperatures, and acids. Therefore, it's crucial to examine the environment from multiple perspectives. It's crucial to remember that the atmospheric conditions vary from one place to another and from planet to planet. Additionally, the latitude and longitude of our earth's surface may also influence these variations. We may find it challenging to create a new design solely for a single location, yet we have the ability

to modify the maintenance schedule, duration, failure analysis, and remedial measures. This is why having a thorough understanding is crucial. Now, we are trying to give us some sort of idea of the overall environment.

We know the environment mainly contains nitrogen oxides, nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2), along with some rare gases. Additionally, the environment can include species such as ozone, hydrogen peroxide, sulfur dioxide, hydrogen sulfide, nitric acid, ammonia, hydrochloric acid (HCl), chlorine (Cl), formic acid, and formaldehyde.

Note that we measure these levels in parts per billion (ppb). When comparing indoor and outdoor environments, indoor levels of certain contaminants, like ammonia and formic acid, are often higher than outdoor levels. This indicates that indoor environments are not always safer and may contain significant contamination, which must be considered in design.

The main question is identifying the worst contaminants. Determining the severity isn't straightforward; comprehensive knowledge is required. Common atmospheric gases, such as nitrogen and oxygen, and rare gases like neon, krypton, helium, and xenon, dominate the troposphere, the lowest layer of Earth's atmosphere.

Since N_2 and rare earth gas, or maybe rare gases, do not interact with the metal surface, they are more inert, and that is why we say that we do not have to consider those nitrogen no need and rare gases no need as such. However, we know very well that oxygen plays a very important role because oxygen can really react with the surface, and then it participates with the various environments and plays a very crucial role. It is also the also the main thing that it accepts the electrons; we can say so, and it plays a crucial role as an electron acceptor, particularly when we are talking about the cathodic reaction, which we have discussed in the corrosive environment in the chapter on corrosion. Carbon dioxide and water also play a significant role, making them the primary factors. So I will say one of the worst is oxygen, followed by carbon, and water vapor, followed by carbon dioxide. Therefore, it is important to take these factors into account, as they hold greater significance than nitrogen or rare gases.

So if we look at the gases, or maybe water vapor as a gas, in this case, I say they eliminate all other oxygen, water vapor, and carbon dioxide, and it is unfortunate that many people have not considered carbon dioxide, and they say the contribution of carbon dioxide is negligible; we do not have to consider that. However, if you consider the ppm levels of carbon dioxide in our troposphere, they are approximately 330 parts per million. This concentration can contribute to acidification by lowering the pH level and promoting the formation of corrosive species that can severely damage metal surfaces. Therefore, carbon dioxide plays a crucial role. It's worth noting that nitrogen, rare gases, and oxygen, along with water vapor, are the most important elements. Consider the presence of naturally occurring sulfur compounds, such as sulfur dioxide or hydrogen sulfide, commonly recognized as significant contributors to atmospheric corrosion. Why is this the case? This is because these species contribute to the formation of sulfuric acid, which is known to be highly corrosive, especially to metals, and can cause severe damage. Now, let's turn our attention to nitrogen oxide. While nitrogen itself is not particularly significant, it does play a significant role as a pollutant. It primarily originates from the environment, particularly automobiles, and it significantly increases the rate of corrosion. This is because nitrogen oxide forms a type of acid known as nitric acid, which is also corrosive in the environment.

Now, a chlorine compound, or perhaps any type of chlorine present in an environment, can form either hydrochloric acid or hypochlorous acid. In this case, we use the word HOCL, which is also corrosive to metal. In this case, the overall corrosion rate depends significantly on the concentration levels of corrosive species. There is a threshold concentration below which gases or elements will not affect the exposed metal or material. However, if the concentration exceeds this threshold, it will lead to increased corrosion. Another factor to

consider is temperature, which can alter the concentration. Also, whatever the bond on the concentration will change in the presence of moisture, or maybe the duration of the exposed time is 5 minutes, 1 hour, 2 hours, or something like that, will also change. So the overall impact will be kind of all factors considered together, and that will give reasons. To clarify, I am examining a case study in which we expose lead, a tarnish-free lead coupon, to the humidity in the carbonyl atmosphere. We maintain this relative humidity at approximately 75%. We identify three levels in the carbonyl atmosphere: formic acid, formaldehyde, or acetic acid.

As a result, there are six figures labeled A through F. Figure A shows a surface with no exposure, representing a clean environment. Figure B shows the effect of formic acid, labeled FA. Figure C combines formic acid and formaldehyde, labeled FA and F. Figure D combines formic acid and acetic acid. Figure E combines all three: formic acid, formaldehyde, and acetic acid. Finally, Figure F shows the effect of acetic acid alone. The scale of 10 microns (10 μm) is used throughout.

When it comes to E, it has all three exposures, and when it comes to F, it is only the acidic acid. Now this is being given, and then here it has been mentioned clearly that the PPM level. So PPM and V, V is basically specifying the volume; it is not a mass; it is a volume has been considered here, and if you look at all the PPM levels, the maximum PPM V level has been given for the formaldehyde, and interestingly, formaldehyde is not affecting the late surface. So, concluding that if formaldehyde is not affecting the latex, it will not affect any metal surface is not correct. If you provide some sort of hydrogen oxide, then there is hydrogen peroxide, and there is a possibility that this will also act.

So everything depends on the environment is environment, how what is the concentration. Now even though very high concentration of formaldehyde is not affecting surface. You can compare A and C we do not find much noticeable difference. Now coming to the B and C we do not find much difference some are difference will come because formic acid has some sort of effect on the late surface. Coming to the last one also the D in this case we can see D and F we find the effect as more or less same in this case or in fact, D E F more or less same.

So the mix main contribution is coming from AA. So, in this case really exposure of the acidic acid is really affecting the surface. So that is a severe compared to other two. While formic acid comes in between, and that is why we are writing here the lead does not appear to have a corroded when exposed to the formaldehyde. So, when formaldehyde has exposure to the surface, lead surface is not really affecting. Another one we say that this can be say the novel in the sense that the no observed adverse effect level. It is a terminology has been utilized to find out what is the minimum concentration below which there will not be any effect of the surface, any effect of the contamination on the surface degradation.

So that is very important to understand. From a novel perspective, lead corrosion compounds primarily form in the presence of acetic acid. Lead corrodes more quickly with exposure to acetic acid compared to formic acid. So in this case when there is a formic acid there will be some sort of acidic action or when there is some sort of corrosion, but it will be much lesser than acidic acid alone as such. What is really happening is a formic acid also strongly reacts. It is not that it is not reacting, but it is forming a passive layer that is a major point. Some chemicals they form layer on a surface, and then they become a passive that means a second layer will not be formed.

I mean we only talked one layer and that is what is the beneficial. Many times, we use a word oxide and you say that the contamination layer acts as a lubricant because that is a passive layer. It will not allow metal to get exposed to the environment. It is a protective as such. And then what we say that novel particularly NOAL for the formic acid is generally 0.1 ppm and the ppmv particularly the humidity level, and naturally the humidity increases this level will increase.

So they as per the literature 0.1 ppmv is between the 54% to 75% relative humidity. If it is a lesser than 0.1 ppmv effect will not be there. If it is a more than only the effect will be there. As mentioned, formic acid tends to create a stable film primarily composed of lead formate or lead formate hydroxide, which prevents further formation of any oxide layer.

So it is a stable it remains there like oxide layers. So, it is a stable it is kind of the naturally formed coating. So it is acceptable and then it will be useful. However, if there is a transportation of any device and there is a thin layer already been made on the lead surface, but because of the handling and because of the transit if the surface get a scratch, naturally the lead surface again virgin lead surface will be exposed to the environment another layer will come. So, if there is a continuous kind of abrasion or erosion then this kind of layer also will be very harmful for the product. So, there are different thing if there is a mechanical reaction then it even a formation will be a problem.

So then in the situation formaldehyde will be far better coming to formic acid. However, if there is no mechanical action it is only chemical then formic acid is ok. It will not really deterred at the surface significantly because only the top one layer will be made and it may act as a protective layer against the metal exposure. Now we are trying to cover really what is a environment and how it affects overall, and how it is really harmful for us. So let me consider one very interesting topic what we use our satellites, and that too in a low earth orbit, and LEO is a very well-known thing, and we say that LEO orbit is around the earth and the span is something like altitude is variation from a 200 kilometer to 2000 kilometer around our earth surface. Then if we use a satellite what will happen in satellite may complete one cycle in something like 88 minutes to 128 minutes, these are rough figures may be the newer satellite will may take a lesser time possibility is here.

Now, why are we considering LEO satellites and why have they become so popular? The primary reason is their utilization for internet access, broadband mobile communication, and remote sensing. So, this is a what we say digitized world in this is and this kind of satellites are very useful. Now if these are so useful then why we are considering and this is not a topic related to digitization or digital thing, but major thing is environmental gas environment and environmental degradation. So, we say the atmospheric gases something like oxygen, ozone, water vapor can accelerate the degradation of satellites, which are useful for the LEO reason being these contaminations remain in a low earth orbit. So low earth orbit this kind of contamination are there or this kind of environment, and when the satellite has to be in this environment so that is where the we really required protection surfaces for satellite.

Why reason being the we say the atomic oxygen can erode and oxidize this exposed satellites surface, and then it also keeps a limit also like this satellite has to be removed after 2 months or after 5 months or after 10 months depends what kind of layer we have given. Another one is that also that UV exposure to this kind of satellite, so this is an environmental contamination or environmental corrosion or environment damage for the degradation of the surface. So, this is a noticeable and then it should be considered now what is the really the problem with satellite. We say when we are designing something if the relative speed is lesser than there will not be much erosion, but here satellite has to have very high speed.

So that is why we say the satellite must maintain a fast speed to stay in orbit. If the speed is not maintained it will not be in orbit so this complete design will change. This process is called high-velocity impingement. In the atmosphere, numerous ions continuously impinge on the satellite, causing severe oxidation of its material. The exposed surface undergoes oxidation, leading to the continuous removal of material layers. That is why we really required something better material it will completely damage, otherwise this process will completely damage the

crystalline structure. And what is the really how do we observe it has been say the cutting and groove then the cuts, and then the groove may be some sort of deformation has been observed on the surfaces, and if the particles which are getting impinged on a surface and angle of attack is also. Then maybe orientation is right that the severity of the corrosion increases significantly. And then another one thing is comes as the high pressure also is sometimes subjected to so there is a abrasion, there is an erosion, there is a addition also and all are happening in our own environment to a satellite which is really very beneficial to the our society.

So that is why we want to consider one of the case study and then some sort of observation on this kind of surface. So here I am trying to show in this diagram there is some sort of satellite and there is a earth environment. When we refer to a low Earth orbit (LEO) satellite, we are considering its environmental degradation and the various environmental risks it faces. It is not a one or two I showed some sort of abrasion, addition and erosion, but there is a possibility some sort of chemical action also.

So what we talk about some the mechanical, but chemical also will act on the surface. So, this is why we were saying now here the contamination maybe because of oxygen also, and we will consider from where the atomic oxygen comes, and then why it has been there in environment we will consider those, but there is a naturally the photon radiation will be there. There will be number of charged particles. So, there will be some sort of high activity, and temperature effect also will be there thermal cycling also effect will be there. So it is something like a fatigue is also going to happen and on the top of that, there will be particles which will be coming and hitting the surface at the high velocity, because the satellite itself is moving at the high velocity, and that is going to really impinge on the surface. So there are the factors not only the atomic oxygen which we will be considering, but there are number of other mechanical, chemical factors or maybe say heat factors also.

When designing a satellite, the designer must consider several parameters, including the mission duration (how many months it will remain in orbit), the relationship with the solar cycle and solar events, the satellite's orientation, the type of exposure it will have to the sun, and the velocity it should maintain. So, these are the factors really overall effect the results. Now in this major thing is from the abrasion point of view I can think about orbital debris of the OD. Now why from where the OD comes you must have heard about the rockets, when the rockets are launched some sort of disintegration of the rockets will happen, some solid particles will be remaining in a environment. So this is what we say the solid rocket boosters and a spent the fuel which has been already consumed is a one thing, but what will happen the remaining fuel, because this not going to come back to another environment, remain in the kind of orbit and then this is a causing some sort of debris which debris generation, and this is the reason when they have done a study they found a more than a 50% of the metal among the material which goes with the rocket it, remains as a debris form it remains in environment and then in 1980 somewhat they established one procedure. What we call the passivation procedure and then they say that whatever the material it should not really expose to the surface, and then because of passivation they had to release the fuel which this rocket is carrying with the in body as such.

So the fuel will be leaked out will be removed and will be kept in a environment, there assuming that in there will not be much damage reason being that if the fuel is intact in the rocket or into the vehicle then there will be possibility of the more blast. So, I can say the one what part passivation is started. So passivation involves releasing the rocket body whatever the fuel was left in a rocket body to stop them from a bursting. If the fuel remains there then there is a possibility what they have done in simulation, they found that there is a possibility of the bursting and then if the bursting happens, then there will be more and more number of debris will come in environment to avoid more number of debris, they release the liquid as such in this case. So and that is what will happen in this case the liquid oxygen and hydrogen propellant which was used in a rocket is left, there may be the release into the environment but that has become a now a major drawback.

There is a reason that the collision and explosion of the fully intact in the cell life to the large the with this kind of fuel, which are in the remain into the environment really there will be possibility of the more, we say that erosion of the satellite cell. This is crucial because if erosion occurs, satellites may disintegrate into multiple fragments, ranging from small pieces to larger debris, potentially leading to severe catastrophic failures. So we want to avoid the satellite erosion holes in that because of the impingement, and even though we know the particles will be there and debris will be there in environment, even though passivation policy which has started in 1980 that reduces more number of debris, but still that whatever the ions which have been released in the environment atomic oxygen, which has been released in environment it will also have impact on a satellite body or satellite surfaces also. So naturally we need to think how to avoid that what should be done. So a lot of research has been done on that so I am just trying to present one research work was done and we have picked up from a literature.

So here you are able to see here that in the case study low earth orbit satellite environment in degradation they have mainly focus only on atomic oxygen exposure when atomic oxygen exposure is given to the surface what will happen to that. We say that the reason being atomic oxygen is very highly reactive, and then it can act as a erosion against the Kapton foil which has been kept on the surface of a satellite as such. Naturally though there is already foil on a satellite and now they are trying to figure out what will be remedy of this foil, what kind of a top layer or top coating should be done on this. So, they were trying to make some sort of protective layer on, and then increase the life of this Kapton foil. So, what they created a some sort of a layer 10 nanometer coating and of course it can be 10 nanometer coating to the 100 nanometer coating palladium material.

So it is been done and as I mentioned here Kapton foil is something like a 25 mm this has experiment had been done in the labs, and then they have been prepared. So this is shown in the surface 25 mm thick and then the scale has been shown 100 μm and A and B has been shown here in this case A in A case only the particle has been impinged, and particle size has been given in this case particularly we say that particle in the projectile a particle which is getting impinged on the surface is something like a roughly 1 mm in size. And then it is a creating with this big hole 1 mm is a creating this big one hole and then the small holes are because of the other particles or other projectiles, which is roughly they have used a 100 soda lime glass particle assuming this will be the particles in environment when there is a some sort of debris. They are treating that this is the 1 mm size projectile is a debris 100 μm soda lime is a debris, and then it remains in environment. So this A shows without oxygen in presence of oxygen B shows a more in presence of oxygen, and then when they expose this surface they found that size of the impingement or maybe the hole size is increasing in presence of oxygen.

Numerous experiments aimed at obtaining more accurate results have demonstrated this. They demonstrated Figure A and not only made assumptions, but also provided backscattered electron images. By comparing the surfaces, they saw what happened to a 10-nanometer-thick piece of palladium-coated foil that was exposed to oxygen. They saw that it grew bigger. And another one is that they found particularly the foil, which has oxygen almost 20% extra; this is a reference that we are picking, and then this is impacted with the projectiles, and this is the only exposure to atomic oxygen, and now atomic oxygen is present and impacting. So in this case, only the impact is a kind of erosion of the surface; it is only exposure to atomic oxygen, and this is the combination of these two. In this scenario, it's evident that the holes are growing in size. This erosion is evident in areas such as A and B, and it also occurs in E and F when oxygen is present. We can clearly observe in C and D that the chemical activity of oxygen creates the small holes.

Therefore, it's crucial to note that the size, or more accurately, the damage, has significantly increased in the presence of oxygen. The policy of releasing leftover fuel, including oxygen, into the environment aimed to

prevent debris creation. However, the release of atomic oxygen into the environment inadvertently exacerbates surface damage. So that is why we say that it is important to note that, and then whatever we were thinking, releasing atomic oxygen in the earth environment or earth orbit will not impact the surface, but it is not literature that has been found that is really increasing the size. And another thing is that when they compare the two cases, we say that only the particles are getting impinged, and they assume initially that the particles will remain there in that low atmosphere, in orbit as such, or in an in an earlier orbit as such. In this case, they found that approximately 18% of the damage occurs in the presence of oxygen or atomic oxygen, particularly in the central area. However, they also found that around 13% of the damage occurs in the peripheral or corner areas.

So they try to reduce the particle sizes or the debris, but oxygen, which is getting released into the environment because of minimizing the debris, increases the damage by 18% . It may have been a lab experiment, but in reality, they have not done it. Therefore, further research may be necessary to fully understand the situation, but my point is that, while there was a positive outcome in this case, the release of oxygen into the environment also raises the possibility of potential harm. We will continue this discussion in Lecture 14. Thank you for your attention.