Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 34
Economic Losses by Corrosion Degradation

Hello and welcome to the thirty-first lecture of the course on corrosion, environmental degradation, and surface engineering. The present lecture will focus on the economic losses resulting from corrosion degradation. So, we are going to discuss losses caused by corrosion degradation, and the whole course we have been given more emphasis that degradation or surface degradation should be minimised as much as possible to almost negligible level. So, let us start with this lecture, and then what we are trying to understand is: is it possible to come to zero? Can I really eliminate complete corrosion?

For most materials, we either synthesize them in the lab or obtain them from natural sources, which often requires mining. During mining, materials frequently form oxides—for example, iron forms iron oxides. To make these materials more useful or increase their purity, they undergo various processes in mills and other operations, each of which requires the input of energy.

When we extract materials, they initially have low energy content, and we continually add energy to transform them into useful products, such as underground pipes or automobile bodies. In both cases, steel is commonly used, though polymers are also increasingly utilized. Taking iron as an example, the material will eventually corrode, forming rust, which often leads to its disposal. Interestingly, rust is just another form of oxide, so the material essentially returns to a similar state from which it started. This raises the question: can we truly prevent this process? The reality is that complete prevention of surface degradation due to corrosion is impossible. While we can mitigate it, eliminating corrosion entirely is unachievable.

However, we can delay corrosion and extend the service life of materials significantly. This is because the driving force behind all corrosion processes is the system's Gibbs energy. When Gibbs energy is high, the likelihood of corrosion increases substantially. While we can't prevent corrosion entirely, we can slow it down, extending the material's lifespan from, say, 5 years to 10 or 15 years. To put it simply, when producing metals or engineering components, we continually add energy to the system. As a result, metals have a strong tendency to return to their natural, lower-energy state—typically an oxide form. This natural drive to return to a lower-energy state is the fundamental reason behind corrosion.

We can extend the service life of materials by applying effective corrosion management techniques, which delay the material's natural tendency to reach equilibrium. As we've learnt throughout this course, a natural oxide layer forms on the surface of materials, particularly ferrous materials. This is also true for aluminium, where a surface oxide layer is commonly observed after finishing. These oxide layers typically have a thickness of 10 nanometres. So, it is not a huge thickness, or they are not thicker than the 10-nanometre thickness, and we know because of this sacrificial layer thickness materials can be utilized in the virgin state; we cannot utilise those materials, but because of the oxide layer, we are able to utilise the most of the ferrous material and aluminium materials. So, this is very important to understand, and then we have learnt a number of mechanisms. So, we can say understanding corrosion and utilising a data-driven approach, because I mentioned very clearly that there are many processes involved in an atmosphere and corrosion will happen one way or another because of the different mechanisms.

So, doing accurate modeling well in advance will be very difficult, and that is why we really require data capture—

maybe online or maybe in situ—and then processing those data. So that the protective coating can be formed, or even if there is a protective coating if there is some sort of flaw or maybe some sort of fault in that, that can be diagnosed well in advance. Based on this information, we can continue to modify and enhance the material, thereby improving the overall working condition. As the corrosion resistance increases, we also discover that we can apply a surface treatment to prolong the component's lifespan. Furthermore, we discover the frequent use of coatings, which serve as a crucial first line of defence against corrosion.

So, whatever the coating we use, it is a first line of defence against the corrosion, whether we are using automobiles or aircraft, whichever situation, and that is where it is important for us to learn even the coating. In the previous lecture, we learned how to select the best coating based on its features. What we've learned about corrosion is that it involves two basic electrochemical reactions, one occurring as an anode and the other as a cathode. Now if you want to really delay this kind of action or reaction, then we use some sort of inhibitor, and this may be nitrite, or maybe phosphate, or maybe some sort of organic compound; they are added to the electrolyte in order to slow down the corrosion process, whether it is anodic process or the cathodic process. So we try to delay using our engineering knowledge, and then we have some sort of sensor, and we have extensively, and then the covered non-destructive testing.

So we can figure out what the faults are that are really emerging in a system, and then we can take a number of preventive actions. So we can delay corrosion, but we cannot eliminate it, and the data-driven approach becomes very important to understand and apply. When discussing the data-driven approach, we need to focus on Condition Monitoring (CM), also known as condition monitoring. This involves monitoring the condition of the institution, followed by data acquisition from a sensor. Those data need to be processed, and after doing a processing, we need to figure out whether there is some sort of fault and some sort of processing must be done. Furthermore, we advocate for the adoption of a prognostic approach that optimizes the maintenance strategy, with the aim of extending the product's useful life.

So the question comes: can we really do without a data-driven approach? No, it is not what is the real reason because there are a number of industrial and manufacturing processes where there are a number of degradations, and then they are not revealed immediately. That is why we require non-destructive approaches. So, things that are not visible to us, and then whatever you do estimation of the life, or estimation of the failure time, that may not be correct, and that is why we really require a data-driven approach. So, whatever theoretical calculations we make, the model needs to be redefined repeatedly using iterative methods, which is important to understand. Another key point is the relationship between condition-based monitoring and the degradation process. We model this process and collect data to estimate the remaining useful life. Finally, we consider economics, which will be the focus of this lecture. Understanding the connection between condition monitoring, degradation modeling, and economics is crucial for making informed decisions about failure behavior.

If we are able to connect these four five streams, then overall the results will be more favourable, and that is what we are going to cover in the present lecture. Let's begin by focusing on the primary topic we are trying to address: corrosion or its effects. Now why does the corrosion really happen and we are not able to eliminate it? Now what is the real reason we say that there is close proximity to the water or humidity? Water is essential for human life, and then we know that our environment has humidity. So these are the important parts of society as such, and then we have mostly the metal environment or maybe the different places, including buildings or maybe artefacts, and those things are there.

Previously, we believed that corrosion solely affected metal, but current research and discoveries reveal that corrosion also affects ceramics, polymers, and composites. So almost all the materials get corroded over time. This is a crucial point to note, as numerous research articles have quantified the substantial financial losses associated with the corroding process. It is very important for us to understand that when there are substantial financial losses related to the corrosion and that happens because of the corrosion, material degradation happens much faster. On the one hand, we aim to extend the lifespan of the systems by addressing corrosion and reducing its rate. We understand that corrosion alone does not accelerate wear damage, but corrosion or corrosion-assisted corrosion accelerates it significantly.

Studies show that financial losses due to corrosion amount to around 3% of GDP. In India, this figure is about 5.95% of GDP, a significant number. In developed countries like the USA, it's about 3% of GDP. We can analyze why this difference exists—why it's 5.95% in India and 3% in the USA—but even in the USA, the cost of corrosion is estimated to be between $2 trillion and $4 trillion per decade, or about $0.2 trillion to $0.4 trillion per year. This is comparable to the economic losses from major natural disasters, like Hurricane Katrina in 2005. However, while natural disasters occur occasionally, corrosion is an ongoing, annual problem. Therefore, we should pay more attention to the financial losses caused by corrosion. According to a 2011 report by the National Research Council, corrosion not only impacts the economy but also affects national security, reducing the readiness of military equipment like tanks and missile launchers.

But if those get corroded, what will happen? There will be a huge loss, even though when you want to operate the machine, it will not get operated. This remains one of the major issues we face today. Supposing we have implants in a body and they get corroded because there are a number of fluids in a body, there is also a possibility of corrosion. Naturally, this would lead to significant health and safety issues. When it comes to energy and fuel, we understand that pipelines exist, and they can corrode over time. If gas leaks back into the environment, it presents a problem. Leaking fuel results in both direct and indirect losses. And we have learnt in the Bhopal tragedy case also that causes the major problem.

Natural treasures or artifacts are also affected by corrosion. Even with constant polishing, these items eventually lose their original shape, color, or beauty. This is another major loss highlighted by the National Research Council (NRC). Additionally, corrosion affects productivity. For example, when a bridge undergoes maintenance, the road might be closed for 7 days, 10 days, or even a month. As a result, someone who normally crosses just 1 kilometer now must take a detour of 5 or 7 kilometers. This leads to lost time and reduced productivity.

So that loss is also important; we already covered in detail in our course about infrastructure and engineering devices, including ships and airplanes. And of course, whatever happens, whatever the degradation, it is released back to the environment, and the environment gets polluted. This report is commendable as it highlights the significant amount of research in corrosion science and engineering that is still needed. If I were to articulate these concepts in a slightly different way, it would enable us to conduct more effective research. The National Research Council emphasizes the importance of corrosion education. The reason being that many people who even do corrosion research will be focussing only on one type of corrosion, which may be say the very small element, but the need to really educate society about this kind of fault or this kind of financial loss is very important. That is why we say that an RCA expresses the need for the corrosion education to build national liabilities to respond to the emergency, and the situation related even the national securities.

So those things are important, and we say that even the cost that we have been getting into the tabular form number of times those costs are symbolically how to maintain the system, how to replace the system, and then these are the direct causes, but what will be the cost related to the even military case if there is a response is longer one and we are not able to immediately react whatever the attack happens. Therefore, the responsibility of bearing the cost naturally falls on society. This even the military delay will be causing on the to a nation bigger way that is need to be understood, and another one like a bridge, that know maybe they go for some sort of breakage of the bridge, and then overhauling is being done or maybe we say that some maintenance work or maybe some portion that has got damaged is getting replaced, but major problems will happen to the traffic.

Traffic jams and pollution caused by maintenance or repairs also need to be considered. Although some models project this data, we still need to validate and refine it before sharing it with the public, so people can understand the broader impact. Decisions about infrastructure should benefit society as a whole, not just the contractor handling the project. The real loss is to the public. Additionally, corrosion can affect medical devices, like needles or implants. If a needle becomes corroded, it can harm the person receiving the injection. Similarly, corrosion in implants can lead to serious health problems.

So those things are important, but these numbers have not been documented across the nation, and even GDP 3 percent 3% whatever is shown for the USA. In fact, these numbers, which are indirect numbers, are causing a problem to the society, causing problems to nature or to the environment; they have not yet been well documented. That's why the National Research Council (NRC) advocates for further research in these areas to improve outcomes. So these are all things against corrosion. However, there are also positive aspects to consider. This report emphasizes that by comprehending corrosion and understanding how to remove the material, we can also achieve effective manufacturing, a fact that has been demonstrated in numerous manufacturing processes.

Let us take an example of semiconductors. The manufacturing of semiconductor devices heavily depends on repeated etching. We understand that removing material and then depositing it results in the formation of oxide on the surface. How can we proceed with this multiple oxidation process? Therefore, corrosion science teaches us how to remove material, deposit it, understand the parameters, and fine-tune the process, particularly at the nano level. Even the natural oxide that forms on the metallic surface only occurs at a level of 10 nanometers. We have been talking too much about the micro level, but if we are able to do a really good job at 10 nanometers, then why do I really require a three-dimensional system as such? Therefore, learning, understanding, and future research will benefit society significantly.

This is what we are trying to think in the direction. I give an example of only the semiconductor industry, but you look at various material science or material synthesis or even performance analysis, even the sensors and even the biodegradability or even the recycling of the battery or even the battery design, which may be non-ferrous metals. Infusing the science of corrosion everywhere can significantly enhance our understanding. In summary, a thorough understanding of the science and technology underlying corrosion greatly benefits society in a variety of ways. So this kind of course is very important. If we learn mechanisms, we know how to really detect the faults and how to really think about a coating or kind of the barrier between the system and an environment, then it can really help society in a much bigger manner.

Let's look at a quick slide from 2017 that compares corrosion costs in different countries. The comparison includes developed countries like the United States, Japan, and the United Kingdom. In these countries, the service sector bears the majority of the corrosion costs. For example, in the U.S., the service sector accounts for 79% of these costs, and in Japan, it’s 73%. Agriculture contributes very little—only 1% in the U.S. However, in India, agriculture is responsible for around 17% of the total corrosion costs.

In countries without significant agriculture but with a large oil industry, about 51% of corrosion-related failures come from the industrial sector. In contrast, in developed countries, the industrial sector accounts for about 20% of corrosion costs—20% in the UK, 26% in Japan, and similarly 26% in India. These numbers can vary from country to country depending on the dominant industries. Instead of focusing on just the overall corrosion cost percentages, like 3%, 5%, or 6%, it's important to consider the specific sectors that contribute to these costs.
We can go with the segments and then figure out which is a more critical segment and where we need to focus. That is why this paper is important from that angle. We can conclude from the profiles of the United States, the United Kingdom, and Japan, all of which are recognized for their advanced industrial and service economies, that they share a similar pattern. When it comes to India, its robust agricultural base contributes to a higher rate of equipment corrosion, particularly in the agriculture sector.

In summary, they do not have a significant agricultural sector, but they do have a robust oil industry. Therefore, the cost of failures or corrosion is expected to be higher on that side. However, in this paper what is not there, that is what there is a need to emphasize. We say occurrence of the missing deadline because of some failure, and then we are not able to meet the deadline and able to cause some of it, so there will be some cost. It has not been accounted for; even mishaps, forced shutdowns of industries, or machines not counted due to various corrosion-related accidents, have not been accounted for.

So this kind of cost has not been accounted for appropriately. While some industries are implementing this, it is not readily available in an open document format. To make the right decisions regarding corrosion, we need more data. In my view, we've only been exposed to about 50% of the corrosion problems or financial losses caused by corrosion, but the reality could be at least twice as much. This slide, which I introduced in the first lecture, illustrates the contribution of corrosion in various sectors in India. For example, agricultural losses due to corrosion account for 6%, while sectors like mining, manufacturing, oil and gas, water management, and electricity all contribute to corrosion costs, with electricity alone at nearly 10%.

In the construction industry, corrosion-related losses are about 3.2%. Overall, corrosion costs account for 5.95% of GDP in India, but if we break it down, the direct cost is 2.3%, while the indirect cost—such as delays and failures—adds another 3.65%.

From these data we took from the references. So that the one-star reference is here where we try to compare the cost of the corrosion, which is roughly around 1.67 lakh crores in this case, and then we took this as a 3-star reference, where the reference has been showing that even the complete budget for education in India is roughly 1.13 lakh crores, which is a lesser than the cost of the corrosion. Therefore, we need to increase our education and awareness about corrosion to significantly reduce its costs.

Now, I'm attempting to reiterate some of the points from the previous slide question, emphasizing that quantifying corrosion is a challenging task. However, we must undertake the necessary modeling and update it using a data-driven approach. The earlier slide showed the direct economic losses, which account for 2.3%. Indirect losses, on the other hand, occur due to shutdowns and efficiency losses caused by corrosion. Corrosion can lead to cracks or material loss on surfaces, reducing efficiency and resulting in product loss. Sometimes, we also over-design systems because we anticipate material degradation or cracking. For example, in large bridges, we might apply higher safety factors (such as Sub T2 or Sub T4) to account for corrosion, leading to unnecessary over-design. This means we're using more material than needed, which increases costs.

So those losses are also there. This table, sourced from a reference, clearly shows the number of GD and GNP. Notably, instead of using UDP, the authors have presented the losses as such. You can see here in this case and then what we are able to realise that India's name is also there, and Japan is also there, but in this we are able to see some different methods, so which have been utilized by the authors. Table 2 is the source from which this table was derived, and it was published in 2006. The cost of corrosion and the resulting financial losses are the focus of our discussion. These losses include reduced production, which we've already mentioned. One of the more challenging aspects to quantify is the loss of human life. Additionally, there's the loss of products, such as pipe deterioration and reduced plant efficiency. Another significant consequence is environmental pollution. Although the government may impose taxes on companies that release pollutants, the overall impact on human life is substantial. For example, the Bhopal tragedy highlights the severe effects of industrial failures.

We also discussed over-design, where we account for material degradation by using higher safety factors, which leads to unnecessary excess material and increased costs. There are methods, such as the Olig method, How method, and input-output method, that can be used to assess these issues. We'll cover these three methods in detail in this and the next lecture. The Olig method, in particular, has shown good results since its publication in 2001.

Direct and indirect costs make it difficult to make precise decisions due to a lack of reliable data. For example, when considering anti-corrosion measures like coatings, surface treatments, or using nano additives, these are direct costs that are easier to calculate, and decisions can be made with more confidence.

But because of this addition, because of this coating, the life of the system will enhance by 5 times, which is exactly not possible. That is why we require a data-driven approach; we need to keep getting data, and then based on that, we need to really get results. Either we do an accelerated test or some other results, but estimating future maintenance even is very difficult because there is a huge number of parameters, and we really required good science to really think about because those things are very uncertain, and to convert to certainty only the data, or maybe the knowledge and even the tested knowledge are very important to think from that point of view. Even sometimes, in some references, they say the direct cost means a design cost, a manufacture cost, a fabrication cost, and even the overhead charges like management charges. When discussing indirect costs, it's crucial to understand the burden society will bear and the methods used to calculate them. In some cases, big contracts have come up now, and we know that even in the situation, parties have to bear, but they do extra taxation. Maybe you know, if you take the example of the highways, and then the whole highway is in contract for 15 years for 25 years. Whatever the maintenance-related thing the concerned company will do, we have to bear the cost, or society has to bear the cost also. Therefore, it is crucial to understand that society, in one way or another, bears the cost when it becomes involved.

So that is why the knowledge being spread is very important to understand, so we go ahead. Even something as simple as knowing whether a lawsuit has been filed or if a specific case has occurred is crucial. There are many cases where courts have imposed penalties on companies, especially when the damage leads to environmental cleanup or affects public welfare. In these situations, the company bears the financial burden, but society also shares in the cost. To minimize future damage, it's crucial to effectively utilize corrosion engineering, which is why we emphasize its importance. With the right knowledge, we can develop better policies and implement effective measures. As I mentioned earlier, even issues like traffic delays add to the overall cost, and companies, while bearing part of it, must also consider the wider societal impact.

Traffic delay: somebody is getting late, and then the cost goes to him or maybe her. These are the important aspects where we need to really think and then come up with some good models, and that is why the NRC says that there is a lot of research need in this kind of area. So this is what we really need to think about for the future. Now coming to the three models that I showed in my previous slide, you say that the three methods to quantify corrosion are the Olig method, as I mentioned, and then the method of input and output, where we really required a lot of data. The Olig method calculates the corrosion cost based on the preventive measures or strategies we implement, accounting for any associated costs.

Again, we won't account for indirect costs in this scenario. In this case, the focus is primarily on estimating the cause of the corrosion prevention technique. Of course, they try to distinguish between indirect and direct costs, indirect and indirect costs, or maybe the corrosion expenditures. And then they mention very clearly that owners and operators incur direct costs for corrosion avoidance—maybe when they are thinking about the coating, when they are thinking about corrosion-resistant materials, or maybe some sort of cathode protection. This is a direct indirect cost that is borne by the users. Now if some damage happened in your systems, then basically you need to bear it, or maybe the customer or user needs to bear it.

Generally, indirect costs are associated with the burden on society. While in the case of the home approach they have a thought over the impact, the economic impact, what will be the cause of some sort of failure that has happened, and what will be the impact on the others also. And then they try to really do it by instead of going for the complete system what will be the individual characteristics and then individual requirements, particularly for various sectors. So these things were accounted for in this method in a slightly better way. When it comes to the input and output, there are numerous parameters that need to be tabulated before developing this approach.

Naturally, this input-output approach will be comprehensive, but we require a significant number of data points for this purpose. Regrettably, despite our awareness of significant economic losses, we lack a robust method to proceed with a thorough cost assessment.

Our goal is to understand and minimize these losses as much as possible. In order to make informed decisions, we need knowledge. People might estimate the cost differently—someone might say 5%, another might say 4.5%, or even 6%, depending on the costs they're considering. There will always be some subjectivity in these estimates. However, with continuous data collection, we can refine these models and make more accurate assessments.

So even at the initial level we have rough data, maybe some models available, and then we take it to another decision now itself. So that is why this lecture is important. Even if we lack a concrete method for analysis, we can still identify the numerous factors that are directly related to corrosion. Could we seriously consider reducing the economic and societal impacts of corrosion? This would be a significant step in the right direction. There are a number of methods available, but I have specifically mentioned three. These methods are available from a management perspective, and they are referred to as corrosion management financial tools.

So what is the cost of the corrosion, which we have been discussing already there, and then, as I mentioned, these are the tools that are assisting the societies or industries. This method is now associated with a society; therefore, it is related to industry. Industry's ability to reduce costs and enhance life indirectly will benefit society, but there is no direct correlation. There is another method, what we call a life cycle cost analysis, to some extent. We can perform a return on investment (ROI) cost-benefit analysis. Occasionally, we will delve into the concept of life cycle cost analysis. This involves considering the initial cost of purchasing an item, followed by operational costs, maintenance costs, refinement costs, and finally, disposal costs.

Disposal costs can be tricky. In some cases, when we want to discard a machine, we may need to pay to dispose of it. In such cases, the disposal cost would be a positive value, indicating an added expense. However, in other situations, like when selling a used car, we might get money back, meaning the disposal cost would be negative, reducing the overall expense.

Regarding life cycle costs, we need to consider both the initial investment and ongoing operational costs, which may continue for several years. Additionally, factors like inflation and interest rates must be accounted for. This is where net present value (NPV) comes into play. NPV helps us assess future costs and benefits by calculating their value in today's terms, which allows us to make more informed decisions.

Occasionally, we need to consider a benefit-cost ratio. So we say that future benefits and future costs need to be brought to the present system, and then we can take a decision based on that. So indirectly we can take a number of corrosive resistance measures, but the question comes whether those measures will be really useful, whether they really give some sort of enhancement in a performance, or enhancement, or maybe the making of a better environment for society. If we fail to accurately measure these factors, it will be challenging to make a sound decision. While the decision may not be 100% accurate, it will still be sound.

As I previously stated, we can proceed with a data-driven strategy. Today, we continue to refine our approach; we are making decisions and achieving some level of efficiency or benefit-to-cost ratio. Tomorrow, we will improve because we will have better data. Even if the data is slightly less, we will still be able to identify the problem, determine where it needs to be addressed, and determine the best way to address it. So these are the important things to understand, or we say we have done corrosion cost analysis in this course. What we do is basically take all the measures, and then we know very well that in some sort of organisation, some machines are getting failed, and they are buying new machines, or maybe they have bought initial machines, and then they are taking some measures on that.

Therefore, both the cost and the data will be accessible. So corrosion cost analysis will not be that difficult. When it comes to life cycle cost analysis, we will examine the entire life cycle, including the cost of procurement, the type of maintenance, the cost of operation, and the cost of disposal. So those things are there. Now somebody says I will go ahead with the ROI analysis. I need to make a decision based on the provided life cycle cost. Will that be beneficial? Should I invest money, or should I not invest?

This leads us to ROI (Return on Investment), a management tool commonly used in decision-making. In cost-benefit analysis, we calculate the present value of future costs, such as maintenance and disposal, and make decisions based on those values.

Another important management concept is risk assessment, which involves determining the probability of failure or success. These probabilities are key to understanding potential outcomes. Additionally, maintenance planning and optimization are critical. Even if I maintain my system well, if the returns aren’t significant, the investment may not be worthwhile. Therefore, a comprehensive approach is needed to make well-informed decisions about maintenance and related investments.

To understand what I said, let us take one example. We say in this case we are trying to figure out life cycle cost analysis (LCCA), and what is given to us is something like the formula: what is acquisition cost or input cost, and then operational cost, maintenance cost, and disposal cost. As I previously mentioned, the disposal cost can either be positive or negative, depending on whether we receive a payment or have to make a payment to a third party to confirm that the machine is disposed of. Now coming to the cost side we can figure out, and then if we are trying to keep all the cost in present value, then we need to think about inflation and what is the inflation, whether in this case we are taking inflation or maybe the rate of interest around 8 percent 8%.

In this scenario, the value of r is 0.08. What are the given costs? The initial cost is approximately 12000, which could be expressed in either rupees or dollars. The recurring cost is estimated to be approximately $1,000 for maintenance and repair, and $3500 for gas usage. This leaves us with a final cost of $4,500, or perhaps a disposal cost of around $3,000. We are assuming that the life of the provided item is five years, correct? So we can estimate what will be the overall cost, or we say that the life cycle cost analysis from this point of view, and we can use a small, we would say that algorithm or maybe a MATLAB program.

So here we have written AC 12000, RC if you have 4500, RV 3000, and then the total duration of the system is 5 and the interest rate has been given around 8 percent 8%. So we will take value from that point of view. The interest rate, when divided by 100, yields an R value of 0.08. Even though we have fixed the maintenance cost at approximately $4500, we still need to factor in today's time and express the present value in this format.

In this case, the Present Value (PV) is calculated using the formula: $1/(1 + r)^5$, where r is the interest rate, and we are considering a 5-year period. The value decreases over time, starting with a factor of 0.92, then 0.85, and gradually declining. From a summation perspective, over the 5 years, the total amount paid is approximately 17,967.

So it is much lesser because if I talk something like a 4500 into 5000 5 times, then naturally this cost will be on a higher side, roughly coming at only 2500, but in the actual case in the present case we are taking something like a 17,967, which is a lesser. Coming to the residual values, which is a 3000, the present value in this situation will be roughly 2041.7, a roundoff of something like a 2042 that will come out. Therefore, we are attempting to calculate the total cost in the current scenario, which ultimately amounts to 27,925 over a 5-year period.

This is a comprehensive life cycle cost analysis of the benefits we are receiving. Knowing the quantifiable benefits of this device allows us to determine if the cost-to-benefit ratio is higher, thereby guiding our decision to invest or not. So this is finally showing how much really we are going to invest in whatever the machine in the car or maybe whatever the equipment we are buying. So this is the present value of the cost from that angle. In this case, we are considering a rate of interest of approximately 6%, as opposed to the previous case's rate of 8%. We are discussing the initial cost, followed by the benefit, which is 3000. Finally, we are attempting to determine the benefit compared to the last time we discussed the cost.

Now here we are also taking some sort of benefit. We are dividing the benefits into annual amounts. This represents the initial cost, which could be as high as $100,000. The benefit is expected to be 50,000 per year in the first year, 30,000 in the second year, and 60,000 in the third year. We are trying to calculate this based on a three-year timeframe. Are we really fine? Will we receive this benefit or not? This is the outcome we have achieved.

As I mentioned in here, we are taking the R value as a 0.06 as a 6% overall, and we are counting based on this, and then what comes out to be something like starting from 0th year today's itself. So 1, 0.47, then 0.2, and then, in this case, factors are changing, and what we are getting as an as an overall benefit to the cost ratio is something like 1.24. So it is a kind of advantage, and we can go ahead with this number as such. However, there will be some sort of point coming that in between the number two year when we are tabulating it, at the end of the second year we have a benefit of only 30,000. Now why not have 50,000? Why not have 60,000? So when we tabulate the numbers, when we compare them, then there is also the chance that we can improve the system also, and then there is a sum flow, and then we can improve that also. So those things are important to consider when we are documenting; when we are using these formulas and some sort of calculation, it really hints at the direction in which we think and then overall increases the benefits for us. Now we think about economic analysis, basically controlling or minimizing surface degradation. At that time, I also stressed the importance of making informed decisions when allocating funds, which necessitates knowledge about surface degradation.

And then in this situation, what we say is that what is the cost and what is the saving, and then saving, we need to also think from a nuanced point of view or maybe accounting for the interest in this. So that also mentioned that if this overall cost is decreasing, suppose number of years, and the interest rate is increasing, then what will happen? We need to really recover the whole amount in a much lesser number of years. If it is not, then it is not really the right decision to invest money; it will be a bad decision. In this scenario, the interest rate was only 0.05 over a period of 10 years, resulting in an overall annuity of approximately 7.72. When we consider the 10 percent (10%), we arrive at a calculation of 6.14. This is the same slide I presented in an earlier lecture, but I'm attempting to relate it to the current topic. And we see here also in the situation if this green line goes on the negative side there is no point this will be unprofitable to go ahead with the surface controlling surface degradation.

There is no point in going ahead with the surface degradation. Of course, if we focus on society and consider the socio-economic impact, as I mentioned in the IPCC report, we can accurately determine these effects. If we consider it quite possible, we may make a decision. Controlling the degradation of surface damage is crucial, and it is imperative that we take action for the betterment of society. But if we think from only an industry point of view, we may make a decision about an industry; this is not important because it is not going to give us any profit. However, this is where we require policies when everybody has knowledge, and then we know that this system, which is that we are not taking appropriate measures, is really costing a society.

These factors are important when we consider the savings associated with taking measures to prevent surface degradation. We need to assess the probability of failure and the probability of success, depending on whether or not we implement surface degradation prevention methods. Without measures, the probability of failure will naturally be higher, for example, around 0.2, 0.3, or 0.4. After applying the measures, the probability of failure will decrease.

This means the risk of failure will always be present, and the cost of failure—whether per year or per month—can be calculated. These costs will translate into savings when we take preventative measures. The savings can be incorporated into our calculations, along with the initial cost, the system's lifetime, and the assumed interest rate or return rate. In this case, we assume an interest rate, which is used as the expected return rate. For example, if the machine is expected to yield a return of 15%, 10%, or 5%, this will influence the decision-making process.

Higher return rates are often expected in businesses that want quicker returns. However, in some cases, businesses aiming for immediate returns might fail to launch a product or system successfully into the market.

This slide repeats the concept of probabilistic analysis for controlling surface degradation. We use the same formula as before to calculate the cost of failure. To clarify, let’s consider an example: Assume the probability of failure without any preventive measures. Here, 'P' represents the probability with preventive measures, while the alternative scenario reflects the situation without any preventive actions.

So that is why we say the probability of no preventive is 0.3, the probability of preventive measures is something like 0.1, and then the failure cost that will occur will cause something like 100,000.

We calculate the benefit of taking measures as follows: 0.3 minus 0.1, multiplied by 100,000, which equals $20,000. If we implement the measures, the benefit comes out to $20,000. Naturally, we need to consider the initial cost, the desired rate of return, and, once we input this data, the overall results will likely be more favorable.

However, estimating material degradation is challenging due to limited information, which makes it hard to decide whether to take action or not. The investment in measures to prevent material degradation can seem unappealing if the expected rate of return is high, as shown in the previous slide. For example, if we expect a 15% return, we may decide against adopting new methods for surface degradation prevention.

On the other hand, if the expected return is only 5%, we may be more inclined to proceed. This is why, as I mentioned in earlier lectures, governments often provide initial grants or funding for risky projects, helping ensure their success. From a business perspective, high returns are desirable, but with government support or subsidies, a lower expected return may still be acceptable.

This is of utmost importance, and decision-making or policy-making hinges on it. Now, let's focus on the methodology we should employ to consider the corrosion cost or reduce it. As demonstrated in one of the slides, different countries have different sectors, some of which are more prone to corrosion than others. So we should assign the sectors, and even the sectors—what are the subsectors that are more prone to corrosion? It would be beneficial if you could conduct a thorough study of these areas. However, as we said, most of the reports—annual reports or IPCC reports—are available. We should review these reports, either through the software or directly, and then incorporate them into the system.

We are now also learning from experts. If I conduct research for the next 20 years, it is inevitable that I will accumulate a wealth of hidden knowledge. We haven't documented everything on paper, which we refer to as tacit knowledge. Therefore, conducting interviews with experts can significantly assist in extracting this knowledge. This process involves the initial identification of a sector or subsector, followed by the identification of experts from industry, agencies, or authorities who can provide relevant data. Therefore, once we obtain relevant data from both external sources and established literature, we must process and analyze the data. Based on the analysis of all the data, we need to develop a corrosion model, estimate its cost, and assess its impact on society.

So we say the national economy will be affected. That requires considering knowledge diffusion, society's awareness of knowledge, and anti-corrosion policies. Therefore, the first step is to estimate the overall cost. Once we have corrosion-related and corrosion mechanism data, we should consider the impact on the national economy. Once we have these data, we can raise awareness in society, propose anti-corrosion policies, and then disseminate the data to enable people to make informed decisions. We know the water is really corroding, or maybe humidity is also corroding; some chemicals are corroding.

So we should not keep them open, which will really react with the materials. So those things are important to understand. If I see from a bigger perspective, what we say economic analysis of corrosion is a comprehensive procedure that encompasses the cost of the corrosion in many economic sectors. So, we really need to figure out which sector is really affected severely.

We need to approach this by considering the importance of data collection. As I mentioned earlier, gathering insights from experts who have years of experience in a particular field is essential. This type of knowledge, known as tacit knowledge, often resides only in their minds and is difficult to document. The challenge, then, is how we can effectively capture this expertise. This process is referred to as gathering expert input, a common tool used in management. In addition, collecting data from relevant literature plays a crucial role and can greatly assist us in making informed decisions. After that, we move on to data processing and analysis, which are equally important steps in the process.

After collecting data, we must process it in a manner that allows us to identify distinct patterns. This is what we've learned from the data-driven approach: we need to identify patterns, determine correlations, and identify trends. Based on these findings, we propose models, which should then continuously update themselves. The significance of a data-driven approach lies in its ability to refine, project, and identify any research gaps from this perspective. Now another thing, as I say, is that once we have all the data available and their impact on the national economy, it must be assessed directly or indirectly whether people have knowledge. If people possess knowledge, their understanding will significantly improve. Maybe we have not reached some area, while when the common public is getting aware of those data and the knowledge, naturally they will be involved in what will happen in the situation.

There will be economic growth, there will be employment, and there will be good competitiveness. So overall, this is required. We required economic growth, employment, and competitiveness for the overall development of society. This can be achieved by implementing the right measures. Another important aspect is the development of anti-corrosion policies. If some companies are not prioritizing societal well-being and are focusing solely on their own profit, we must ensure that we refine and have a clear understanding of anti-corrosion policies. Once these policies are proposed to and adopted by the relevant authorities, we can monitor their enforcement. If a company fails to adhere to these policies, we can intervene, educate, and guide them to align their practices with societal needs.

Furthermore, as I mentioned, data fusion is crucial. All stakeholders involved, directly or indirectly, should have access to the complete data and the science behind it. Often, a lack of knowledge creates confusion and misunderstanding, and addressing this knowledge gap is key to minimizing those issues.

If we possess sound knowledge, we can transform society into a more advanced form. So these things are very important for us, and I believe if we are able to do that, it will be overall very good for society. We now turn our attention to the challenges the National Research Council highlighted in 2011. They say corrosion research grant challenges and possible solutions should be addressed, and then we already have learned something like understanding corrosion mechanisms, prevention mechanisms, or even the selection of which method will be good—continuous monitoring, environmental challenges, modeling and prediction, education, and workplace development. These are the topics that have been partially covered in this course. If I were to present the corrosion grant challenges in a slightly different light, I would argue that they are serious concerns, and that any obstacles related to corrosion that we are unable to address immediately could potentially be addressed through research collaboration.

When discussing research collaboration, it's important to note that academic institutions not only conduct their own research, but also collaborate with industry. As an example, I work in mechanical engineering. If I want to engage in collaboration, I should work with material scientists who are involved in chemistry, engineering, or other disciplines. What kind of collaboration is very important, and as I say, the partnership with industry is important. So in a holistic manner only the development can happen, and what we have already studied in this present course—we say corrosion mechanisms—were described in the present course. Information and mechanisms related to localised corrosion, galvanic corrosion, stress corrosion, corrosion cracking, even the corrosion under extreme conditions like a high temperature, chemicals, environment, you mean radiation environment, material degradation mechanism, and environmental impact on those kinds of degradation have already been informed in this course. We also discussed the use of corrosive-resistant materials and the selection of coatings. We also discussed inhibitors that can effectively reduce the rate of corrosion, allowing for more efficient collection and utilization of data.

We have provided an overview of the data-driven approach, which initially assumes a model or possibly a train, and then obtains continuous data that can be further refined. We also discussed the concept of a life cycle assessment. Based on this, if we aim to extend the life of a component by a few years, we can determine the necessary mitigation approaches, such as corrosion mitigation. We also discussed the associated costs of these mitigations, as well as the potential benefits of enhancing the overall life cycle of the system. These factors should be taken into account. Based on that, we can think slightly about the MATLAB coding also; we say the computational modelling and then productive tools using a kind of machine learning. Artificial intelligence is very critical for the future, and those things should be accounted for in a proper way. So, these are the important things for us, and thank you for attending this lecture. Thank you.