Corrosion, Environmental Degradation and Surface Engineering

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Lecture – 28
Failure Mode and Effect Analysis (FMEA)

Hello and welcome to the 25th lecture of course on corrosion environmental degradation and surface engineering. In the present lecture, we will be discussing the failure mode and effect analysis. In the previous lecture we have discussed something about the fault and failure, and I emphasise that we should think about the fault, not a failure because failure is the ultimate final thing, then we will not be able to do much about that. However, in a failure mode and effect analysis, we need to consider the failure modes, which we have already covered, but this will provide some sort of initial input for the product design. So, most of the time failure mode and effect analysis is good for the design stage or the beginning stage, or when you want to change a material, you want to change a lubricant, you want to change a surface engineering, you want to do something different that people have not done, and in that situation you can go ahead with a FMA. So, what is really required in this case? In the last lecture, I mentioned that maintenance is what really gets a direction from a fault detection, and then what kind of actions should be taken.

So, maintenance strategy is basically decided based on the fault detection. Now in this case, what we are mentioning is that maintenance fault detection and FMEA are crucial components of engineering in relation to corrosion and environmental degradation or deterioration. As a result, we will not be aware of many environmental factors. So, when we design initially, FMEA may be using the FMEA and then try to figure out faults, and then we can change the maintenance strategy based on that.

So, the reason being, we can really refine our model based on whatever is unknown to us, and that is why we have been placing more emphasis on a data-driven approach. We say the modelling analytical models can really give an initial direction for the development or product development or process development or system development. But once it is implemented, then we should start working on the sensors or then data collection related to faults and do remedial action. So that the failure should not happen at all, if it happens, it should give well-in advance notification. So, the proper maintenance strategy can be decided, and in this failure mode in effect analysis, we assign some sort of number that is called RPN. The risk priority number for each failure mode will have some sort of RPN number, which we need to assign based on the severity of the failure.

If it is very severe, it will have the highest value; if it is almost not possible or it will not really happen in some situation, it will get a minimum value. Now this minimum value and maximum value depend on how we want to really give numbers. The way we have earlier decided earlier weighted objective method. So, where we will be giving numbers 1 to 10, a similar procedure will be followed; in this case, we will be giving a mostly ranking based on the 1 to 10. The 10 is the worst; 1 is the best.

In the earlier weighted objective method, we followed a reverse scheme, where a score of 10 represented the best and 1 the worst. However, in this case, a score of 10 is the worst, and 1 is the best. Therefore, a lower risk priority number is more favorable, and we aim to promote that.

As I mentioned earlier, after one or two more lectures, we will begin discussing the topic of maintenance. I also noted that when we encounter FDD (Fault Detection and Diagnosis), we need to shift our maintenance approach from preventive to a more adaptive one. Preventive maintenance involves scheduled tasks like regular inspections, cleaning, and lubrication, which may occur every 24 or 48 hours, weekly, or bi-weekly, depending on the requirement. However, we need to transition from this to corrective maintenance, which is condition-based and responds to what is actually happening in real-time.

Again, if we are able to bring predictiveness into the maintenance aspect, then we will know well in advance how we go ahead. In other words, if I want to really elaborate, we say fault detection is a process of determining what is wrong with the system by analysing and comparing several features. In one of the case studies we examined, which may have been further discussed in the previous lecture, we examined 10 features. So, we are assuming several features or several signals because one feature or two features may not be able to give a complete number of faults. So, we consider several features and signals. We are again based on a statistical method, or it may be the data that we have available, and then the history or the past can be initially made to provide a normal signal. What will be the normal signal when there is no fault? In the previous lecture we considered one normal gear, one crack gear, and one broken gear.

So, we could compare the signal. So, everywhere, the normal signal will be important. We need to compare; nothing is absolute; we need to be compared and then make a relative ranking, and in this case, I can say we are giving a lot of emphasis on the fault. So, in my words, I can say the failure analysis is a reactive measure. Failure has happened; we are analysing it; then it is a reactive measure.

The goal is to ensure that similar failures do not occur again, making this a reactive measure. In contrast, fault detection takes a proactive approach, and the aim of this course is to strongly focus on the proactive side. We should aim to reduce failures to an almost negligible level.

Now, returning to Failure Mode and Effect Analysis (FMEA), I want to emphasize that while the course doesn't solely focus on failures, FMEA offers a systematic and proactive method for identifying potential failure modes. Each subsystem may have different failure modes, and it's important to address these accordingly. We identify potential failure modes and prioritize them based on their significance, which is where the Risk Priority Number (RPN) comes in. In today's lecture, I will explain how to calculate the RPN for various systems.

In summary, the primary goal of FMEA is to reduce the severity and likelihood of failures, which in turn enhances the quality, reliability, and safety of the product. Achieving this is crucial because it aligns with the objectives of this course, where we strive for better quality, higher reliability, and improved safety, while also preventing any degradation to the environment or the product itself, ensuring optimal results.

This analysis helps determine the appropriate maintenance strategies and surface engineering requirements, bridging the gap between identifying different types of failures, their mechanisms, and modes. By calculating the

Risk Priority Number (RPN), we can prioritize which failures need immediate attention. Although reaching absolute zero fault may not be feasible, we aim to minimize faults to a sustainable level where the severity is low and manageable. In cases where faults are minor or the associated cost and time constraints are minimal, lower RPN issues can be temporarily deferred without causing significant concern.

So, this is important; another thing FMEA is continuously getting updated. So, somebody who has done FMEA analysis around 10 years ago will find some new updates in the literature. So, my request is that we continue to review the updated FMEA on a regular basis as newer and newer information comes in. Now in these days we are talking about the digitisation, we are talking about the machine learning, and these all tools have been implemented with FMEA also. So, there is a need to continuously improve because this is a good feature to connect the past and connect the literature with future research. So, this is a good interface, and we should really explore this interface more and more.

So, what we can say is that the FMEA helps the maintenance team find and prioritise failure modes; maintenance action should be taken based on available information, and then we try to minimise the failure to almost zero. The question comes: what are the steps that are required to complete this process? So, we will be discussing those steps and what we say: that we really required RPN, which is a risk priority number. This is important, and then, as I mentioned, if the FMEA provides, then they provide some sort of failure mode, or, in other words, if I say, try to figure out what could go wrong. Now, what goes the word failure, but what will be the effect of that failure? What will be the effect of that fault if that happens? So, this is what would happen if the failure is happening, and then what will be the impact of that, and finally, it should also tell how to fix it.

So, some sort of brainstorming and what are the ways to field again? We are coming from a literature, let us say, that indicates this is the fault and how to correct it. If we are able to line up everything in a proper order, then at least we will be able to give a first product or first process, which can be implemented, and then it may be that when we discuss maintenance, we will be adding sensors. So, that recent information or in situ information keeps coming to update the FMEA program, or maybe say the whatever the algorithm, whatever the maintenance strategy we are writing. So, in FMEA, we say the problems are looked at in order of highest risk priority number to the lowest. So, we give a maximum weightage to the highest risk priority number; this is like what we use in our PCA. We try to figure out characteristics numbers, or the highest Eigen value will be contributing the most, and maybe lower Eigen values can be rejected.

We can effectively reduce the dimensionality in this process. In such cases, failures with the highest Risk Priority Number (RPN) will be given the most attention in terms of resources like time, cost, and effort. On the other hand, failures with the lowest RPN can either be addressed later or potentially removed from consideration. For example, if we identify 40 different failure modes and the top 5 account for 85% of the impact, we may choose not to focus on the remaining 35 failures, which collectively contribute only 15%.

The decision on how to approach these issues depends on individual priorities, introducing a degree of subjectivity. Some may aim for perfection, but that would significantly increase costs and time. Ultimately, how quickly a product needs to be launched or how swiftly ideas need to be implemented will determine the approach taken in this analysis.

So, we can see the risk priority number. RPN facilitates better decision-making. So, it is basically a kind of helping to take a decision. So, artificial intelligence can also be added to this kind of work in setting up the decision-making in setting up the corrective action, whether you want to correct 5 failures or we want a design. So, those top 5 numbers should not happen, or you want everything. So, that can be decided.

Now, we are saying that it will help; it will yield beneficial outcomes in terms of time and money. Naturally, no matter how much time we have or how much money we have, if we have infinite time and infinite money, then all the corrections and every fault should be removed, but if we do not have infinity money, infinite money, and infinite time, then we need to really take a proper decision, and that is where the RPN will help us. Now, how do we calculate RPN? We say there are some factors, what we call severity factors, and then occurrence factors and detection. So, they are SOD, and then how do we get a severity? We say that what happens when something goes wrong, like you know the really impact of a sketch and what will happen if there is some failure, will occur. We will take one case study, and then we will elaborate on that.

This refers to how often a failure is likely to occur, or the probability of something going wrong—whether it's 1%, 10%, 50%, or even 100%. Detection, in this context, is about our ability to identify such faults when they happen. For example, with subsurface cracks, detection can be challenging. As I mentioned earlier, during vibration analysis, we faced difficulties distinguishing significant cracks.

This raises the question: what tools do we have for detection? If we lack the necessary tools, it becomes harder to detect these faults. In such cases, we may need to invest in advanced equipment or explore alternative methods. However, if these resources aren't available, we may have to assign a high detection number, such as 10, indicating that our capability to detect the fault is severely limited.

So, now in this case there are 3 factors, which should be given a score between 1 and 10, as I mentioned earlier in the weighted object method, we used 10 as the highest number, best number, and best feature. While in this case we are giving the reverse, we say the 1 is very good may be the best in this situation and the 10 is the worst in the situation. So, if you initially find it very difficult to differentiate between the 1 and the rise in a 1 to 10, it can be 1 to 5 as well. Initially we are going ahead with the relative ranking, and then we are trying to figure out which features, or may be the failure modes, we need to address when we want to bring a new product or new process to the market. So, given a score between 1 and 10 based on how important they are, and then RPN is calculated by multiplication as into O into D, simple mathematics can be involved.

There will always be some degree of subjectivity when assigning scores from 1 to 10. For instance, one person might give a score of 1, while another might give a 2 or 3 for the same scenario. This subjectivity can be minimized through tacit knowledge—gained from experience in the field—or by referencing established RPN ratings, such as those found in the ASM handbook or other similar sources. These references provide predefined ratings and comparisons that can help standardize the scoring process.

Both literature and experience are valuable resources in this context. This is why FMEA is such an effective tool, as it helps bridge the gap between the current situation and desired outcomes. It serves as a useful interface, where a higher RPN number indicates more potential for improvement. Addressing these higher-priority issues will lead to faster outcomes and a higher return on investment.

So, ROI will be high, and then if we put in a lesser effort, the results will be better and better. So, this is a kind of RPN importance; if the number is higher, immediately we will try to address that problem, or if it may be a failure problem, try to get a solution on that. So, now what is the framework? You know, a number of people have given different kinds of frameworks; we are just going to opt for one that is like a traditional RPN system. What is in this tradition? We did try to provide a scale that may be 1 to 10 on a severity occurrence and detection that is one. After that, if this is an initial thing and is not required immediately, it will be required later.

So, how do we start? We start by assigning or finding the part or the system that we need to analyse, which will be known to everybody. So, dig out first what you want to really analyse, and then in the situation what will be done that you will try to go ahead with some components. So, if there is a big assembly, it is subdivided into several subassemblies, divided in number of components, and then divided in number of features. So, it is basically a top-down approach; we go ahead with the top-down approach. Now once we have a feature or component, or may be a subsystem, we try to figure out what the failure mode of each will be, because every feature may fail, or maybe every component may fail, or the subsystem may fail.

Fail means whatever we intended or whatever we want, we are not getting it. So, that is the failure. So, we try to figure out failure mode or potential failure mode, and after that, we try to figure out what will be the impact of that failure. So, determine the effect of each failure mode; if we are able to define it, then we need to evaluate the score. So, this will give me the severity ranking; that is what we say initially.

This leads to the question of how to assess severity, whether it's at a level of 1, 5, or 10. As we've discussed, the scale can range from 1 to 5 or 1 to 10, depending on our preference and the amount of knowledge we have. If we have limited knowledge about the system, we might use a 1 to 5 scale. With more knowledge, we might use a 1 to 10 scale, and if we have extensive experience, we could even consider a 1 to 100 scale. However, the most common approach is the 1 to 10 scale, which is what we'll use in this course.

This scale helps assess the potential impact and seriousness of a failure mode. A score of 1 represents no significant impact, while a 5 or 10 indicates a severe consequence. These impacts could range from minor effects to hazardous situations, such as safety risks, catastrophic failures, or major financial losses.

So, these are the possible things that are what we need to really think about and may be subject to some extent; may be one is to one gives a one number, the other one may give two numbers, but whoever gives whatever number they need to give some sort of reasoning for that. So, this is important now; once we determine this, then comes what are the root cause failure modes, and then if you can really evaluate that. So, that is what the occurrence will come; also, in this case, how fast or if we have already the literature available, we can also determine, or may be we have done 10 experiments, and we are finding 5 times failure is happening. So, we can give that type of occurrence ranking or probability of failure. The last one is the prevention of the possibility that what kind of detection we can really do whether we are able to find the crack or not.

The first step is to determine the impact of the identified failure mode on the system. Next, we assess the probability of failure, followed by the detection—how effectively we can detect the failure. These are the key factors in evaluating failure modes. We need to consider the Probability of Failure (POF) and whether we have the ability to detect it properly.

These aspects are crucial in the process, and based on them, we assign an occurrence score (O), a detection rating (D), and a severity ranking (S). The Risk Priority Number (RPN) is then calculated by multiplying these values: $O \times D \times S$.

Now, let's elaborate on this process with a case study. We'll look at a journal bearing as an example. To study this product, we may need an engineering drawing to identify possible assembly issues and evaluate the interference, clearance, and potential impact on the system.

We may also require a three-dimensional model of the product to understand the various stress levels and then figure out whether there will be any kind of stress intensity factor that will be on the higher side or maybe there will be some sort of crevice. So, we can figure out those things from using the 2D and three-dimensional models, and if we have prototypes available, that will be far better. So, now in this case, figuring out how different parts of the system fit together is our study, and then that is why we require 2D and 3D systems. And in this case, we are talking about the journal bearing, and then what is the journal as such? Everybody knows it, but just for completeness, I am just trying to write a few lines on that because a journal is made from a steel rod in this situation because it can be polymer or aluminium. But for completeness, we want to really define there is a steel rod that spins in the softer bearing, which means the bearing is softer; they do not have the same hardness. You remember that rolling element bearing that the hardness of all the rings is very high, and then hardness is far more than the kind of even the journal when on which we mount it. While in this case the bearings are softer, and then we say that bearing is a sacrificial element. Now, in this case, we understand that the journal must deal with external pressure and load. There may be a possibility we have mounted a gear, we mounted a bearing under the pulleys, we mounted several discs, and other items that will be loading the gear or loading the journal.

So, if I want to analyse the journal as such, we need to really account for those features. Similarly, the bearing, similarly, the lubrication. So, we really required what are the possibility values of the journal, what are the possible values of the bearing, and what are the possible values of the lubrication supply system. If we analyse this, then we can say we can develop RPN for the bearing for the journal for the lubrication system. Therefore, the journal bearing system constitutes a complete system.

Now, we have divided into three sub-sections: one is a journal, another is a is a bearing, and the third is a lubricant supply, and in each case we will have a separate RPN. It is not the same RPN for the system; we can do a ranking, and then we can say the highest number RPN will be addressed first. Once that is done, we can do a recalculation. So, in this case, when we do this kind of RPN calculation and then whatever the corrections based on our understanding, we go back and again calculate the RPN. So, it is an iterative procedure unless we come to the lesser number; we say we continuously iterate it.

So, that better and better solution can emerge again. We are not doing anything new; we are trying to extract the knowledge from my literature and trying to build everything on that. Now, whether we have experimental data, we have theoretical data, we have analytical data, we have some sort of software-related animation, or the calculation, those can be utilised in this case. Now, if the correction becomes more extensive and we are unable to accurately define the RPN after a certain number of iterations, then the process is complete, the FMEA is completed, and we can proceed with production. Now, let us take an example. This is the general bearing example.

Now, this is the engine bearing, and then there was some sort of cavitation. We showed that we have experimental results as well; we performed some results on the prototype that was available in our system.

In this system, we have a lubrication system and a shaft, which is fitted with a sleeve that allows us to adjust the dimensions of the journal bearing. There's also a lubrication supply system with a feed hole in the bearing, as shown. Journal bearings are a common topic, and most of you have likely studied them. Typically, there is convergence in the bearing where a full film thickness develops, followed by divergence.

In the divergent region, cavitation often occurs, which can lead to cavitation erosion, as seen in this case due to cavitation within the bearing. Now, we are analyzing a similar system, which is divided into three parts: the journal, the bearing, and the lubricant. Our goal is to evaluate the performance of the system or, if we intend to design a new system, determine the best approach to proceed.

One approach is to follow a data book and adhere strictly to what's written in the literature, making everything according to established guidelines. The other approach is to use Failure Mode and Effect Analysis (FMEA) to improve the shaft, bearing, and lubricant, and then implement a maintenance strategy based on a data-driven approach, continuously refining the system over time.

If we choose the second approach, we must focus on identifying potential failure modes. Each component, like the shaft or bearing, may experience more than one type of failure, and it's not always something we can predict from historical data or literature. When we research potential failures of a journal bearing, we might encounter numerous sources and different failure modes.

Given this, it's important to categorize these failures. If we can group similar types of failures together, this classification will help us manage and address them more effectively.

Now, what are these categories? We say that we already have studied something like abrasive wear. So, abrasive wear is a one-category adhesive wear; another category may be adhesive wear itself, which will have some sort of severity index. Abrasive wear will have a severity index, something like a very low coefficient of wear or a very high coefficient of wear or a or a medium coefficient of wear, but we try to bring some groups first. Now, in this case, there is a possibility of fatigue, where fatigue will be subsurface fatigue or surface fatigue. Surface fatigue we will have a separate method to detect, and the subsurface we have a separate method. We have also processed; we have done some sort of entity selection based on what kind of faults we have, and then we choose an appropriate entity method for that purpose. There is another one, which we call because of the humidity, there is a possibility that the corrosion will change the surface in a manner that the corrosion can be avoided when we choose a material that is better. Now, as we go for the corrosion-resistant material, it will turn out to be costlier.

If there is no humid environment and no risk of moisture, I may opt for a less expensive material. However, if moisture is a possibility, I would choose a more costly material. The choice completely depends on the specific situation, and the cost will vary accordingly.

Another issue to consider is frictional corrosion, which is similar to fretting corrosion, involving plastic deformation and fatigue fracture. Indentation occurs when a particle with sharp asperities causes an impact, leading to abrasive wear. While abrasive wear involves the removal of material, indentation results in grooves or depressions on the material's surface.

Additionally, issues can arise when geometries are not manufactured according to the required tolerances outlined in the drawings. This is why it's crucial to carefully review the drawings and ensure that manufacturing capabilities can meet the specified tolerances. For example, in journal bearings, there is typically very low clearance, and even slight variations can significantly affect performance.

Another potential problem is uneven wear, where some areas experience more wear than others, affecting overall system performance. To detect these issues, we can analyze the system's performance using techniques such as oil analysis or W analysis, and by inspecting the surfaces. For reference, the figure shows one journal without any fractures and another with visible fractures.

So, these are the extreme cases again we need to consider when we are considering FMEA we need to consider all the failures and what is the really severity quite possible finally, the arcane number for this kind of failure fractured surface of the shaft better not be almost negligible. So, then we will not consider that time, but initially we need to consider. Even as I mentioned, the aim of the course is only for fault detection and fault, but when we make a FMEA, which is a kind of bridge that brings knowledge from literature, and then on our own desktop or maybe our own system, that will be very useful. So, unless we have complete knowledge, we will not be able to make something very better, or maybe the very new one, which is better. Now let us say that is a brainstorming from related the journal or coming the brainstorm related to the bearings.

Now what we say is the bearing could fail because of the improper geometry. Again, same thing, non-uniform wear, or maybe here that in some sort of clearance is changing, then again it will impact the performance. Of course, this requires more detailed knowledge about the journal bearing. Now another possibility is that the foreign particles that are in the environment get embedded in the material because the material is generally soft material and spalling abrasive wear adhesive wear. So, whatever the categories we have a cap for the journal is more or less similar kind of categories being given to the bearing failure also. However, this may be more or this may be less than we can If there are chances, we assign the number of numbers, and then we can figure out what the chances are of the failure.

So, more or less the same kind of failure has been mentioned over here, and some failure has been shown here. You can see that access to frictional heat has burnt out the lubricant, and that is what is indicated over here. As I mentioned earlier, the uneven wear is evident in the edge loading, which could potentially be caused by a misaligned shaft with one side pointing downwards and the other upwards. So, there is a misalignment between the shaft's axis, or maybe the journal's axis, and the bearing, and this kind of failure will occur. There are two types of cracks present: a surface crack and a subsurface crack. There is some sort of pit formation, a more severe wear, and some not a hail that the axial cracks, while in this case circumferential cracks are also there. You are able to see the certain circumferential cracks on the surface.

And this is another one coming with one side, which means there was an excessive load, and that is why the bearing has only one side mark. Here there is excessive friction or maybe the loading, while in this case because the marks are the same, and then along the circumference and then the part of the circumference, and then the same features we are getting almost all the surface, this portion of the surface right. So, this is what we mentioned:

quite possible the load has gone on a higher side, while in this case friction has gone on a higher side. So, these are some sort of pictures in which I am trying to show the failures will be assigned some sort of rating, and then if we read literature like the ASM handbook, they provide in which situation this will happen. So, we need to really imagine those situations given numbers and then figure out in our system what is really dominating.

Another one is the potential failure related to the lubrication system. Lubrication system failure happens if the oil is getting leaked or is only partially supplied. It may be common that the pressure pump was not working properly or oil was supplied, but there was no filter resistance system, the filter got chocked, or maybe the filter was removed, and during the maintenance and if they did not put it back, there is a possibility. And then another one is a temperature control was not there we were supposed to supply the 40 degrees (40^0) temperature either it has gone on higher temperature or lower temperature. So, it is an unfavourable situation. Another possibility in this case is that the debris was not filtered. There is another possibility of contamination; it may be the moisture is a contamination; it can be supplied with moisture. So, these are the important aspects, and then we need to really give a rating based on all the kinds of failures that we can imagine, and then we say, in this case, the moisture in the lubricant really is a problem. Oxidation of the lubricant is also a problem.

And then another possibly another thing is that may be lubricant was used for the over more number of times. Every lubricant contains some form of additive, and over time, these additives will be consumed. Now, if all the additives have been fully utilized, it's possible that the larger chain has disrupted a smaller, potentially less significant chain, rendering it ineffective and failing to fulfil its intended function. So, that's what I've been saying: the lubricant additives are running out. So, the lubricant additives have been broken or maybe change in form and then may not be useful.

Another issue to consider is the incorrect selection of lubricant viscosity, as well as unfavorable working temperatures, both of which can lead to lubricant failure. As I previously mentioned, temperature plays a significant role. When evaluating lubricant failure and calculating the severity index or RPN for the lubricant, all these factors must be considered.

Additionally, while we may focus on three main components—lubricant, bearing, and journal—there is always the possibility of a fourth element being introduced into the system. Since the bearing subsystem is interconnected with other systems, it’s important to consider the larger context. We typically focus on the journal bearing, which involves three key components: lubricant, bearing, and journal, but we must also account for any other assemblies or super systems that may impact overall performance.

Now, I am looking at the super system in this case. So, there is another possibility that if there are rotating masses and that is causing some sort of balancing problem, or maybe that there is a nut and bolt connection, they are getting loosen, or maybe that suddenly they are taking and giving up a high load alignment, maybe and then some sort of seal is getting leaked. So, there is no failure of the lubricant as such, but the seal failed, which is why the leakage is happening. Therefore, there is a possibility. So, we also need to account for those. So, in this manner, system subsystems and supersystems can be accounted for, and we can provide some sort of ranking.

Now, what is if then? The question comes: can we really go ahead with an if then scenario? What are the results or effects if a certain failure mode happens? So, this is step number 3. We need to really list all potential effects related to each failure mode. Now, we are saying that each failure mode may have one or more possible effects; that is what we have already mentioned, and then these effects are important.

So, that we can really give some sort of CVOT index or RPN index as such. Now, this is a kind of table. Now, at this table also may vary from one literature to another literature. What we are giving the severity related to in the ranking. This is one kind of table, but as I mentioned, it can be slightly different from other literature.

What we are saying is number 1, rank number 1, that there is no effect. No effect of this severity on the bearing performance at all. It cannot be in the sense that there is no impact as such. Very slight number 2, slight number 3.

Now, coming to the hazardous major serious extreme. So, numbers are increasing. Now, here what is really happening initially: there is no high friction, no wear also. While slight and minor, we are assuming there is some sort of friction force. You know that the coefficient of friction for the general bearing is generally 0.0025. Now, if the friction coefficient increases naturally, that can go to the third level, fourth level, or fifth level.

Now, instead of not only in the friction, when the wear also starts coming, W.C. starts coming, and that is again documented in all the ASM handbook and the literature that says that if the friction as well as the wear occur, then we are going ahead with the number 6 onward. So, for less than 6, we say only friction. We are not getting any wear particles. There is no particle coming out because there is a clearance fit, and then lubricant is sufficient, and then it is running well.

If the rating is 6 or higher, the situation becomes alarming, and we must address it. Just as we assign a severity rating, we also assign ratings for occurrence and detection in a similar manner.
Now, let's say this particular failure has never occurred before. I may refer to literature and find documented failures related to journal bearings or lubricants. If no failures have ever been recorded, we can assign the lowest rating. However, if the certainty of failure is very high—almost 100%—then the occurrence rating would be closer to 10, though this extreme is rare. For comparison purposes, we usually assign a scale from 1 to 10.

In most cases, the occurrence rating will likely fall between 2 and 5. If the failure is happening occasionally, a lower number is appropriate, but if it's more frequent, especially with a ranking of 6 or higher, this signals a more serious issue that requires attention.

The same approach applies to detection. If we have robust sensors and software that can detect all types of failures, the detection rating will be low, reflecting that proven detection methods are available. However, if there is no detection method in place, or it is impossible to detect the fault, we assign the highest rating, indicating the difficulty of detection.

Then, in this situation, where there are more than 5, we can say that this is a problem for us; we will not be; we wish it was an alarming situation for us. We do not have good capabilities, or may be very slight capabilities, very slight capabilities, almost negligible capabilities. So, if that is a situation, better we work on the sensors to figure out how to detect the fault. And then, in this case, the failures are happening more frequently; naturally, we need to work out why this kind of failure is happening. So, this gives a kind of brain-storming good session that we need to figure out why the failures are happening or failures are not happening, then I will not worry about that failure.

Quite possible we may have 40 failures and the 5 failures are not happening at all in literature, but that initiation happened may be the in the team we thought this failure was also possible. We cannot deny we need to really list on those failures, and then based on the occurrence, or may be when we do a literature review, we find that there is no probability that not a single failure is listed; may be the people have done a lot of research and do not find any failure at all. So, I will give a 0 or possibly a 1 as my lowest ranking. And then once that is done, we try to calculate RPN because numbers have been decided for the CVOD, numbers have been decided for occurrence, and numbers have been detected by the detectability. Then we can find out that RPN is a CVOD for occurrence O and detection, and we can almost use it.

Let’s consider the example of a journal bearing. Several defects have been identified, such as abrasive wear. In this case, the severity (S) is rated at 4, the occurrence (O) at 3, and detection (D) is very easy, so we assign a detection rating of 1. Therefore, the Risk Priority Number (RPN) is calculated as 4 × 3 × 1, which equals 12.

Now, when we look at adhesive wear, detection is also not very difficult and can be identified relatively easily.So, when the CVOD level is 4, the occurrence is 4, and detection is easier. So, it is 16. The subsurface fatigue detection has also gone to the worst side. I can't really detect it; maybe we don't have good entity techniques available. So, then we will not be able to detect easily in this manner, or maybe we need to do offline or maybe CV once in a while kind of thing. So, that is a 7 number. Similarly, even surface-initiated cracks or fatigue, which start from a surface initiation, could also be attributed to this technique.

We have suppose, and then we will give a lesser number; otherwise, it is going on a higher side of 7 numbers.Similarly, we can easily detect moisture in lubricant or corrosion, but when it comes to fatigue fracture, we do not have the tools to really check it. Even the severity of the fatigue is really going to really disintegrate the part.

So, there will be problems. This issue pertains specifically to the journal. Now, one good point is that when we are going as a RPM, these are the just numbers. Now, the maximum number has reached something like 128. So, this is very severe from looking at the journal as such. Then there are 2 failures related to 126. So, if really I want to go ahead with a journal design, I will prefer more on indentation and fatigue, whether surface fatigue or subsurface fatigue.

Of course, this needs to be examined; 140 is also there. So, this is also the fatigue: all 3 fatigues—subsurface fatigue, surface fatigue, and then fatigue fracture, which is enhancement. So, these three, followed by indentation, will be given more emphasis. So, we can really start, of course. If somebody says now, we want to also include a 96 number, we also want to include a 72 number. There is a possibility thermal cracking is also possible, or maybe fatigue corrosion is also possible.

So, this is the basic approach we need to take. I’m using these numbers just to demonstrate the method, not to focus on precise accuracy. This is purely for illustration to show how the method can be applied.
Now, in the case of the journal bearing, it’s important to note that we don’t always observe uniform wear on the surface. Even when debris is present, it's difficult to determine whether the wear is uniform or non-uniform unless

we have adequate tools to properly assess it. The same challenge applies to fatigue corrosion, where obtaining reliable data can be tricky.

For example, subsurface fatigue may occur but detecting it can be challenging. However, if we have a good wear debris sensor, identifying this issue becomes easier, and we can assign a lower detection rating, such as 1. Similarly, with adhesive wear, if we can detect it easily, we would also assign a low rating, depending on the available tools and sensors.

We have gathered this information from existing literature. So, we can say and they have given 4 phone numbers because maybe they will they may not have this kind of capabilities, but in my lab we have a wear sensor that can really detect immediately what kind of debris is coming, and we can really classify that debris whether it is abrasive debris or adhesive debris because these are different in shape, and maybe the longer the debris will indicate clearly the cutting wear, and that will be on maybe the plate shape kind of a bigger size, and debris will say adhesive wear kind of thing. So, these are the possibilities. Now, in this case, this numbering may not go into micro detail, but it is quite possible that in this present lecture I am just trying to elaborate on how to use this method. This number may change based on the availability of the equipment sensors, so how are we going to detect it?

Another aspect to consider is the lubrication system. In the case of bearing seizure, for example, if the lubricant is not being supplied to the bearing, detection is still relatively straightforward. This is because it's easy to identify when the pump isn’t working, the oil isn’t flowing, or it isn’t reaching the bearing surface—all of which are clear signs that can be detected.

This is why most lubricant-related issues are typically assigned a low detection rating, like 1. However, this can vary depending on the situation. In cases where there is limited visibility and we cannot observe the bearing directly, the detection rating might increase. For components that are exposed and easily visible, such as those that can be checked with the naked eye, detection is simpler. On the other hand, for more complex assemblies—where the journal bearing subassembly is located centrally and cannot be easily accessed—detection becomes more challenging.

So, to really check it, we really require sophisticated tools. So, again, this number can change in the basic requirement. So, this is lubrication-related. Now, we are looking at other than these three factors that we have mentioned: very clearly unbalanced rotating mass, loose parts, some sort of misalignment, and accessor overload. Something has been given. So, this can be given as a number. Now, what is the next tool? To really put every table in a hierarchical order, maybe say the highest RPM should be on the top, and then the minimum RPM should be the bottom because we may reject the bottom one, and then we can say the top one. These are the things we should work on.

Now, let's consider the journal-related data. We observe the highest RPN values as 140, 128, 126, and 126. Based on our specific requirements, we can either focus on these high-priority failures or choose to ignore those with an RPN less than 100. Alternatively, we could decide to address any failure with an RPN greater than 50, depending on our needs.

For the bearing, we see even higher RPN values, such as 324, 294, 288, and 280. The reason these numbers are elevated is largely due to detection issues—failures within the bearing are difficult to detect, leading to higher detection scores. However, if better diagnostic tools were available, these numbers would decrease. From this analysis, we can conclude that the bearing is a critical component within the system, which consists of three main parts: the journal, the bearing, and the lubricant (and possibly a fourth, depending on the system setup). The bearing shows consistently higher RPN values, making it a sacrificial element that typically requires replacement every 6 months or 1 year. This is due to wear, dimensional reduction, and the resulting increased clearance, which affects performance.

Therefore, based on the analysis, we prioritize failure modes that present the greatest risk. Higher RPN values indicate higher risks associated with particular failures, and these require immediate attention. In the final step of FMEA, which is step 9, we focus on taking actions to eliminate or reduce high-risk failure modes. This step completes the FMEA process, emphasizing failure prevention.

In this case, we've highlighted up to 224 as a critical RPN value, with the highest numbers associated with failures like indentation, corrosion, plastic deformation, frictional corrosion, abrasive wear, and improper geometry. These issues demand priority for corrective action.

Even improper geometry is very common. We also made a number of bearings. If you look at all the bearings, there is a huge variation, and then performance keeps changing. That is why we need to give a good tolerance band, and then we say that the bearing may last for 5 years or the minimum will be the 5 years and the 5 plus years or something like that. So, if we go for better and better manufacturing more, and then we say that we can really establish the bearing life or may be component life much better manner. So, if we have good manufacturing capabilities, good measuring capabilities, and good detection capabilities, the component's survivability will be very high. If we do not have good manufacturing, good measurement, and good detection, then survivability is totally uncertain; it may work, it may not work right.

So, these are the things that need to work now. In this case, particularly the RPM for the journal and lubrication system, as we are saying, is really low. So, the journal is about a shaft, and the lubrication system is relatively low because a lubricant sensor was available. So, that is why the number was clear. One of the reasons is that the number has been lower or the reason been detection. We have a sensor; we are able to detect lubricant, but if we do not have a wear sensor, then we are not able to lubricate and find out what kind of debris. However, if we have a wear sensor, we can determine that the number will decrease, leading us to conclude that the RPM number will be reduced. Now, we say the special attention must be paid to the bearing characteristics, particularly the contact zone or the contact surface, and the measuring thing is a rough surface roughness, as low surface roughness will be the better option, and then geometry. Sometimes we go with a different kind of geometry, and then it will have an impact. Sometimes, we implement micro-grooves in the bearing, creating small indentations to manage dust or debris. Additionally, if the hardness of the bearing material is not appropriate, or if specific surface coatings are required, we may use bi-metallic or tri-metallic bearings designed to meet these needs. These approaches are possible depending on the requirements.

To summarize this lecture, I referred to the image from Lecture 4 to highlight the key points. We discussed Failure Mode and Effect Analysis (FMEA) using the journal bearing as an example. In the next lecture, I will focus on magnetic bearings and explore how we can improve system performance. While this case study served as a generalized overview, the next session will dive into more detail about magnetic bearings and their potential for system enhancement.

In this lecture, we examined 40 potential failure modes for the journal bearing system, calculated the RPN values, and determined that the highest RPN failures should be prioritized for immediate attention, while lower RPN values are still desirable but can be addressed later.

And then what we realise in a bearing indentation is that corrosion, plastic deformation, adhesive wear, abrasion wear, and poor manufacturability are the possible. So, when we are thinking about the bearing design, bearing material selection, or bearing manufacture, this kind of failure mode will be very important. Now, we need to think about the remedial action also. So, that is a possible solution that can be given as such. Now, here is the possible solution. The authors mentioned that because the corrosion is really happening, indentation is also happening.

So, that there is a need to change the lubricant, lubricant should have an anti-wear. If the anti-wear properties have been given to the lubricant or maybe the good soft coating has been given to the bearing surface, then indentation will reduce. Then another one is that anti-wear and then antioxidant air where additives have been added, then even the corrosion will reduce, the rusting will reduce. And plastic deformation is also happening. So, again, anti-wear additives will be helpful, and adhesive wear can also reduce the additive wear and abrasive wear.

So, this is the good solution for anti-wear additives. Of course, how much percentage of the additive will be used—that is the detail analysis. Another one is the possibility that the particles are coming out and then they should not really allow an increase in wear rate significantly. So, this kind of surface can be used, as I mentioned the groove arrangement, whether these grooves are really acting as the dust pins. So, this is not especially made; you can look at the thing only that bearing that has been made; it has been finished in a manner. So, that all asperities are cut out completely, and then whatever the values are retained, we are not improving the overall surface roughness significantly, but we are removing the asperities as such.

And as for the many times in a bearing operation we have running in time where the most of the asperities will be removed and then when the values will be retained. Another possible solution is to focus on precise manufacturing, particularly in the contact zone. If we can identify from the beginning the exact area where the bearing will make contact with the shaft or journal, and give maximum attention to that zone—whether it's a 90-degree segment or something smaller—rather than focusing on the entire 360-degree surface of the bearing, we can significantly improve performance. Even if only a 90-degree section is carefully manufactured, it can greatly reduce bearing wear and provide excellent results.

This concludes the case study. Thank you for your time. In my next lecture, we will cover magnetic bearings in more detail, with specific examples and data. Thank you.