Cathodic Protection Engineering
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Lecture – 01
Cathodic protection engineering:
Introduction to the course and understanding corrosion

Hi, in today's lecture on Cathodic Protection Engineering, we shall start with Introducing the course content so as to understand what will be the coverage of this course. In the same lecture, we will also talk about briefly the understanding of corrosion principles because understanding corrosion principles is very important in cathodic protection engineering.

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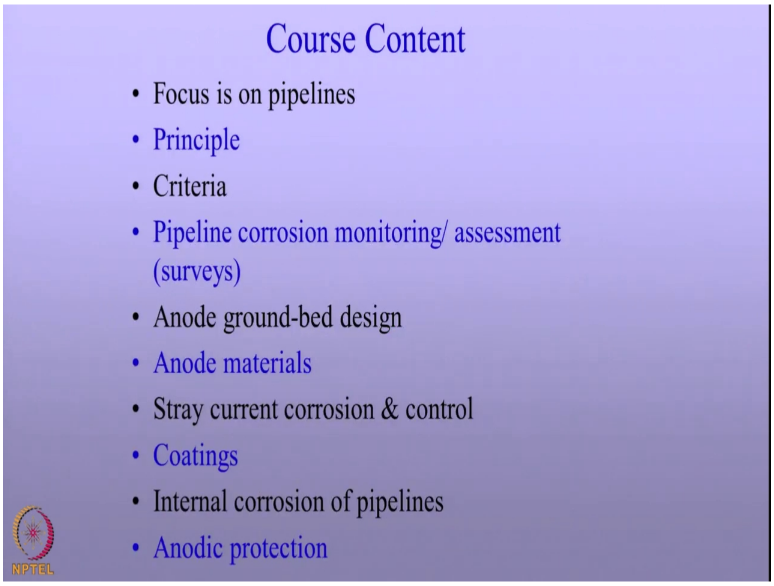

These are the course content. We will first of all talk about the pipelines. The pipelines are the most important thing in any country as it transports large chemicals and gases and oil and so on. So, the focus is given to pipelines.

With respect to cathodic protection engineering, we will emphasize more on principles so that you get a clarity in tackling the real problems. The course will consist of cathodic protection criteria, then we will cover the pipeline corrosion monitoring and assessment surveys. Anode ground bed design is a very important one in the cathodic protection engineering of buried structures.

We will also talk about the anode materials followed by that the stray current corrosion and its control. Stray current corrosion is a very important aspect of buried structures, the buried structures are coated. So, we will talk about the coatings.

It is also important to know the internal corrosion of pipelines because that also affect the structural integrity of the pipelines. In some cases, anodic protection is carried out. So, we will cover briefly the anodic protection of tanks.

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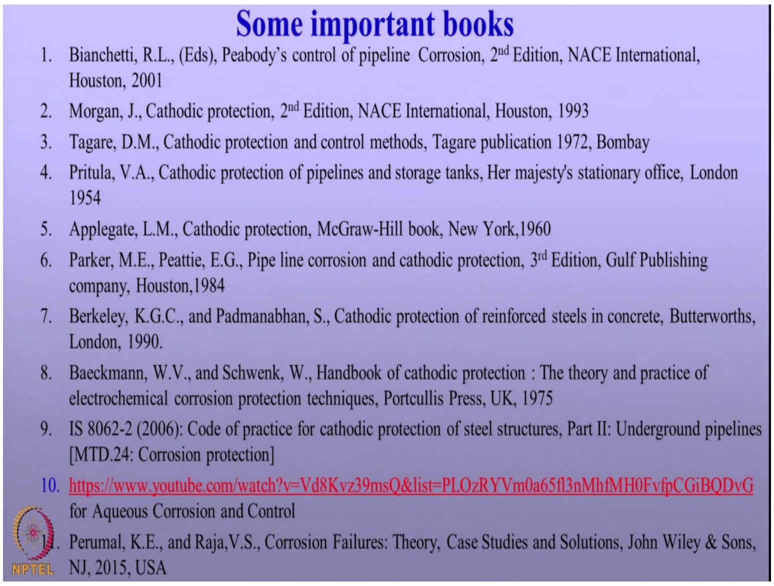

I listed here some books which are of relevance and what you see here is the top the book 1 mainly focuses on the pipeline corrosion. It gives you a lot of practical insight into the corrosion. I would recommend this book. If you like to go for understanding the fundamentals, basics of cathodic protection, the second book by Morgan on Cathodic protection is very useful. The book by Tagare gives you practical insight into his own experience of corrosion control in India. And, I will also recommend you to look at the course in aqueous corrosion control.

I think in understanding of a aqueous correlation control is very essential because cathodic protection involves understanding of corrosion control. For those who have already taken a course on corrosion control, it is not required.

And, again if you want to have some insight into corrosion I will also recommend this book by Perumal and myself on Corrosion Failures, there are first two chapters which covers the basic aspect of corrosion.

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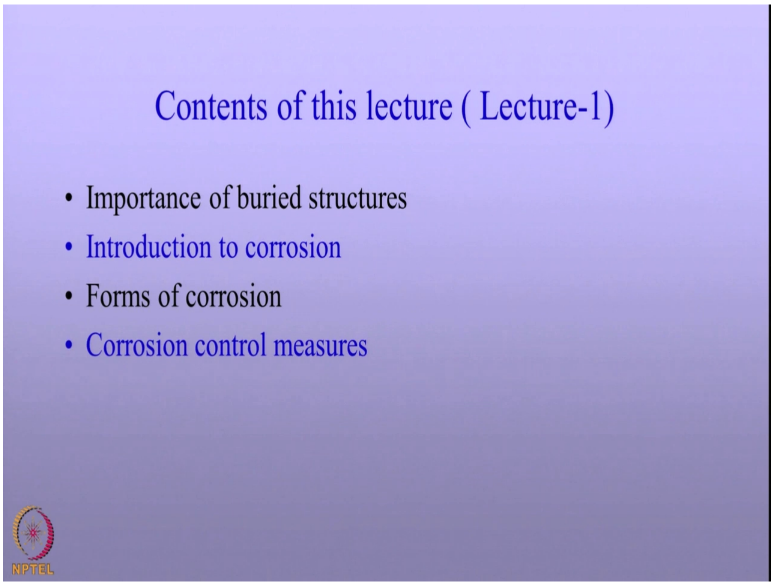

The content of this lecture, today: I will be talking about the importance of the buried structures, the buried engineering structures, why you should be concerned about it actually, how important they are. We shall look at briefly introduction to corrosion which is again aqueous corrosion which is relevant to pipelines to storage tanks and those offshore structures where aqueous corrosion becomes very important.

Briefly we touch upon the various forms of corrosion that these structures are going to suffer and then we talk about the corrosion control measures. So, these are the four aspects that we will be covering in today's lecture.

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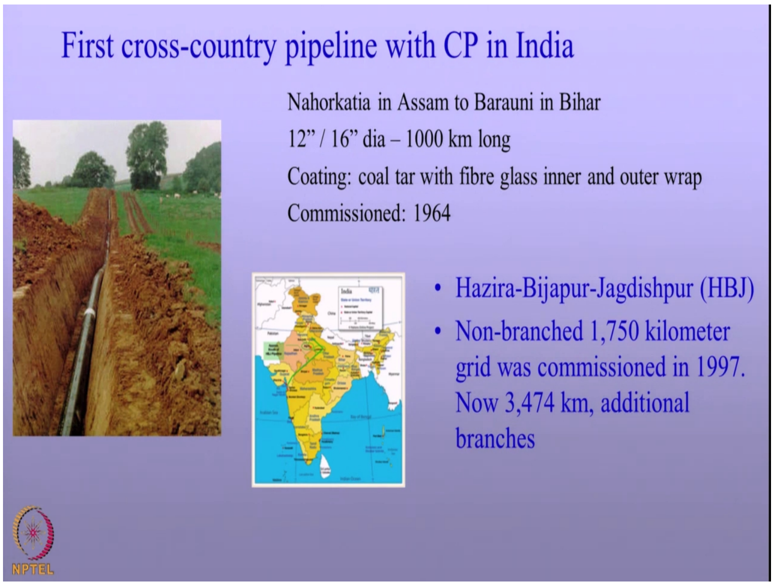

If you look at the pipeline in the country, the first pipeline was established in the year 1964 ok. It was in Nahorkatia in Assam to Barauni in Bihar. It was about 1000 kilometer long pipeline. It was coated with coal tar with fiberglass inner and outer wrap.

And, sometime in 1997 you had another pipeline between Hazira and Jagdishpur it is going towards Bijapur. It is famously called as HPJ pipeline. It was 1750 kilometers long pipeline subsequently there are additional branches added to that and now, it is close to 3500 kilometer long pipelines. What is shown here is the route of the pipeline starting from Hazira to Jagdishpur.

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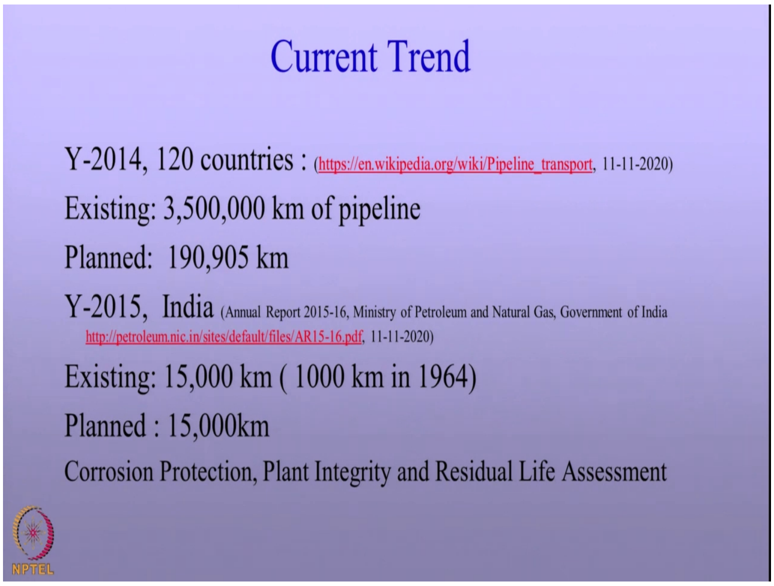

If you look at the current trend, the pipeline is going across the globe. If you look at this, the 2004 data across 120 countries, we have about 3.5 million kilometer long pipelines and in 2014, again they have planned for another 1,90,000 kilometer long pipelines.

With respect to India we can see that in the year 2015, if you look at the annual report of 2015–16 by the Ministry of Petroleum and Natural Gas, Government of India, the existing pipeline is about 15,000 kilometers. Notice that there is 15 times increase in the pipeline length as compared to what we had in 1964. Not only that, currently the government is planning to implement 15,000 kilometer long pipelines.

So, very interestingly if you look at the report, the report also talks about corrosion protection, pipeline integrity and residual life assessment. So, that means, the corrosion of these buried pipelines are considered to be very important in order that they serve without any failures. So, the pipelines are very important, buried structures are very important.

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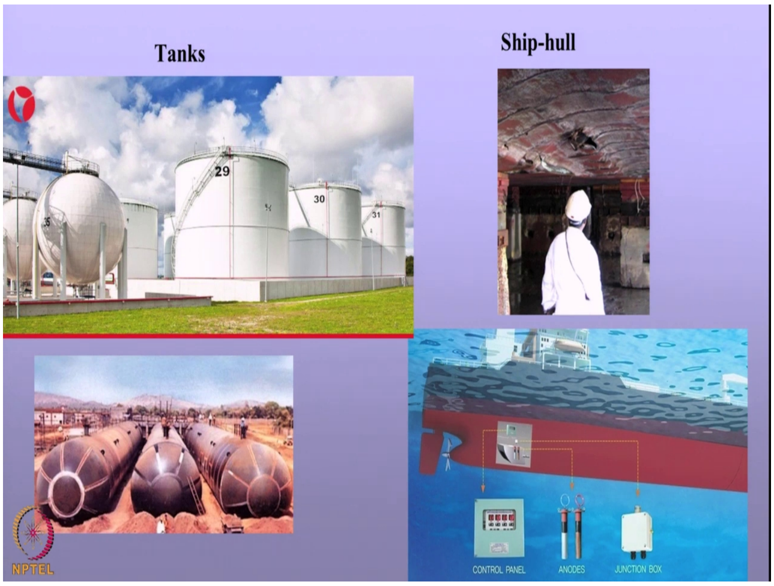

The cathodic protection is also important in another area wherein you have tanks which are kept over the earth little bit buried there actually, they are in contact with the soil. You also have mounded bullet us used for storing, I would say gases or liquids, which are inflammable safely.

You also have corrosion of ship hulls and offshore structures. So, the cathodic protection is very important over a range of structures and so, we need to understand how effectively the cathodic protection engineering can be implemented for all the structures.

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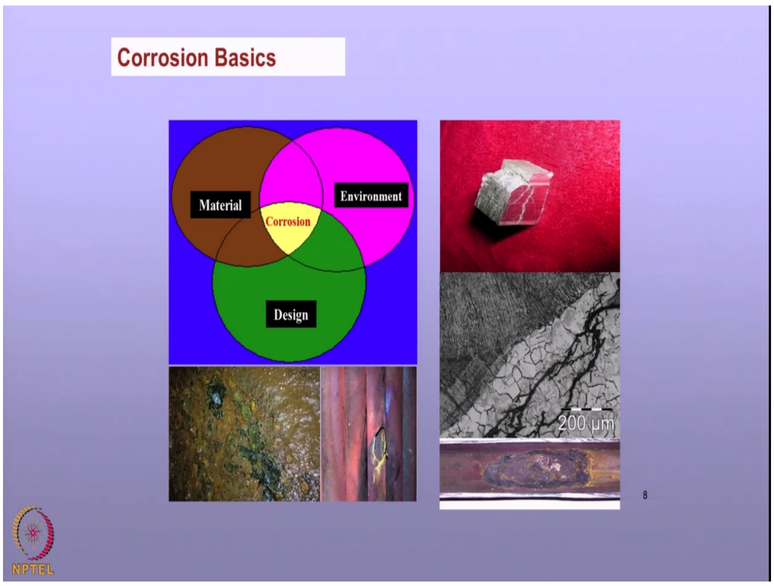

Let me start with the corrosion basics. The corrosion involves, obviously, a material that we talk about, then we have an environment that is coming in contact with the material, but these materials are also subjected to various structural conditions you know. They may be operating loads, tensile, fatigue and so on so forth.

So, all this lead to the corrosion of the materials now. The corrosion materials can be a corrosion uniform may be localized something that you see here in the boiler tubes here or there can be cracks. The corrosion can be very complex, but all we need is a corrosive environment that should be exposed to the you know to materials actually to lead to corrosion.

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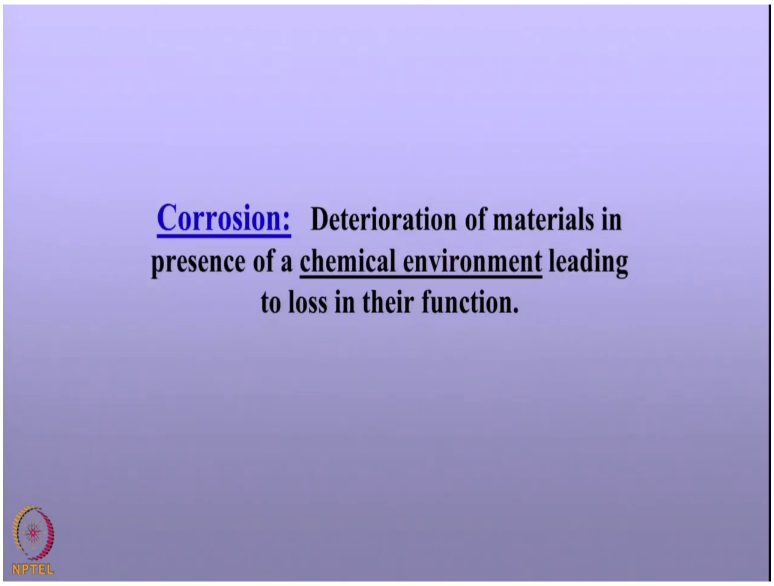

To define corrosion, it is the deterioration of materials in presence of a chemical environment leading to loss in their functions. I would like to emphasize that the failure is due to chemical environment that are exposed to the materials actually.

The failure can happen even otherwise there can be mechanical overall failures, that can be gamma radiation, there can be fire, the structure can fail due to various reasons; when you talk about corrosion it is a chemical environment that leads to the corrosion failures. When I say failure, it is not necessarily the structural integrity loss, it can also mean loss in the function of the desired component.

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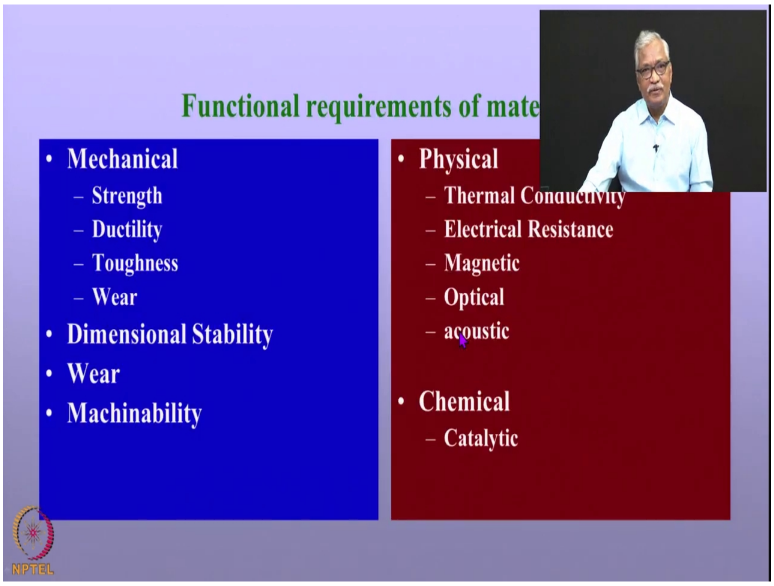

Now, corrosion becomes very important basically because the engineers select materials based on properties that are listed here. On the left side you see that the properties related to mechanical, strength, ductility, toughness where these are the properties which are mainly determining the selection of material.

In addition to that, you also look at the dimensional stability, the wear, the machinability, it also becomes important in some cases. In other cases you could be physical properties like thermal, electrical, magnetic, optical, acoustic for example, or we are talking about a chemical reactor, it could be a catalytic property of the material actually.

So, the selection of materials for applications mainly depends upon the functions, what functions do they perform. So, corrosion is not the main reason why you select material. So, that means these materials not necessarily possess the corrosion resistant properties and therefore, you need to impart corrosion to this material.

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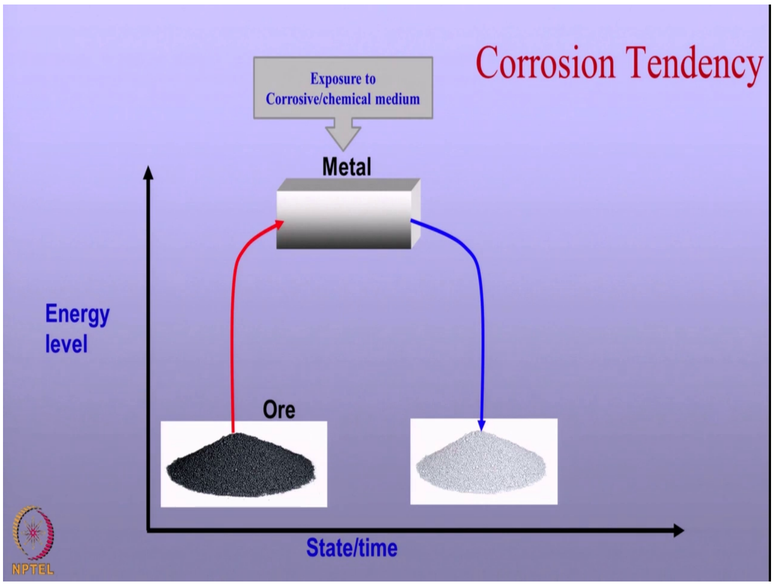

So, let us look at why the metal should fail. What are the reasons for that? The reason for that is very simple. Most of the engineering metals that we deal with may be a steel, stainless steel or titanium, magnesium these are their own alloys. They are all extracted from their own ores. They are in earth crust we extract it by applying energy to it actually.

You provide energy to convert ores into metal; that means, they are going from a low energy state to high energy state and on exposure to the environment, corrosive environment for example, they react and they go back to the same state from which they have come from, because the energy for such a transition from metal to the corrosion product is negative. The energy is extracted from this. The energy is freely available so that the reaction occurs spontaneously.

So, this is about the pictorial view of explaining why the corrosion really takes place.

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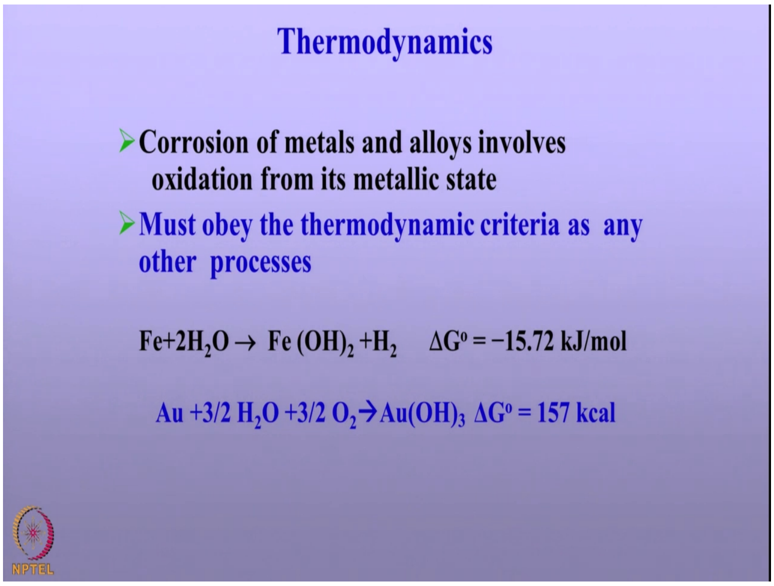

We can look at thermodynamics. You can explain how the corrosion can really occur. What I given here is a chemical reaction between iron and water giving rise to iron hydroxide and also liberates hydrogen in the process ok. The standard Gibbs free energy change for the reaction is minus 15.72 kilo Joules per mole.

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2 \qquad \Delta G° = -15.72\ KJ/mol$$

So, that means, if the iron has to corrode to form iron hydroxide and liberate hydrogen the Gibb’s free energy for that is negative and so, the corrosion becomes very spontaneous. You take the example of gold which is considered to be noble. We all know gold does not really corrode when exposed to water or to many of the chemical environments actually.

The reason being is very simple if gold has to react with water and the oxygen that is dissolved in the water actually, you see the standard free energy change for that is positive; that means, the corrosion does not really occur. So, corrosion is possible or spontaneous corrosion is possible because the Gibb’s free energy change for that is negative.

So, that is the reason why the most metals that we deal with suffered corrosion process. This is the thermodynamic reason why the metals really undergo corrosion.

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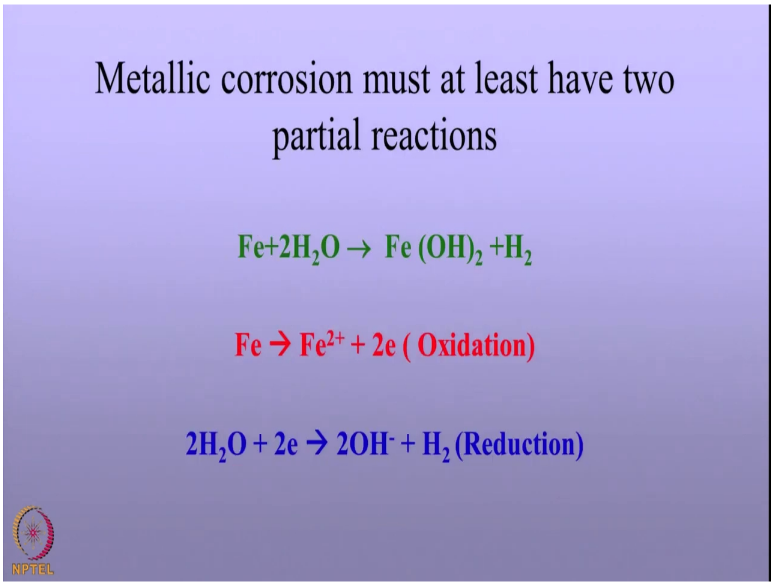

Let us go further into that to understand what really happening in a typical corrosion process. Let us take an example of again iron right, iron reacts with water and forms iron hydroxide and hydrogen here. If you look at very closely what really happens is the iron is getting oxidized to Fe^{2+} and you have 2 electrons that are liberated during the process and we call this an oxidation process.

And, the 2 electrons so liberated reacts with water and then forms hydroxide and liberates hydrogen. So, this is called is a reduction reaction. So, any corrosion process would consist of an oxidation reaction and a reduction reaction, without any of this the corrosion will not proceed. I will give this example in a more you know illustrative way.

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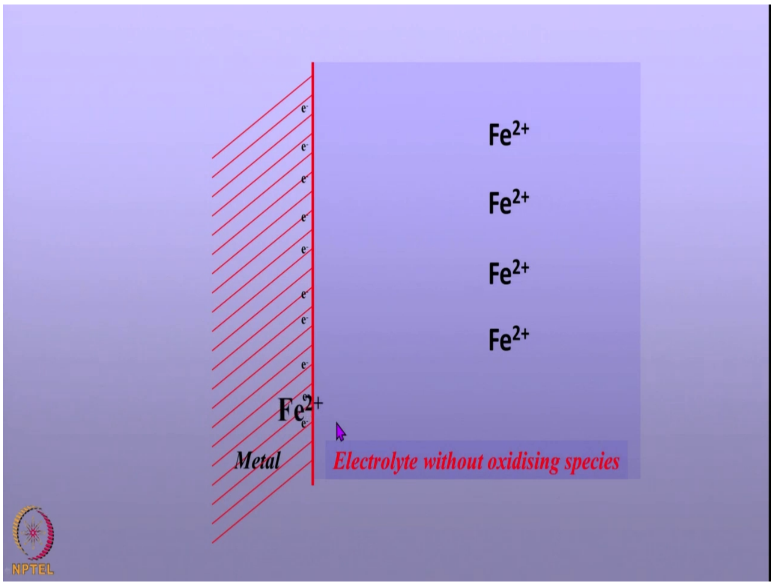

Let us take an example, here iron is exposed to the environment, right and what happens is the ion gets oxidized and the electrons so released they are all on the metal surface. In this case the metal becomes negatively charged and then the reaction does not continue right.

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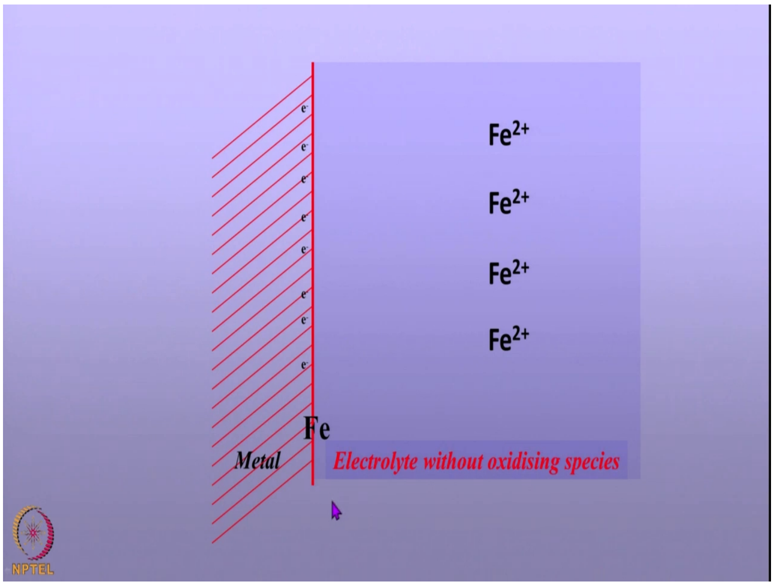

The reaction does not continue actually here ok. I again repeat here this one you see this the as ion is getting oxidized your surface is getting enriched with electrons. Because the surface is getting enriched with electrons now the reaction cannot proceed endlessly and so, the reaction becomes you know it stops again here.

So, in order that the reaction to continue, these electrons have to be removed ok. If the metal has got more electrons no way the reaction will proceed. In fact, this is very important when you talk about cathodic protection. We will see how we stop cathodic protection in practice.

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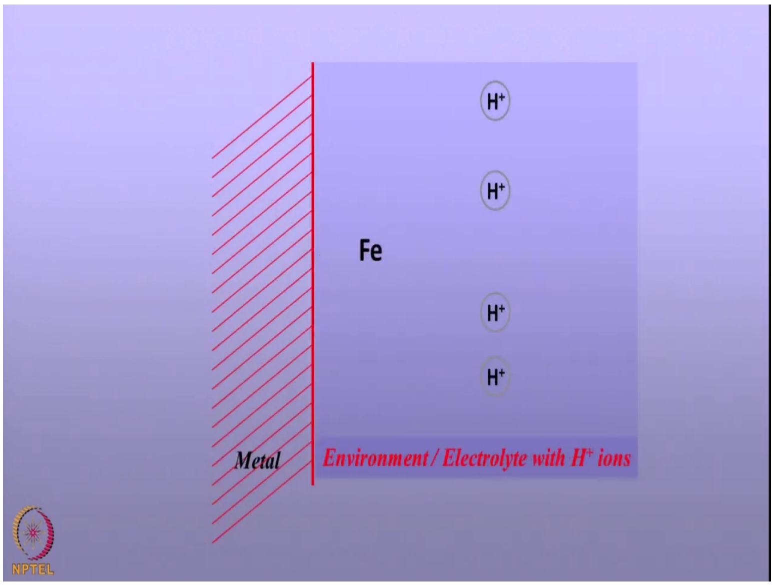

If I have to go to ensure that the metal corrodes at all so, what I should do? There is a metal there is an environment now, the iron releases electrons.

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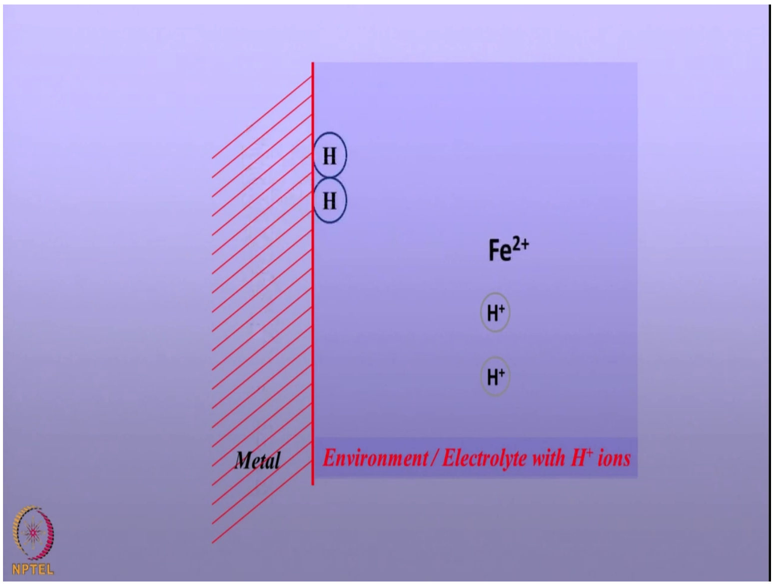

The electrons are taken by hydrogen.

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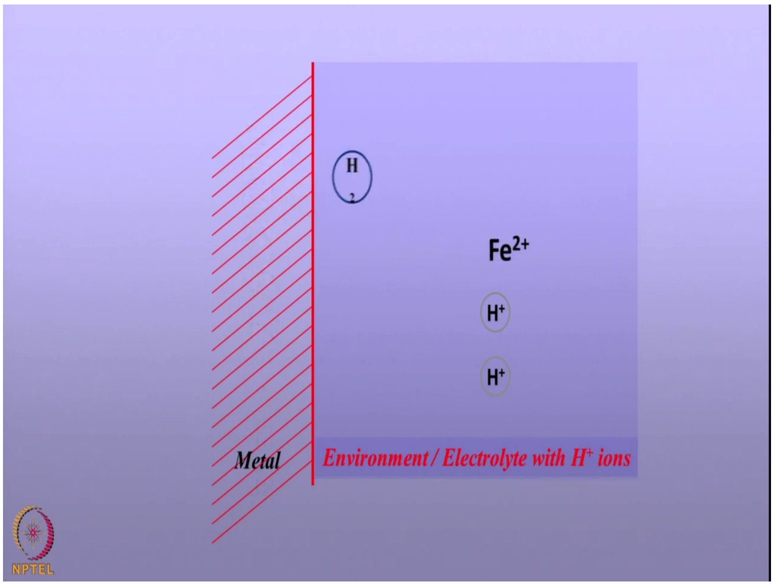

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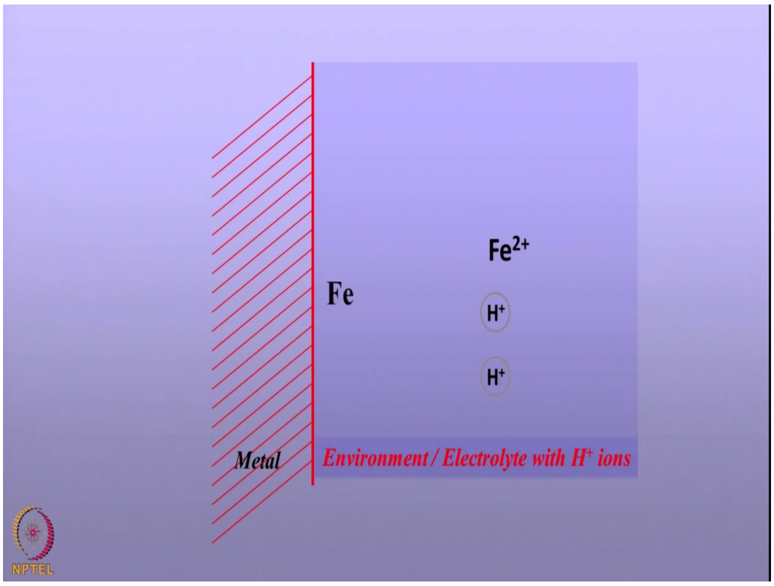

Now, you see that hydrogen gas gets evolved; that means, the metal surface remains neutral all the time ok and, corrosion continues.

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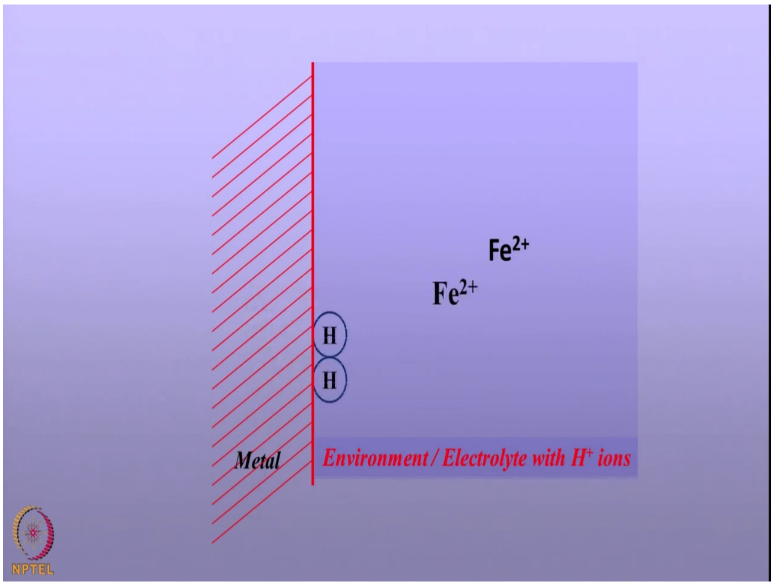

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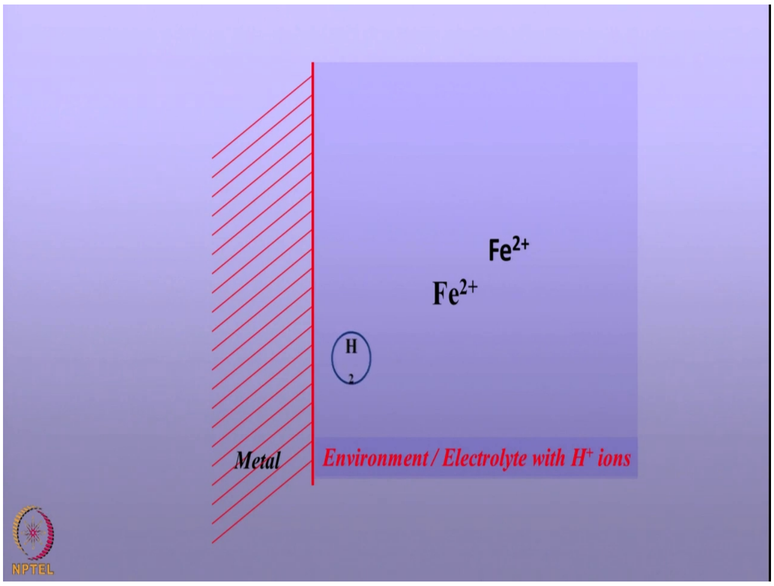

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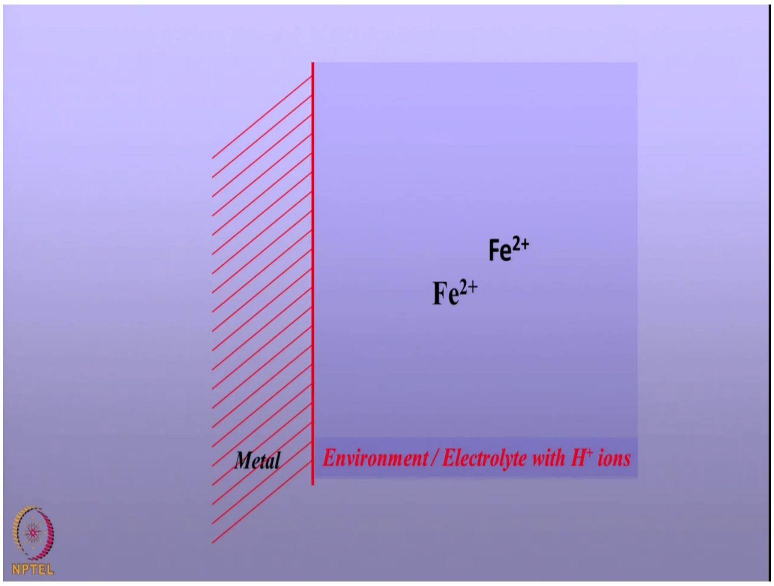

So, one of the important criteria for corrosion to occur is the metal oxidation should be followed by a reduction process so that the electron so released by the oxidation of the metal is absorbed by the environment actually ok. So, corrosion involves metal as well as the environment.

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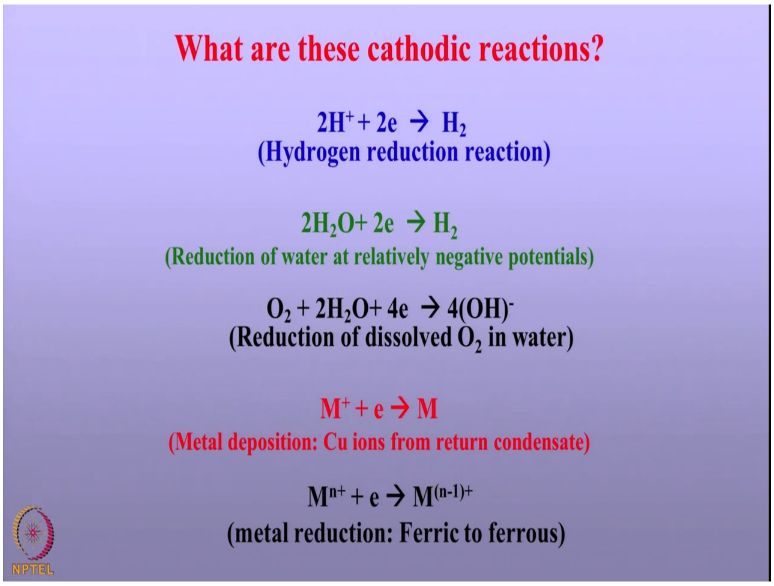

Now, the thing that we need to know is that what are these species that are responsible for corrosion that we should be knowing because if you know them, then we know how do we really stop the corrosion process. I have listed here a few examples. You can have more examples here actually, you can have more cases. What I listed here are the prominent ones.

The one that is given on the top what you see here is H^+ combining with the two electrons giving rise to hydrogen. Where from these electrons come? These electrons they come from the oxidation of the metal, right. So, it releases hydrogen here. So, that is one cathodic reaction, it's a reduction process.

There can be simply the electron reduces the water you do not, and it is a direct reduction process giving rise to hydrogen evolution in the corrosion process at all actually. That is possible once the potential is relatively negative that happens in some cases in some metals.

It is also possible that the water has a dissolved oxygen content right you have this and dissolved oxygen present in the water, takes away the electrons and also combines with water and forms hydroxyl ions. This could be yet another reduction process ok.

If you consider generally these three are the predominant reactions responsible for corrosion of metals. However, there are other reactions such as noble metal ions present in the corrosive environment can also take away electrons and give rise to the metallic you know it is a metal this also can happen in some cases they do happen at all.

And, there are cases like you have a really oxidizers, a cations of high redox potentials can also take electrons and form a reduced species, is responsible for corrosion. And, it is very important that we understand that what are the possible cathodic reactions occurring in a given environment, so that we can control the corrosion of metals.

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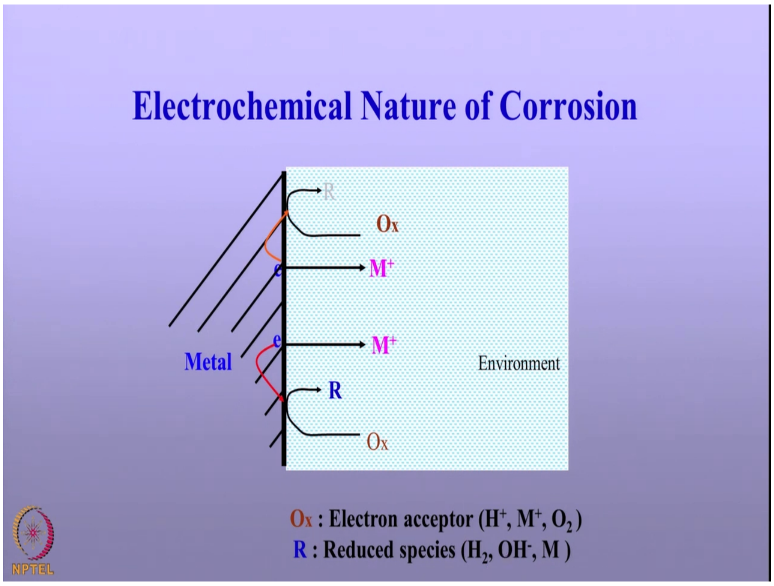

Now, I would again summarize this actually into that you know form I have for example, I have a metal is coming in contact with the environment actually and metal gets oxidized and releases electrons. And, these electrons are absorbed by the various species present in the environment; the various species means they should be able to take away the electrons and become reduced species ok.

So, these all the ones, for example, you know H^+ can get reduced to hydrogen and metal ions can get reduced to metal here; oxygen can get reduced to hydroxide these are all possible in corrosion actually.

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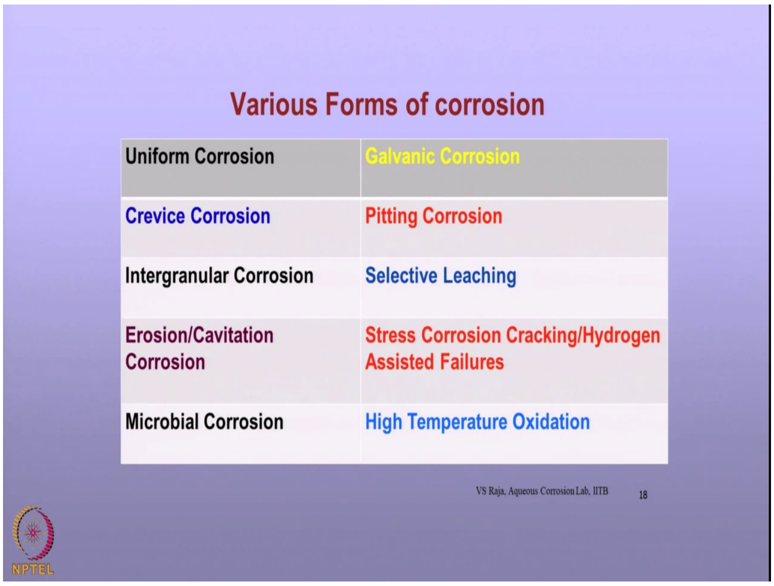

Now, corrosion is really complex. This is what I have shown here is a simple oxidation reduction reaction involving corrosion, but engineering structures are very complex. You make them into different shapes and you can use sometimes bimetals, sometimes you weld them; that means, you rise at temperatures for example, sometimes you have an environment consists of aggressive species.

So, the so called oxidation-reduction reactions occurring on the metal can cause various forms of localized corrosions which are listed here; except the one as I have listed here the top one that is uniform corrosion all other things are all some sort of localized corrosions. When I say localized corrosion; that means, the cathodic reaction and the anodic reaction is spatially located, they do not change with respect to time.

In a uniform corrosion the oxidation and the reduction reactions keep shifting with the space and leads to uniform corrosion. When you talk about all other forms of corrosion the anodes and cathode sides are fixed to the least to the various forms of corrosion actually.

They are like galvanic corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, selective leaching, erosion cavitation corrosion, stress corrosion cracking, hydrogen assisted failures, microbial corrosion, high temperature oxidation. These are I would say major forms of corrosion, there can be you know subdivision of this you can we can always you know see that it really happening.

For example, hydrogen assisted failures you can have maybe two–three forms of hydrogen assisted failures may be hydrogen blistering, hydrogen embitterment for example, decarburization. So, there are you know sub mechanisms how these species really will interact to lead to corrosion.

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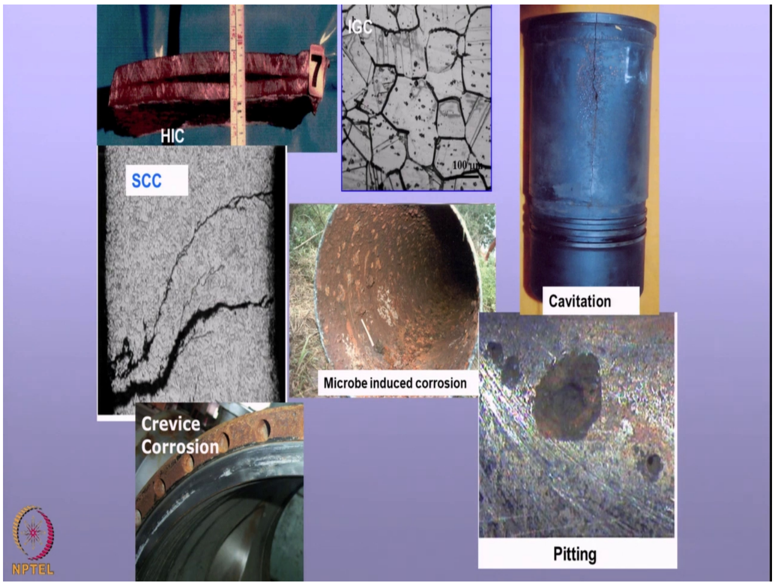

Now, I have given you know how these various forms of corrosion will look like actually. What I shown here is hydrogen induced cracking occurred in a steel structure. You know what happens is on the surface the corrosion occurs for example, and hydrogen is liberated, a part of hydrogen gets into this metal and then they go and get accumulated, builds up pressure, causing the mechanical damage.

So, what you see here is called as hydrogen induced failure happened in one of the refineries actually. You can also have stress corrosion cracking, you apply a stress and metal fails you could fail even below the yield strength of the metal. So, this is a stress crossing cracking of stainless steels you see that branching of cracks taking place.

But, please notice that in all these cases the crack starts from the surface because the surface is where you have the environment coming in contact with this. You have a stress operating environment interacting on the surface that leads to a cracking of metals.

You can have a crevice corrosion what is shown here for example, look at this area ok. This area is a crevice corrosion taking place. It is a flange joint and this is a shell of a heat exchanger. It is weld overlays of 2507 stainless steel was applied onto this steel structure and sea water was being used.

You notice that the normal corrosion is very very less. You do not even see a pitting, but you see a crevice corrosion where the gasket was located actually. So, this is one form of corrosion problem at that location the anode is fixed. That is the form of problem you get it.

You weld a stainless steels, you find that in the heat affected zone of stainless steels especially if the stainless steel has got higher amount of carbon, you find the grain boundaries of the stainless steel get sensitized they become weaker and there is going to be chromium depletion. And so, the grain boundaries are selectively attacked leading to intergranular corrosion of stainless steels.

It can be microbial corrosion microbes are present in the environment actually and they can cause corrosion. We will see this microbial corrosion because it is one of the most important damaging mechanism for underground pipelines and storage tanks. We will spend some time later on microbial corrosion.

We also have a cavitation damage. The cavitation damage can happen in just not on the pipelines. For example, the pumping systems you have let us say impellers ok. The impellers because of hydrodynamic pressure difference you can have bubble formation and then and you have implosion of these bubbles and that leads to the transfer of mechanical damage and so, leads to the cracking of the structures.

Can have a pitting corrosion that is happening on the stainless steel here, this is due to chloride attack that happens on the stainless steels.

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Now, we have seen, you know, very very briefly what the corrosion is. The corrosion is nothing but the oxidation of the metal and then there is reduction of the environment that we deal with actually. We also saw that the corrosion can be very very very complex.

There are ways to prevent corrosion. What I listed here on the left side is this there are several methods. I put cathode protection on the top and, but not necessarily that is applicable everywhere actually, but it is one of the most important methods of preventing metallic corrosion.

However, there are other methods of preventing corrosion. It could be corrosion inhibitor, protective coatings you have, you also select materials properly and then design becomes another important way of controlling corrosion. It is also necessary to mention that we can have a combination of prevention methods.

A cathodic protection can go along with protective coatings. It is very economical actually. In fact, you see that for cathodic protection to be very efficient, coating is very very desirable, without that the cathodic protection is going to be ineffective actually. Similarly, you can talk about corrosion inhibitors can happen along with the immediate selection.

The criteria for that is the cost has to come down. So, that is the basic criteria, you can have more than one method, but from the point of view of engineering using as many methods are possible to bring down the cost of corrosion control. It is not sufficient to have preventive methods; you should also have strategies and practices, so that we can implement these preventive measures without which corrosion control is not possible.

The most effective way of preventing corrosion is to start at the design board, that itself you decide what material to choose; should we go for welding or not, should we go for cathodic protection or not. All this start with design board, so that you have effective control of corrosion during operation and even maintenance of that actually.

The strategy should also involve fabrication – whether you are going to go for simply flange joint or you are going to go for welding. You should take care during commissioning ok. There are cases where during commissioning not adequate care was taken structures led to corrosion.

Operation of course, you suspected because the environments are operating there are other structural factors like stresses are operating in all the thing the corrosion can really occur. Inspection, maintenance or integral part of corrosion control in the industries actually.

Above all it is very important to educate the personnel actually because corrosion in this area it is not part of a normal curriculum for many of the engineering courses. So, it is very important that educate the people in corrosion control and as well as the management.

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Now, before I end, I just want to give some perspective about how you can improve the performance of an equipment, extend the life of the equipment actually. These are the factors

I listed here again these are prominent factors ok, but there are many more one would learn as you get in the field. They are, the design, material construction, specifications are very important. I have seen that in industries people sometime do not differentiate between martensitic steel and martensitic stainless steels surprising corrosion problems and you do a fabrication and quality control. It is easier to weld steel than a stainless steel from the corrosion point of view, it makes lot more difference.

Operation, maintenance and of course, the environmental conditions; how do you really maintain the environment in pipeline corrosion, the internal corrosion of pipelines for example, will talk about how do you really monitor them, so that corrosion control can be significantly improved.

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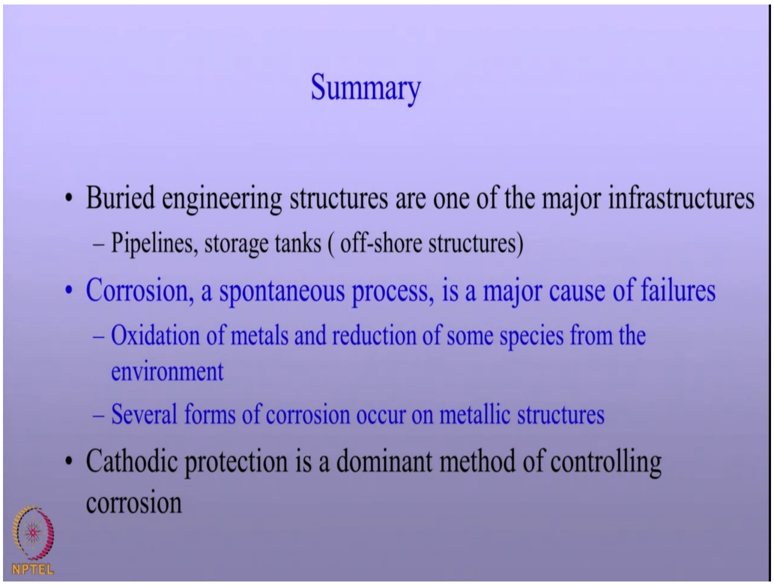

So, what I would like to do is, to summarize what I have seen before I close this topic lecture. We have seen that earlier in India, for example, the pipelines have grown significantly over the years and these pipelines most of them are buried in the soil.

When they are buried in the soil and they suffer significant corrosion, storage tanks are very important for many of the industries actually, if you go to oil and gas industries and you see that there are huge tanks; inflammable liquids are stored actually and they suffer corrosion due to soil. Offshore structures you do not have to mention because offshore structures are exposed to sea water which is very very corrosive.

So, these structures are suffering corrosion extensively and they are very important for any nation. Cathodic protection is the best way to prevent corrosion, we will see later. What also you have seen is that corrosion is a very spontaneous process; you do not have to supply energy for corrosion ok. It is very spontaneous process.

And, for most engineering metals corrosion is very spontaneous they occur. If they do not corrode you get rather surprised why they do not really corrode at all. We also seen that corrosion of metals involve two reactions ok. One is an oxidation, other is reduction. If you can control either reduction or you can control oxidation, you can control corrosion actually or you can control both of course, you can do that.

Corrosion can be complex, there are several forms of corrosion occurs in metallic structures which I am not going to discuss here in detail, we have done it in another course ok. I will of course, broadly touch upon the various forms of corrosion you know broadly some you know related to steels in relation to pipelines we will talk about, but that does not of course, cover all forms of corrosion at all.

And, with this complex you know corrosion thing that happening in long pipelines, cathodic protection is a dominant method of controlling corrosion, that will we will see in this course. I do hope that you will have a brief account of the importance of the buried engineering structures, the corrosion problems these structures really face. And, we will see later how the cathodic protection can be effective in controlling corrosion of these structures.

Thank you.