Cathodic Protection Engineering
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Lecture – 10
Cathodic protection engineering: Worked out examples

Welcome to the course on Cathodic Protection Engineering. We have seen the concepts of Cathodic protection engineering in relation to electrochemistry and the electrical engineering.

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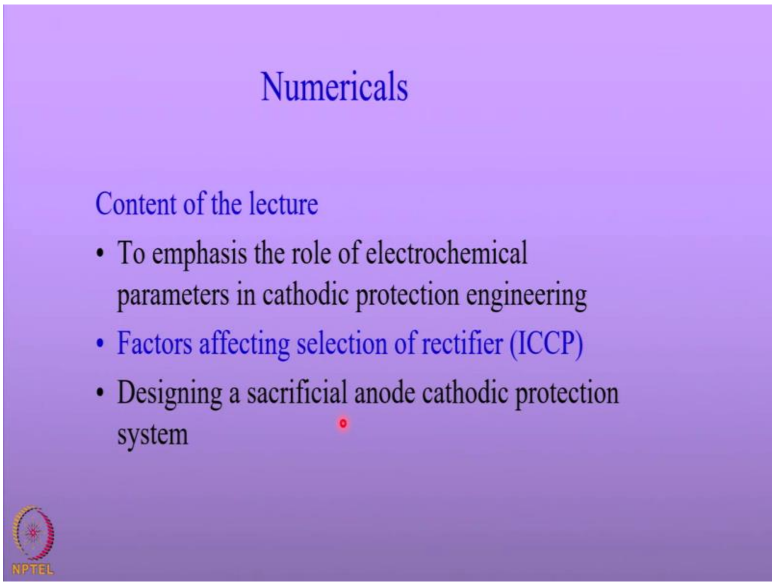

Today we look at some of the numerical that will enable us to understand this concept better; the talk will consist of the following. The first two problems in today we will talk about how the electrochemical parameters would decide the cathodic protection engineering viability. These are today's contents of the lecture we will first look at the electrochemical concepts in relation to cathodic protection engineering.

Then we will move on to the application of the electrical engineering concepts in the selection of rectifier for cathodic protection engineering, then we move on to the design of cathodic protection system using sacrificial anodes.

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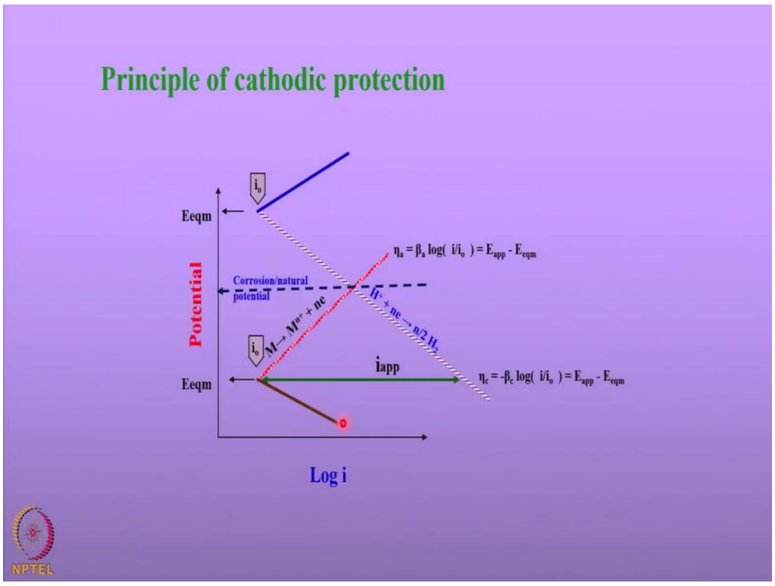

Let me first start with the Principles of Cathodic Protection engineering. We have seen this slide in one of the earlier lectures, we know that when you expose a metallic structure in a soil or any corrosive environment it attains a corrosion potential in the parlance of cathodic protection engineering a natural potentials that is given by this diagram here.

Corresponding to that particular potentials the metal suffers a corrosion given by the corrosion current density in this particular Evans diagram. Let us look at the first concept which is cathodic protection engineering in relation to the electrochemistry, this is an Evans diagram you have seen before that is between the potential and the log current density for a corrosion reaction.

The corrosion reaction involves the anodic dissolution of the metal and a cathodic reaction occurring on the metallic surfaces. So, when the metal is exposed to a corrosive environment or to a soil it exhibits a potential called as natural potentials or also called as the corrosion potentials given by here. Corresponding to this particular potential the metal will exhibit a corrosion rate given by the corrosion current density given by this Evans diagram.

Now, as you notice that the corrosion current density and the corrosion potential are governed by these parameters, such as exchange current density for the cathodic reaction, the exchange current density for the anodic reaction and the Tafel relationship for the anodic reaction that is metal oxidation process. And the Tafel equation for the cathodic reaction that is reduction of some species such as oxygen or H plus ions on the metallic surfaces.

Now depending upon the slope of either the cathodic reaction and the anodic reaction then the current that are required for cathodic protection changes. And also this slope also decides whether the applied potential is adequate to protect a metal to the desired levels, so that we will be seeing in one of the problems.

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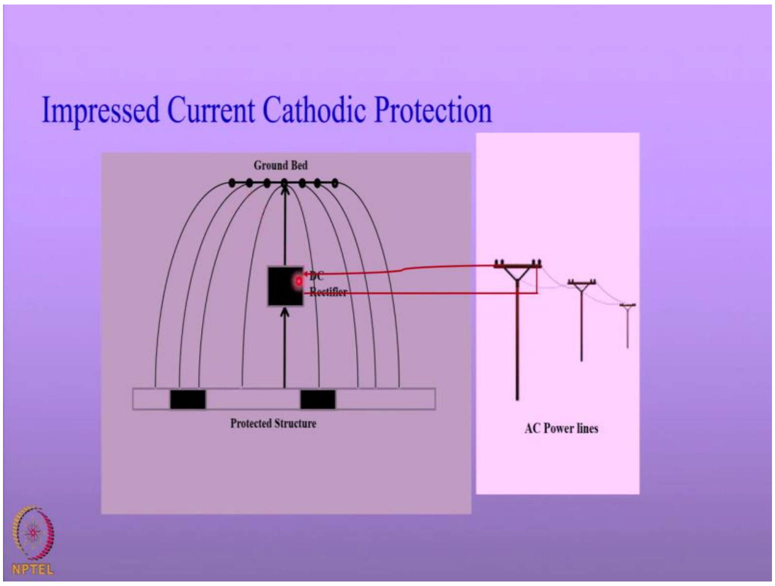

Next is the rectifier selection, now the impressed current cathodic protection of the engineering structures involves the use of the rectifier, the capacity of this rectifier depends upon the current that is required to protect these structures and the resistance offered by the ground bed that is the anodes, the cables and the pipelines. Today we will see a problem that is related more to the anode ground bed.

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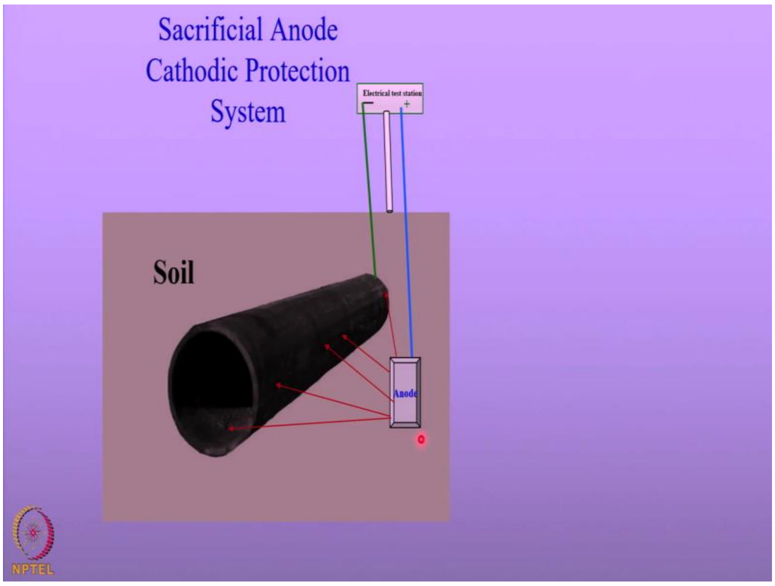

We will look at this the other problem that is sacrificial anode cathodic protection system. In this we need to look at selection of appropriate number of anodes, even the selection of appropriate anodes what do you mean by appropriate anodes it could be magnesium or it could be zinc or it can be even aluminum for example.

So, what decides the number of anodes and what decides the life of these sacrificial anode cathodic protection system. The problem that we are going to discuss today will illustrate three concepts we have just enumerated so far.

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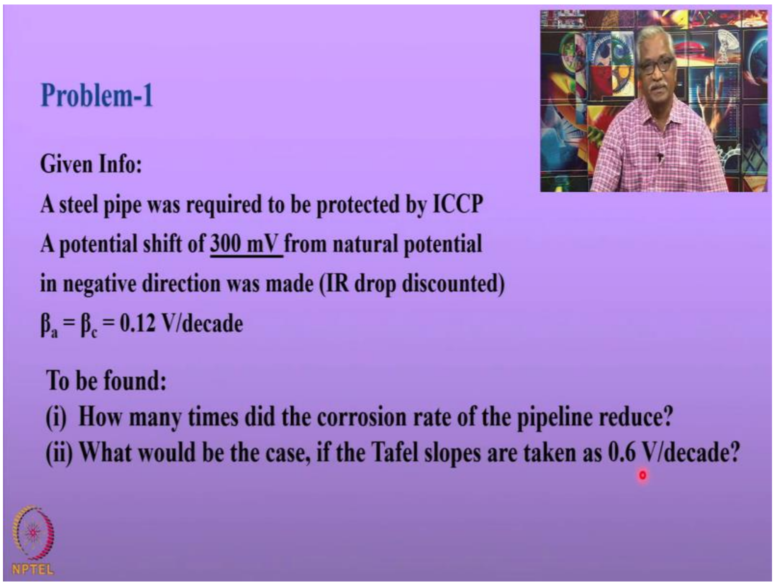

Let us go to the problem number 1, the problem number 1 we talk about the cathodic protection of a steel pipe using impressed current cathodic protection. Here we look at application of 300 milli volt potentials on the metallic surface, in order that the structure is adequately protected. Now the 300 milli volt that we talk about is not of potentials it is essentially the IR drop discounted. So, this potential is the actual polarized potential applied onto the metal surface.

So, we look at the condition in which if the Tafel slopes for the anodic reaction and the cathodic reaction is 0.12 volt per decade. So, what will be the consequent reduction in the corrosion rate of the pipeline ok. So, how many times did the corrosion rate of the pipeline reduce because of the application of 300 milli volt 1 question?

If the Tafel slope happens to be 0.6 volt per decade then what will be the corresponding decrease in the corrosion rate. So, this problem in turn gives us an understanding how the Tafel slopes affect the intended corrosion rates for a given polarized potential. So, let us look at this problem now ok.

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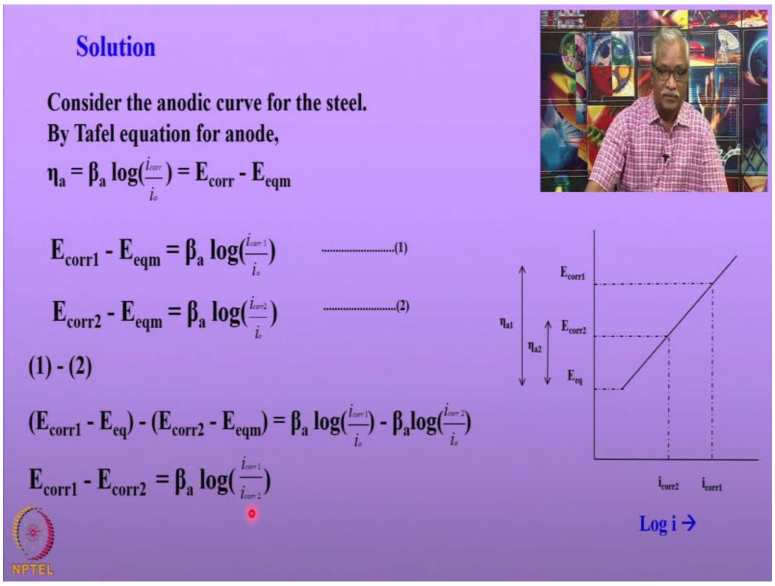

Now, what is given here in the left hand side is the Evans diagram corresponding to the steel that is corrosion of the steel anodic polarization curve that is seen here. And the natural potential is given by this point that is corresponding to we call them as E_{corr1} and the corresponding corrosion current density as i_{corr1} here.

Now, we are applying 300 milli volt in the native direction; that means, the shifted voltage is from E_{corr1} to E_{corr2} and as a consequence the corrosion current density decreases from this value to this value. So, we shall now calculate what is the ratio of decrease in current density corrosion current density, because of the application of 300 milli volt.

So, this we start with the well known the Tafel relationship for the anodic reaction that is

$$\eta_a = \beta_a \log(\frac{i_{corr}}{i_o}) = E_{corr} - E_{eqm}$$

eta is given as beta this Tafel slope log i_{corr} upon exchange current density. Then eta is over voltage is given by corrosion potential minus the equilibrium potentials, that is this is the equilibrium potential and this is the corrosion potential and that is the over voltage a. If a metal is immersed in the soil without the application of cathodic protection.

Now, what we are looking at is we are shifting ok. So, the same equation is given here ok, if we are rearranging the equation over here

$$E_{corr} - E_{eqm} = \beta_a \log(\frac{i_{corr}}{i_o})$$

it is E_{corr} minus equilibrium is given as beta Tafel slopes logarithm of exchange current density upon i_{corr1} that is the metal that suffers corrosion when buried in the soil.

On the application of 300 milli volt the potential shifts from here to this and you can re rewrite the Tafel equation as i_{corr2} upon i_o over here right. So, we can solve this equation to find out the ratio between the i_{corr} in the unprotected condition and the i_{corr} in the cathodic protected conditions by application of 300 milli volts.

So, we can solve these equations and you will you will get the resultant equation here the

$$E_{corr1} - E_{corr2} = \beta_a \log\frac{i_{corr1}}{i_{corr2}}$$

E_{corr1} minus E_{corr2} is given as Tafel slope beta a logarithm of i_{corr1} upon i_{corr2} ok. So, that is a general equation right.

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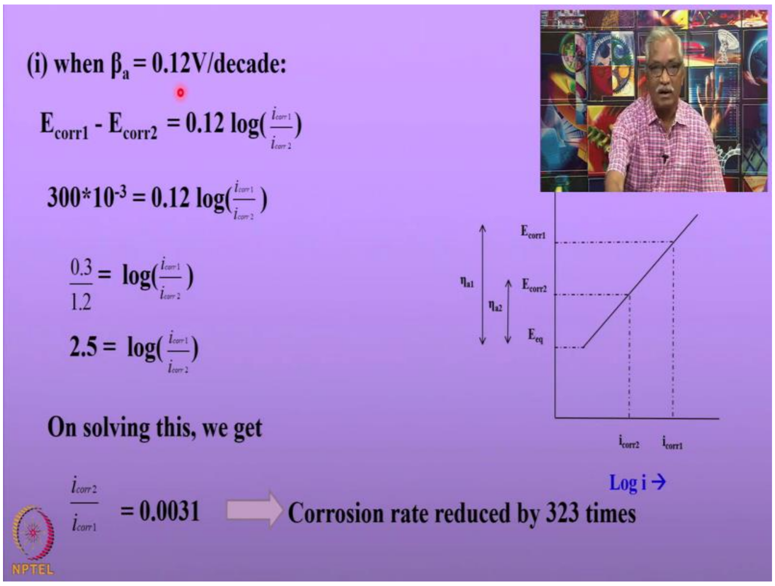

Now, if you are considering a Tafel slope of 0.12 volt per decade and you can see and if the polarized potential is 300 milli volts which is convert into volt here and substituting these values in equation and solving them. You will find that the ratio between i_{corr1} and i_{corr2} is 0.0031. So, that corresponds to a increase in corrosion resistance increase in corrosion resistance by 323 times, should the Tafel slope be 0.12 volt per decade.

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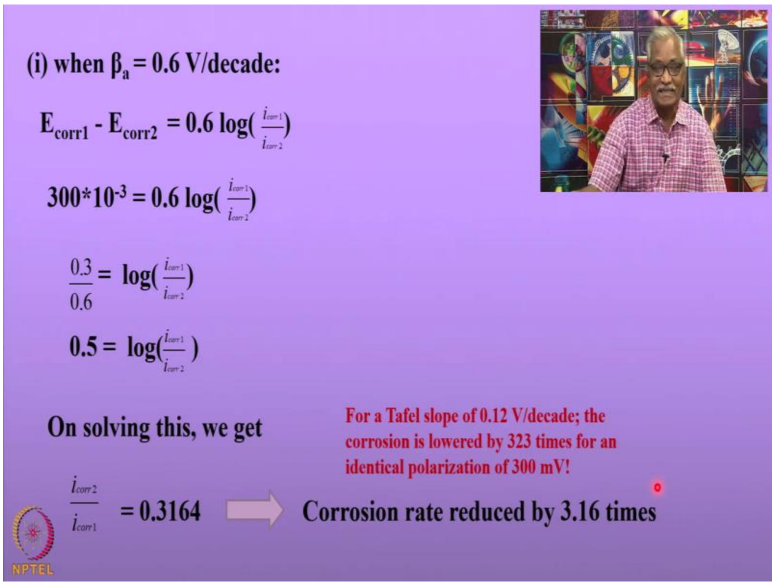

Now, let us look at the other alternative should the Tafel slope be 0.6 volt per decade. So, what happens we can use the same methodology to solve the problem and we retain the applied voltage as same 0.3 volt which is the polarized value in the cathodic protection.

Then as a consequence you will see that the ratio of the final corrosion rate to the initial corrosion rate turns out to be 0.3164 which amounts to just about 3.16 times ok.

So, just compare these 2 values should the Tafel slope be 0.12 volt per decade, for the same 300 milli volts polarized potentials one would expect a increase in corrosion resistance by 323 times as opposed to just 3.16 times if the Tafel slope is 0.6 volt per decade.

So, when you talk about cathodic protection criteria let us say 100 milli volt criteria is very good ok. But we should also know that to what extent the pipeline can get protected from corrosion also depends upon the Tafel slopes.

The Tafel slopes can change depending upon seasonal conditions when it is wet and dry seasons or it can also depend upon the soil chemistry it can happen, it can also depend upon the coating conditions of the pipelines. So, that remains some uncertainty in cathodic protection when we use 100 milli volt criteria.

I am not saying that 100 milli volt criteria is not to be used, but it is necessary that we need to have a perspective how a given situation can differ in terms of how effective the cathodic protection is. So, let us go on to the next problem, this problem deals with a pipeline that suffers from diffusion limiting current density diffusion control corrosion rate it is happening.

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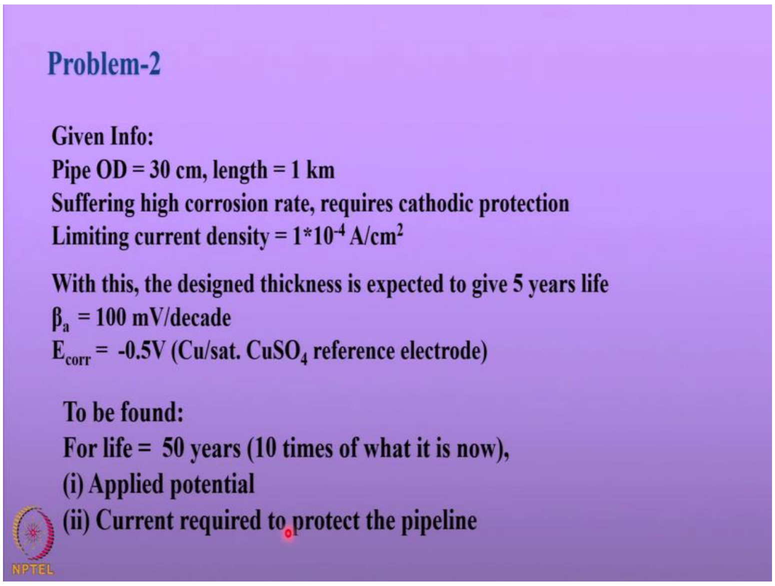

And the especially when the oxygen reduction reaction is the predominant cathodic reaction and that happens when the pipelines have slightly neutral or relatively alkaline soil conditions and where the pH is slightly higher or neutral, for example 7 or 8. The predominant cathodic reaction is oxygen reduction reaction; of course in addition to that there is also water reduction reaction.

But the driving force for the oxygen reduction reaction is quite significant compared to the driving force for water reduction reaction. So, in this case we have a pipeline whose diameter is 30 centimeter the length of the pipeline is about 1 kilometer long pipeline, the measured limiting current density that is cathodic current density is 1×10^{-4} A/cm^2 that is about 100 micro amperes centimeter square.

It is given that the thickness of the pipeline is such that the pipeline will last for a 5 years should there be no cathodic protection. So, one would like to increase the life of this structure by 10 times ok. So, what should be the applied potentials and what should be the current required to protect the pipeline given the Tafel slope, the anodic Tafel slope or the metal dissolution is 100 milli volt per decade.

And the pipe to soil potential that is measured without cathodic protection or it is a natural potential I would call it is minus 0.5 volt with respect to copper saturated copper sulfate reference electrode. These are the values given then what will be the applied potential that will provide us increase in life by 10 times and again what is the current required to protect the pipeline this is the problem.

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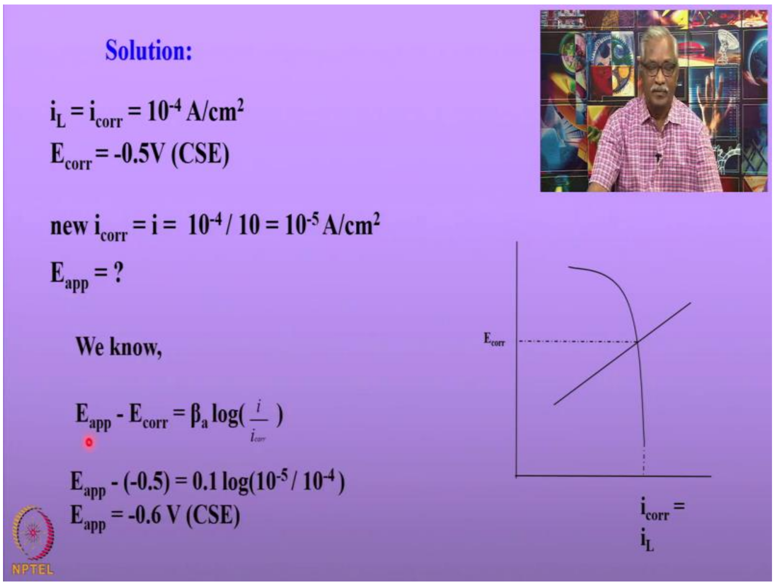

So, let us look at how to solve this problem let us again go back to this basic concept of Evans diagram. It is potential against log current that you see here, the cathodic current is diffusion control limiting current density here you can see that the this line corresponds to the anodic Tafel slope the anodic this line corresponds to anodic kinetics right.

And the intersection point between the cathodic reaction on the anodic reaction is over here and there is a corresponding potential right and there is a corresponding corrosion rate i_{corr}. In this case i_{corr} the corrosion current density equals the limiting current density right.

Now, if you look at this diagram the E_{corr} corresponds to 0.5 volt with respect to copper saturated copper sulfate electrode that is what is given here and because it is limiting current density the corrosion is diffusion controlled ok. The limiting current density equals the corrosion current density, so that is given over here.

So, i_l corresponds to i_{corr} which is 10^{-4} A/cm^2 and E_{corr} is given as minus 0.5 volt with respect to coppers saturated copper sulfate electrode reference electrode. Now, you want to increase the life of the structure by 10 times. So, the corrosion current density which is i_{corr} currently is 10^{-4} A/cm^2 should be reduced to 10^{-5} A/cm^2 that will give you an increase in life by 10 times right.

So, what is applied voltage required to reach this current of 10^{-5} A/cm^2. So, we again use the Tafel relationship that is the governing relationship for determining the potential for a given current density. I have replaced here $E_{applied}$ and E_{corr} because we are moving from

E_{corr} to $E_{applied}$ and E_{corr} here corresponds to the potential where the metal dissolves at a current density of i_{corr} here ok.

So, we need to find out what will be the applied potentials if you need the final current density as 10^{-5} A/cm^2. So, substituting these values here in this Tafel equation and one would obtain the applied potential is equal to minus 0.6 volt with respect to copper saturated copper sulfate electrode. So, we need about 100 milli volt polarization towards negative potentials.

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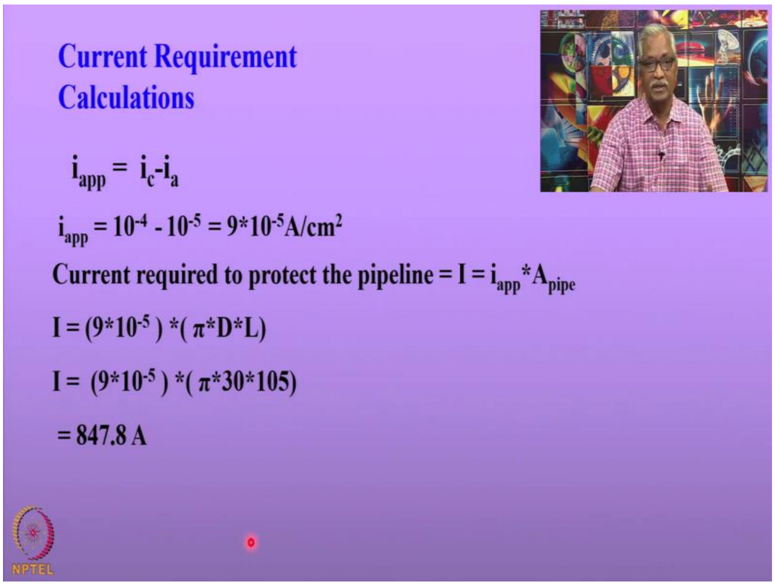

The next thing is what is the current requirement the calculations right, we have seen in the first or the second slide ok. The applied current required for cathodic protection is the difference between the cathodic current density and the anodic current density ok. So, the applied current density is given as the difference between the cathodic current density and the anodic current density.

And we know the cathodic current density does not change because it is under limiting under diffusion control. So, the problem becomes somewhat simple, because the cathodic current density is constant because of the fact that the corrosion is diffusion control ok.

Now, the this difference of 10 power minus 4, 10 power minus 5 which gives rise to 5 10 to the power minus 5 ampere per centimeter square is the current density required per centimeter square area of the sample. So, we need to find out the overall current required to protect the pipeline, to do that we need to know the surface area of the pipeline that is substituted here this pi d into length you can see this and then the current density which turns out to be about 847.8 amperes of current.

You will also notice that the pipeline when it is not supplied with a coating, the current required for cathodic protection is quite significant. So, we will see later that how the application of coatings would reduce the current requirement.

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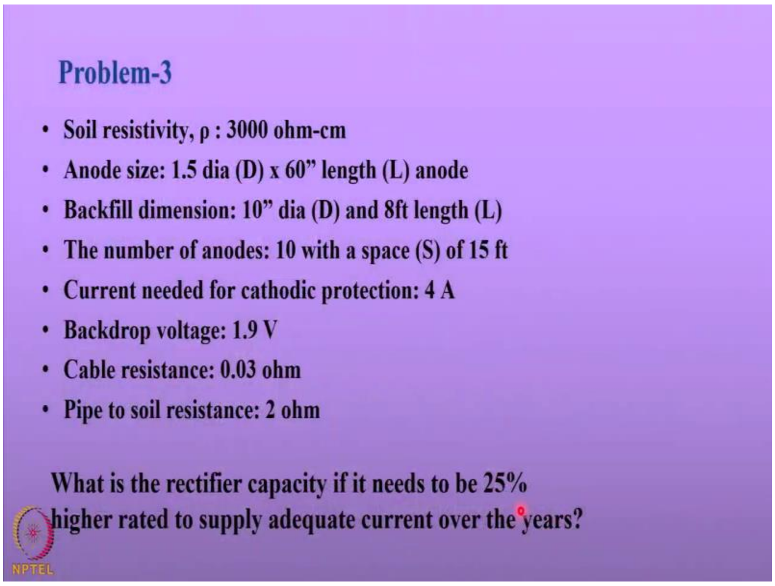

Let us look at a third problem wherein the following parameters are given that is the soil resistivity. The size of the anodes employed for cathodic protection using ICCP method and these anodes are also as you know they required to be buried in a backfill right. So, the backfill dimension is given here the number of anodes and the spacing between the number of anodes are given.

The current required for cathodic protection is given as 4 amperes and the current required for cathodic protection is generally established by installing a temporary anode ground bed and measure the current required to reach a protection potential of minus 0.85 volt with respect to copper saturated copper sulfate electrode.

And the backdrop voltage also can measured by switching off the rectifier and we need to know the cable resistance and pipe to soil resistance. Given these parameters now one need to calculate what is the rectifier capacity and one capacity in terms of amperes is given here.

But there is a small caveat that the current required for cathodic protection might vary with respect to time, because if it is coated with a nice coating as a coating disintegrates the current requirement becomes more. So, what is given here is that with the aging the current requirement increases by about 25 percent.

So, we need to calculate what is the capacity of the rectifier the capacity of rectify, here is refers to the voltage and of course when we talk about 25 percent increase in current that you can always calculate. What will be the overall current required the capacity of the rectifier is known. But what is to be calculated is the voltage of a rectifier is to be calculated.

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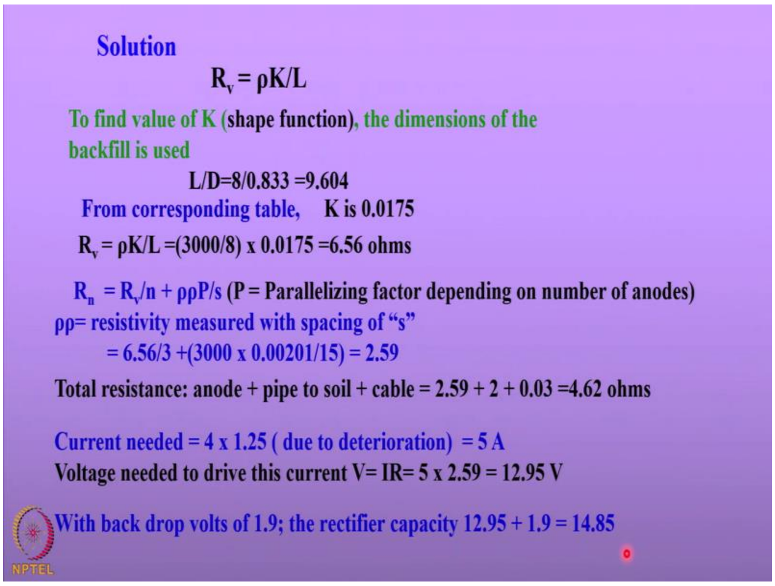

So, how do you look at it we know that in the circuit there are various elements that offer the resistance. If I go back to this the resistance offered by the cable the resistance offered by the pipe to soil is known. So, we need to calculate the resistance offered by the anodes we use this equation that is being given earlier.

The resistance offered by a single anode when they are placed vertically in relation to the pipeline is given by this equation, where rho represents the resistivity of the soil and l represents the length of the anode in this case the length of the backfill we will talk about and K is called as a shape function, it can be obtained using the standard tables the K is related to the length upon d the ratio of the backfill ok.

And based on these values you can you can you can find out the corresponding K value from this tables and you can substitute this K in this equation. And we one would get the resultant resistance which is 6.56 ohms offered by a single anode. Since we have a single row multiple anodes it is necessary to calculate what is the resistance offered by the ground bed, the ground bed consists of multiple anodes.

And so we use this equation which is the resistance offered by the multiple anodes is given by this equation here,

$$R_n = \frac{R_v}{n} + \frac{\rho\rho P}{s}$$

P represents parallelizing factor that depends upon the number of anodes. And this can be obtained from the standard tables and you can substitute these values in this equation you will get that for the three anodes you will have about 2.59 ohms is the resistance offered by this anodes actually.

Now, the resistance offered by the overall cathodic protection system consists of resistance offered by the anode the soil and the cable. So, this is the overall resistance offered by the circuit. In addition to that there is also what is called as the backdrop voltage that also resists the flow of current. So, that should be taken into account right. So, that will come to later right.

So, the current required for cathodic protection including the deterioration that happens over a time period is about 5 amperes. So, we simply apply the ohms law and we obtain the voltage required to pass 5 amperes of current which turns out to be 12.95 volt. So, that is the capacity of the rectifier required to drive the current in the soil, but however if there is a backdrop voltage.

Now, the rectifier has to overcome the backdrop voltage in addition to these resistances which are in series. So, ultimately you can substitute this 1.9 volt which is the back backdrop voltage given here and the resistance I mean the rectifier should have a minimum capacity of 14.85 volts, in order that the cathodic protection can be successfully established.

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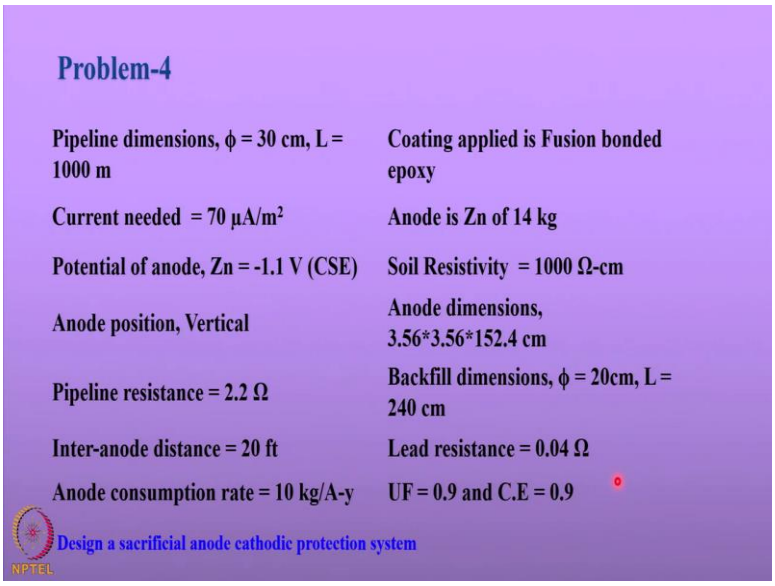

We move on to the next problem that deals with designing the sacrificial anode cathodic protection system. Various parameters are given here in this problem ok, so we need to know the dimension of the pipeline certainly we also need to know what is the current required for cathodic protection and what is the anode used in this case the proposed anode is zinc anode whose voltage is minus 1.1 volt is given here.

And we also need to know the anode is positioning whether it is horizontal or vertical. So, in this case it is a vertical anode the resistance offered by the pipeline as you see in the earlier case you need to know here as well. If you are going to use multiple anodes what are the spacing between these anodes.

As opposed to ICCP systems the sacrificial anode systems, as we see that the anodes themselves provide the required current. In the ICCP systems the current is provide by the rectifier ok. So, the dissolution of the anode provides a current, so we need to know what is the amount of anode required for protection of the structure for a required time.

Now, we look at the characteristics of the zinc anode, the zinc anode has characteristics which is which can dissolve about 100 sorry 10 kilogram per ampere year. So, the anodic the anode consumption rate of the zinc anode is 10 kg per ampere year. That means, if I have to pass one ampere current per or 1 year I would need 10 kilogram of zinc.

We also like to know whether the pipeline is coated if. So, what it is? It is coated with a Fusion bonded epoxy and each of the anode each of the anode we are talking about calculation of the number of anodes required. So, each of the anode the dimension I mean the weight of the anodes is 14 kilograms.

The resistivity of the soil is 1000 ohm centimeter, there are no dimensions given here it is a rectangular shape and it is kept in a backfill of dimension given. It is kept in a backfill of dimension given here the leads used for establishing the sacrificial anode cathodic protection system is 0.04 ohms.

And you all know that whatever the anode that you are going to give not all of them are consumed, we may have to discover the anode after certain dissolution. In this case the utility factor that is 0.9 is utility factor that is when 90 percent of the anode is consumed we may have to replace a new anode that is the value here.

The current efficiency of the zinc anode is 90 percent which is 0.9 fraction. So, given these parameters we need to establish a cathodic protection system using zinc as a sacrificial anode.

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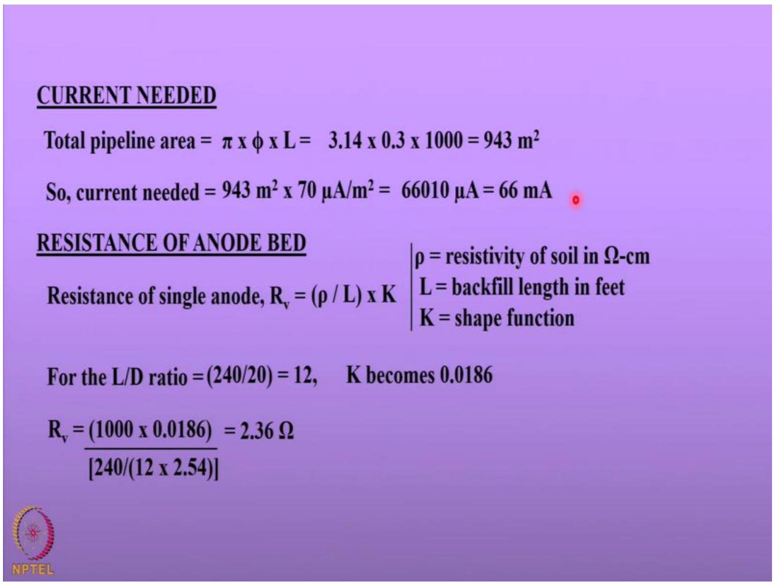

Let us look at the problems, now first and foremost is we need to determine what is the total current required for protecting the given pipelines ok. So, we know the current density it is 70 micro ampere per meter square is the current density.

So, we need to know the total current which means we need to determine the total area of surface area of the pipeline that is surface area of the pipeline that comes in contact with the soil. From that we can calculate the total current which turns out to be 66 milli amperes of current required.

Now, once we know the current then we need to look at the resistance offered by the anode bed. We follow the same example as the previous problem, we determine the resistance offered by a single anode from there we compute the resistance offered by the ground bed consists of multiple anodes.

The equation is well known to us and so when you substitute all these values the resistance offered by 1 anode turns out to be 2.36 ohms. And we need to now decide how many anodes are required, so that the sacrificial anodes can protect the pipeline satisfactorily.

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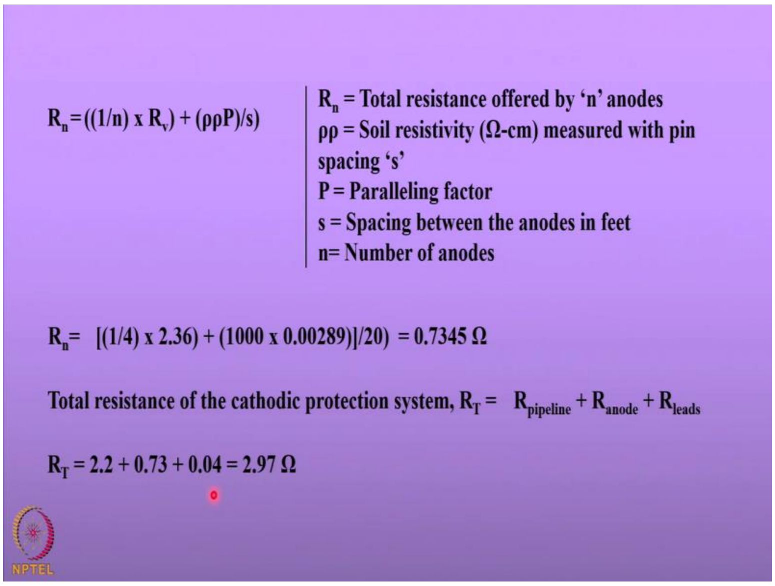

The deciding the number of anodes is sometimes is iterative, because you need to see that the anode ground bed resistance is sufficiently small, so that the anodes can drive the current onto the pipeline right. So, the number of anodes that we need to substitute here we do by iteration method. So, that the resistance calculated based on this equation that is here is sufficient enough or sufficiently small enough for the current to be flown to the pipelines.

So, in this case we did some iteration sometime you took 3, for example when you took 3 obviously the resistance offered was more and that was not satisfying the condition. So, we moved over to 4, of course you can also go for 5. But you will see later that by increasing to 5 you will have excess amount of anode which are not really required both in terms of driving the current and in terms of the life of the cathodic protection system.

So, this is a bit of iteration that you do that. So, once we know the resistance offered by the anode ground bed we look at the total resistances offered by the cathodic protection system, that consists of a pipeline anode on the leads right. So, these values are already known the pipe to soil resistance, the lead resistance are known the anode ground bed resistance has been calculated and you can find out the total resistance offered by the anode ground bed.

So, the total resistance offered by the cathodic protection system is 2.97 volt that constitute resistance from the pipeline anode. And the leads now our next task is to determine whether the zinc anode is able to drive the current against this resistance ok. So, that will be seen in the next problem next.

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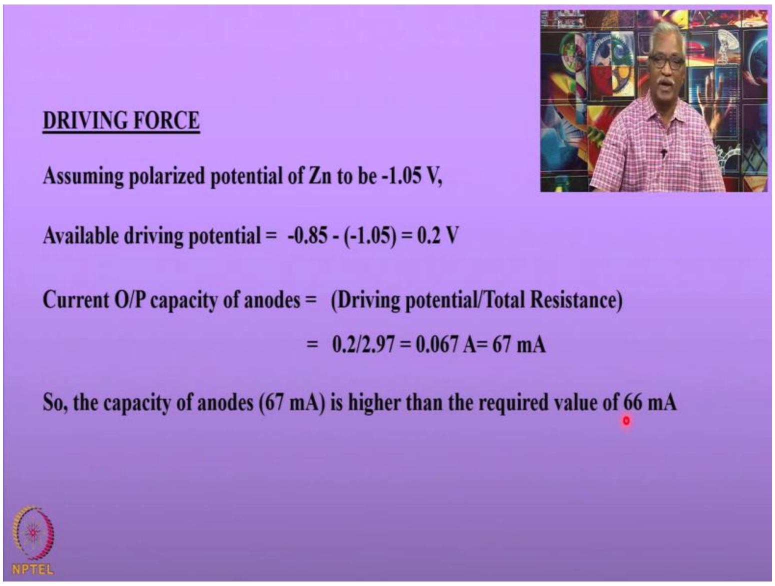

So, we look at the driving force that zinc can really offer, we need to understand there is a difference between the polarized potential of zinc and the actual potential of zinc when you buried in the soil. When you bury a zinc in the soil which is not cathodically connected which is not electrically connected to the pipeline as you seen before is minus 1.1 volt.

When zinc is connected to the pipeline zinc gets polarized and that is how the current is generated and that current passes through the pipelines. So, when it get polarized the ultimate potential is somewhere close to minus 1.05 volt. In fact, the advantage of zinc over other sacrificial anode can be seen here, because there is hardly a polarization you start from minus 1.1 volt and it is moved just to minus 1.05 volt this is primarily because zinc is less polarizable anodically.

In fact, that is one of the reason why zinc is also used as a reference electrode for cathodic protection of the pipelines. So, assuming the polarized potential to be minus 1.05 volt and the minimum requirement for cathodic protection is minus 0.85 volt that is with respect to pipe to soil ok, the driving force corresponds to 0.2 volt right.

So, now the question is this 0.2 volt is sufficient to overcome the resistance which is 2.97. You can see here that the anode bed can give 67 milli amperes of current barely managed to give the current actually and barely managed to give the required current of 66 milli amperes. Should be very comfortable you want to have a better capacity the one way to do is you go for 4 number of anodes, instead of 4 number of anodes you want to go for a better capacity you can use 5 number of anodes.

But you will see later what it can lead to if you are going to go for 5 number of anodes instead of 4 number of anodes. So, coming back to this problem that if we are going to have 4 number of anodes; these anodes can drive a current of 67 milli amperes given the resistance of 2.97 ohms.

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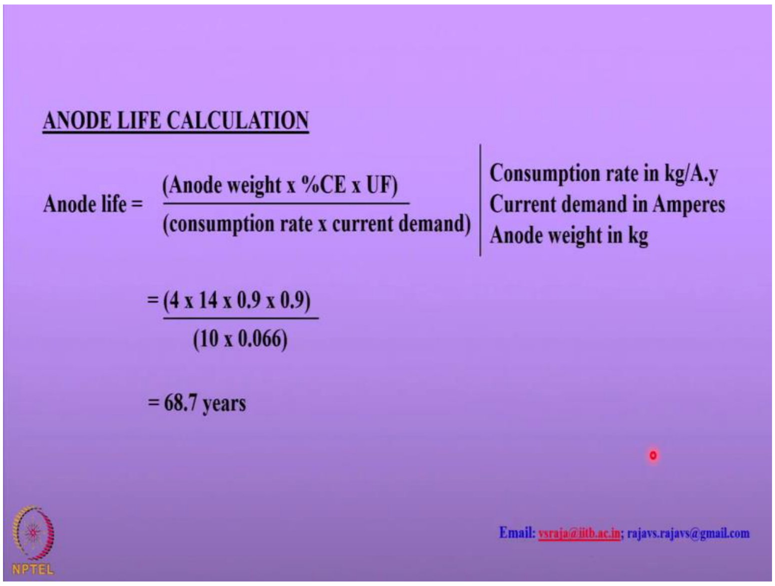

Now, we talk about 4 number of anodes and so what is the life of the anodes the life of the anodes is given by this equation the anode weight, current efficiency, the utility factor, the consumption rate and current demand ok. Now, all these values are known we substitute them in the equation and you will get a value of 68.7 years of service life. So, if you are going to use 4 number of anodes the structure in principle can be protected for 68.7 years.

However, there are some issues that zinc anodes passivate over a time period right. If you also look at the other factor we discussed that the 4 number of anodes barely gives a current right.

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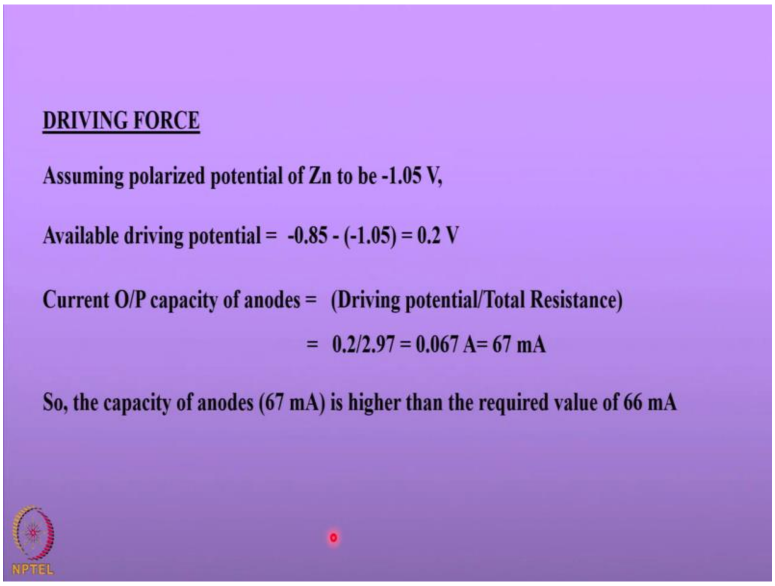

A current of 67 milli ampere as against 67 milli amperes right and we said that you want to increase the number of anodes. If you increase the number of anodes automatically you notice that you know instead of 4 you substitute let us say by 5, then the life of these anodes are going to be much higher; that means, we are wasting the zinc.

And so we should avoid having more number of anodes. In that case what are the other possibilities the other possibilities is that you can look for the magnesium anode. So, today's lecture we looked at the three important concepts and we use the calculations to clarify these concepts, the first was that the Tafel slope is very important even when we describe the cathodic protection criteria in terms of let us say 100 milli volt criteria ok.

You see that how the Tafel slopes can change whether a metal will be adequately protected or less adequately protected. In the second problem we looked at the what are the constituents of the cathodic protection system that decide the capacity of a rectifier. In the last problem we discussed how to design a cathodic protection system, when the sacrificial anodes are used. I do hope that these problems will give you better clarity on concepts.