Advanced Topics in the Science and Technology of Concrete
George Sergi
Vector Corrosion Technologies
Corrosion Control and Cathodic Protection of Steel Reinforcement: Past Present and Future

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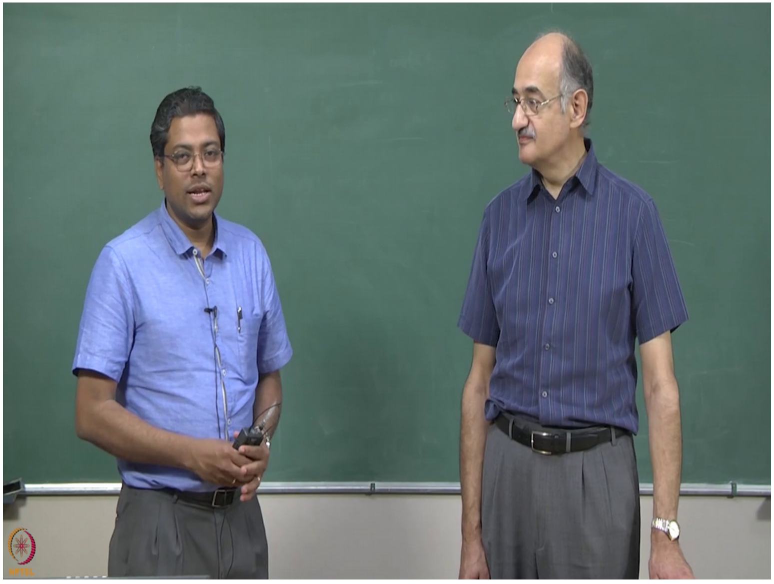

(Professor – Professor Conversation starts)

Doctor Radhakrishna: Welcome to this course on Cathodic Protection of Concrete Structures. Today we have Doctor George Sergi from Vector Corrosion Technologies.

He is considered as one of the pioneering figure in cathodic protection of concrete structures, developing various systems to control corrosion especially for concrete structures. That is what he is expertise on.

And he has about; you know 20 plus years of experience in this area, both laboratory and field experience. He has headed the Corrosion Lab in building, building research establishment in U K and many projects in that, you know in controlling corrosion.

That is his passion, I think and you know as I had talked to him before, he did not want to leave this industry because, after seeing the opportunities coming up.

So he was, you know he was not able to leave this industry at all. So thank you very much for actually working for this long time in this area and then developing new, new systems to tackle different problems which we have.

So welcome to this course and we really want to hear from the inventor on various systems and how the cathodic protection industry for concrete structures developed over last couple of decades.

Welcome you to this course and we are waiting for your lecture.

Doctor George: Thank you.

Doctor Radhakrishna: Thank you
(Professor – Professor Conversation ends)

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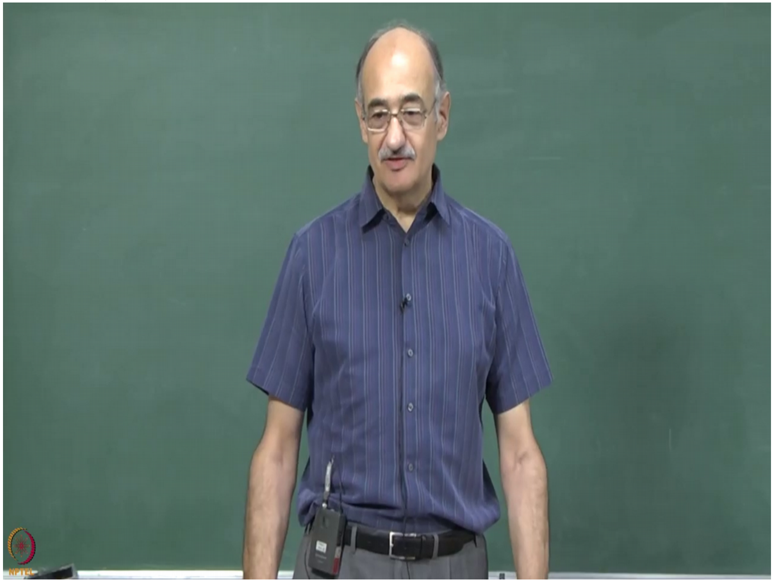

Welcome everybody. Today I will talk about cathodic protection in general, how it has been developed over the, over the years and what have we learnt from it and how

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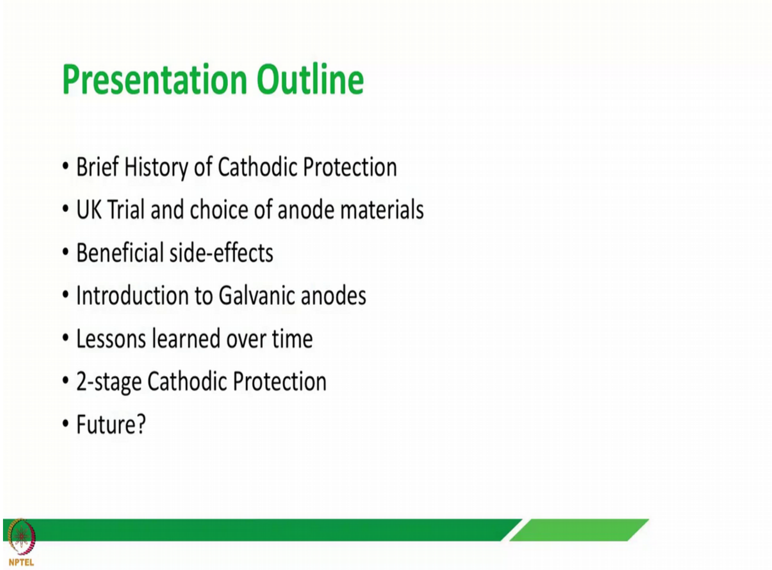

Presentation Outline

- Brief History of Cathodic Protection
- UK Trial and choice of anode materials
- Beneficial side-effects
- Introduction to Galvanic anodes
- Lessons learned over time
- 2-stage Cathodic Protection
- Future?

we look forward to the future.

So we have, what kind of developments we are likely to get. So I will just go through brief history of cathodic protection, look at the very early trials of cathodic protection. Then I will concentrate on U K trial that allowed the process to be developed sufficiently to be used by government agencies in the U K.

I would try to introduce the kind of benefits that you get from cathodic protection other than just the main one of stopping or of reducing corrosion, what are the side effects and how beneficial are they, how can we use them?

Then I will introduce galvanic cathodic protection, then I will go over the lessons that we have learnt over time looking at the results we have been receiving, the trials and then from that we were able to learn how to introduce a new way of kind of carrying out cathodic protection which I call a two-stage cathodic protection.

And then I will look a little bit into the future so that you know which direction are we are actually moving in, which direction I think we should be moving into.

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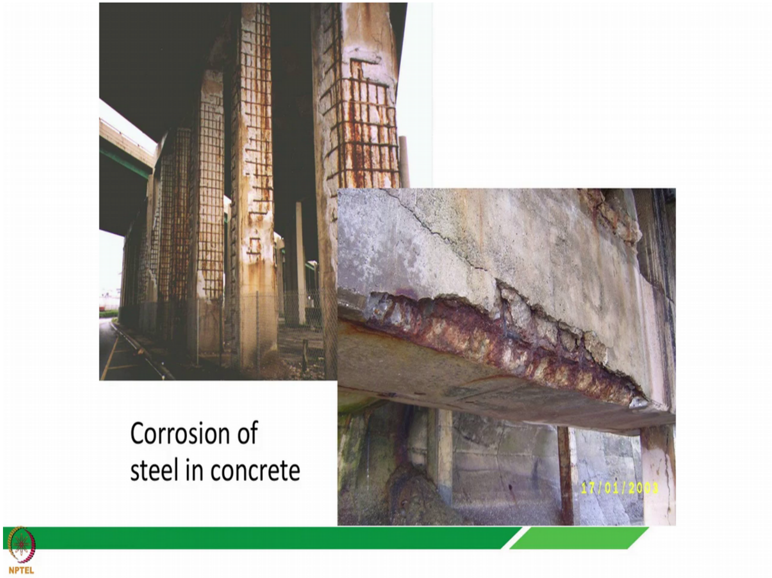

Corrosion of steel in concrete

Ok well corrosion is quite a serious problem really and I have seen enough over in India to understand that it is just as bad here as it is in the rest of the world

In Europe I would not say a typical corrosion problem but what happens is that steel reinforcement corrodes, the corrosion products are very expansive and they crack the concrete that leads to even more aggressive ions getting into the, into the structure and gradually you lose the cover of the steel reinforcement, the cover concrete just drops off and you can see those two slides.

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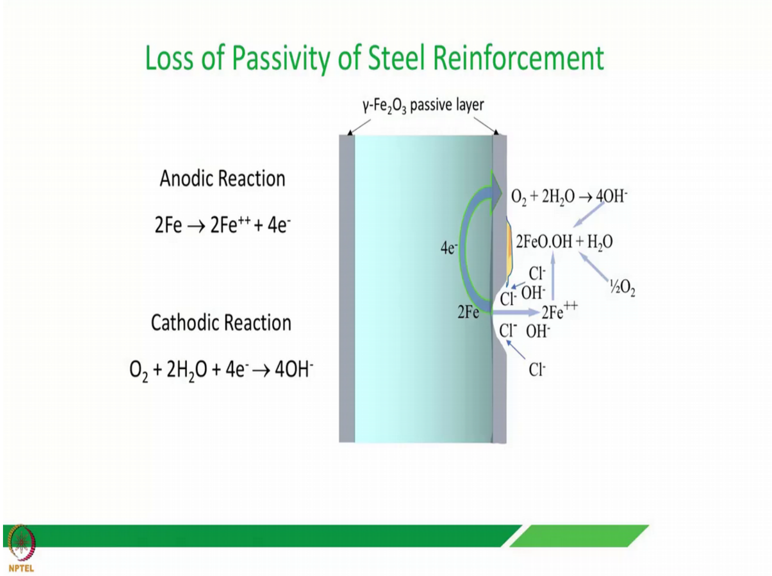

Loss of Passivity of Steel Reinforcement

Anodic Reaction

$2Fe \rightarrow 2Fe^{++} + 4e^-$

Cathodic Reaction

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Ok but how does this corrosion problem actually occur? When we put steel in concrete, it really likes it very much. It forms a very thin oxide layer which is called gamma F e 2 O 3.

And we call that a passive layer, passive because no more corrosion can take place. The whole thing is covered by this passive layer and therefore protecting the steel reinforcement.

But one may have aggressive ions like chlorides and they are introduced into the concrete. They can attack little gaps in this protective layer and then corrosion can start. In the corrosion process basically we are losing the iron that produces electrons.

So the electrons move along this path of the steel reinforcement to a new side which we call the cathode, so where it is corroding is actually called an anode and the other side, because it is like a battery, we need to have 2 poles. You have the anode and therefore you have the cathode. The cathode is further up.

So this would be the cathode and at the cathode we have the different reaction, the cathodic reaction which uses oxygen in water from the environment, from the solution and that produces hydroxyl ions.

Now remember this process because it is a very, very important process. Hydroxyl ions are the same as what is in concrete which makes the concrete alkaline and the alkalinity is what protects the steel reinforcement.

So producing hydroxyl ions is a good thing. But on the other side, on the anodic side we actually get acidification. So this is the sort of a dual process going on, one is producing alkali, the other is producing acid.

Ok and eventually we get the iron ions moving towards the cathode, hydroxyl ions coming towards the cathode and they mix in the middle and produce the corrosion product.

Just notice where the corrosion products actually sit. They are not on the side of the anode. They are in between the two.

So they allow the anode to continue to corrode. There is nothing to stop it.

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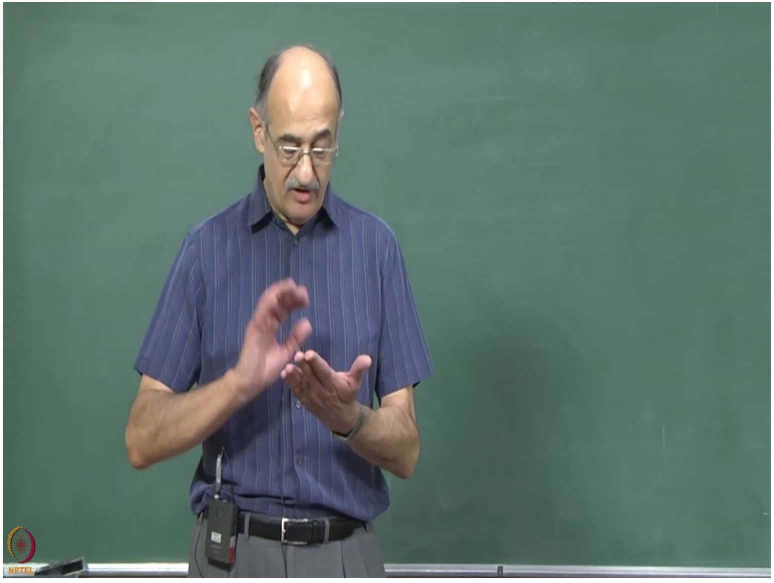

So you do not form corrosion products right on top of the anode and therefore anode continues to corrode.

So remember these two processes. The anodic reaction which is 2 F e plus plus, that is the corrosion product, plus 4 electrons, the 4 electrons are taken up by the oxygen and the water for the cathodic reaction and that produces 4 hydroxyl ions.

Ok now how do we stop this process? We try and reverse the anodic reaction which is the corrosion reaction. And one way of doing this is by a process called cathodic protection.

And in its basic form cathodic protection is basically

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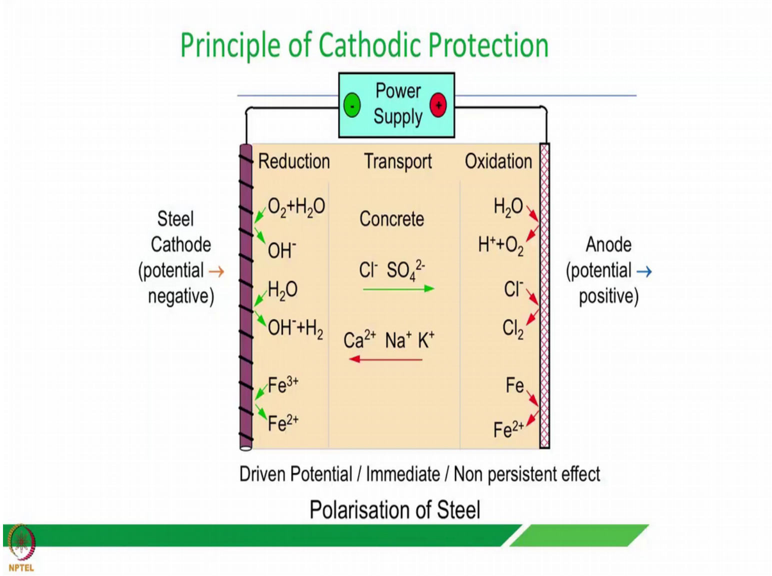

Principle of Cathodic Protection

Driven Potential / Immediate / Non persistent effect

Polarisation of Steel

connecting the steel reinforcement to a negative, negative pole of the power supply that delivers electrons to the steel reinforcement which forces it to become the cathode.

So the electrons are taken up by the oxygen and the water and they produce hydroxyl ions like I was saying before. The positive side, we have to connect something else otherwise there is not going to be current flowing.

So we have another electrode which could be steel but that is not a good idea. It could be any material that is suitable, that is conductive. We normally, we can normally put that on the surface of the concrete or somewhere where it is not causing any damage.

Then there should be as well as the electronic current that flows between the power supply and the wires, you need an ionic current to flow between the two electrodes. And that ionic current is carried by the ions.

So chloride ions, sulphate ions, calcium ions, sodium, potassium ions they are the current carriers inside the electrolyte because concrete is porous in fact. It has a pore electrolyte within it and this pore electrolyte is full of ions of this so.

So one of the beneficial processes is you can see is that chloride which moves away from the steel reinforcement, it is negative and it does not like the negative side so it moves to the positive side. So we are moving chloride ions away from the steel towards the anode.

We can do the same with sulphates but they are not so important. In the other direction we have calcium ions, sodium ions, potassium ions because they are positive ions they move away from the positive towards the negative. So we are changing the chemistry around the steel reinforcement as we apply this current.

And therefore we are primarily producing alkali hydroxides, calcium, sodium, potassium. Sodium, potassium just increase the p H, calcium hydroxide when the p H is high, it is very insoluble.

So it starts precipitating out as a solid and that can also be beneficial because it starts blocking the pores around the steel reinforcement. It finds the gaps and it starts build up a solid layer which could be physically protecting the steel reinforcement.

So what are the things that we have learnt so far? We know we are producing hydroxyl ions at the steel and that attracts the alkali ions and we get alkali hydroxides around the steel which are beneficial that they are the ones who build up the passive layer on the steel

And you are moving the chloride ions away from the steel which are the bad guys, they are the ones who are actually causing the corrosion in the first place. So quite apart from the fact that you are trying to hold the potential of the steel in an area where it does not corrode you get also these additional beneficial processes happening.

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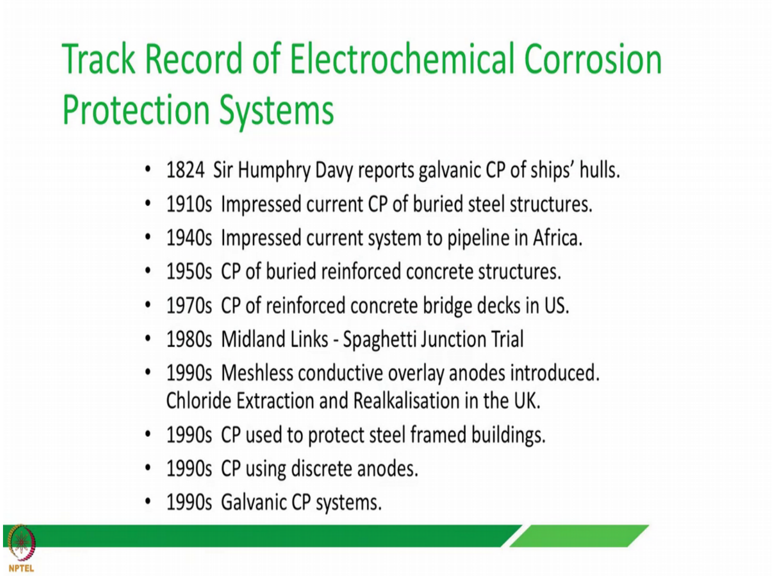

Track Record of Electrochemical Corrosion Protection Systems

- 1824 Sir Humphry Davy reports galvanic CP of ships' hulls.
- 1910s Impressed current CP of buried steel structures.
- 1940s Impressed current system to pipeline in Africa.
- 1950s CP of buried reinforced concrete structures.
- 1970s CP of reinforced concrete bridge decks in US.
- 1980s Midland Links - Spaghetti Junction Trial
- 1990s Meshless conductive overlay anodes introduced. Chloride Extraction and Realkalisation in the UK.
- 1990s CP used to protect steel framed buildings.
- 1990s CP using discrete anodes.
- 1990s Galvanic CP systems.

Ok just a brief history of the electrochemical corrosion protection systems, cathodic protection in other words.

We go way back in 1800s when a British inventor called Sir Humphrey Davy reported that he actually used galvanic anodes, zinc in actual fact that just touched the bottom of the ships, so the holes of the ship which were corroding in the sea water.

All he did, he attached the galvanic anodes, the zinc anodes and what he saw was the zinc was corroding away but the steel was not corroding. So it was protecting the structure.

But then that was kind of forgotten because other things happened and there was an additional problem that was introduced; because he was doing that he was killing some of the natural things that was taken out of the ship and people did not like it. So it lost its significance at that time.

But move on to the beginning of the twentieth century, 1910s was really the first time that the cathodic protection was applied in a steel structure that was buried underground.

That was relatively easy because you have a lot of electrolyte, lot of water and therefore the current can flow. Then we move on to the 1940s before we see a cathodic checking of a pipeline in Africa.

In 1950s we started doing it on, on steel reinforced concrete but again underground, 1970s was first time that they attempted to use cathode protection on structures that were above ground, because they are drier, electrolyte is less it is more difficult to pass the current.

But the Americans tried out a few techniques. They had some success on actually flat structures where they could actually put the anode on the surface

But it was not really until the 1980s when the problems were beginning to appear in the United Kingdom that a proper trial was carried out to see whether there were enough materials or suitable materials that could be used for cathodic protection.

And then after that there was a generation of ideas and all of a sudden things were happening. In the 1990s just about everything else happened. Like there was introduction of chloride extraction, which is obviously a process that you can apply.

It removes the chlorides if you do it properly. Those re-alkalization, you know how we are producing hydroxyl ions and therefore we are realkalyzing the concrete around the steel.

They then started to use it on another structures, steel frame structures which is just steel formations that I have got facades around them which was so (()) (14:23), it was impossible to protect but they found the way of doing it.

And also in the 1990s there was the development of the galvanic anodes which I would, I would concentrate quite a bit today, Ok but I will talk a little bit about them. 1980s now we call the Midland Links. That was the first trial that was done, in fact real wider I believe, it was done in the U K and this was the superstructures (()) (14:47) they were trying to protect.

What had actually happened was a motorway link, so elevated, elevated road structures throughout the Midlands which is the middle of the country and these were, because of bad design in the first place, they were starting to show corrosion.

They were only in the late 1960s so within less than 20 years or so, 15 years they started to corrode. And reason was

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Impressed Current Cathodic Protection

Conductive Paint Systems

the expansion joint. And through the expansion joint, in the UK because it is cold they throw the icing sources on to the road.

And these icing sources were seeping down on to these beams, they were running down the crossbeams, down the columns, so there was seen a lot of corrosion occurring because of the chlorides that were impregna (()) (15:43), they were actually being diffused into the concrete.

So they asked around to see what sort of the systems they can actually apply as anodes. There was a conductive paint system which was primarily carbon as you can see. This is the same where they actually coated with the decorative coating so that it does not look black. This proved quite successful.

And another one

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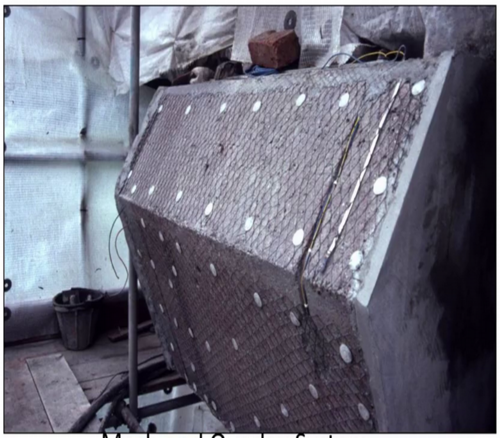
Impressed Current Cathodic Protection



Mesh and Overlay System

was called the mesh and overlay system. So specifically like a chicken wire mesh. But it is made of titanium.

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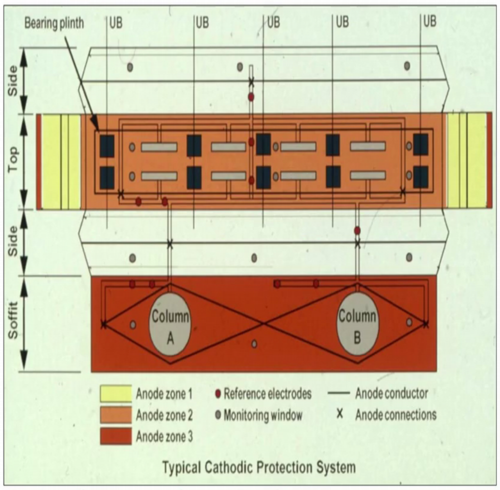

Cathodic Protection – Zoning Arrangements

And they coated that titanium with mixed metal oxides which made it as conductive as they could get it. And then they put a layer of cementitous material on the top. So this was actually to develop the anode side, that means the passive current.

So these two systems were the main ones that came out of the trial

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Thermal sprayed zinc

that were actually showing promise and they started to use them. Later they started producing more products, as you know once the idea comes out people start thinking about, manufacturer starts producing things.

And they start producing what we call the

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Ribbon anodes applied
to the underside of a jetty in Jersey

ribbon anode which is this, it is basically very fine mesh but it is in small sizes so it can cut the concrete. Rather than putting over across the surface the concrete, you can put into slots (()) (17:16) in the concrete at regular intervals like this.

And they also develop what we call discrete anode so

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Discrete Anodes

the simplest one obviously, just the short cut (()) (17:29) of this ribbon. But they start introducing tubular anodes that you can actually insert into real holes in concrete, very useful if you need to get a steel reinforcement very, very deep into the concrete and it is a critical area that needs protection.

You can then drill a hole, put an anode inside, very close to the, to the steel that you want to protect. And this is another way of doing, just make a grid,

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Impressed Current Cathodic Protection

Discrete surface mounted titanium oxide tile system

on to your structure, drill the holes on to the grid and then just insert the anodes at appropriate distances. And that just gives a global protection of your structure.

Ok so a little bit of electrochemistry. The original idea that they have was that if corrosion is happening as it happens underground with pipes and anywhere this corrosion process, what you are trying to do is reverse that corrosion process.

You apply a charge that opposes the corrosion which is the anodic reaction. So you produce a cathodic reaction on to a surface, try and eliminate the anodic reaction.

So the

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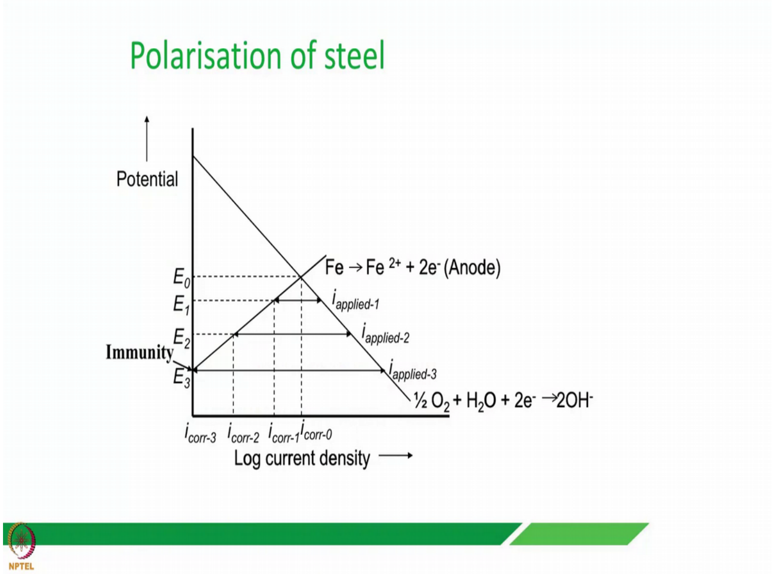

Polarisation of steel

original idea was Ok. This is what happens when you have iron and it is corroding. It is an anodic reaction which I talked about before if you remember, as cathodic reaction which is oxygen and water picking up the electrons from the anodic reaction.

And together they polarize to this level here which we call the corrosion potential. So if you go on to a site and you use a reference electrode you can actually measure the corrosion potential of the steel reinforcement. It tells you whether the steel is corroding or not.

So whether it is below minus 200 roughly. It means it is corroding. If it is above, remaining is corroding. If it is minus 400, it is definitely corroding. If it is above minus 200 roughly then you assume that it is passive. But you measure that from the surface of the concrete.

But that also gives you a corrosion current which you can also measure. There are some techniques that allow

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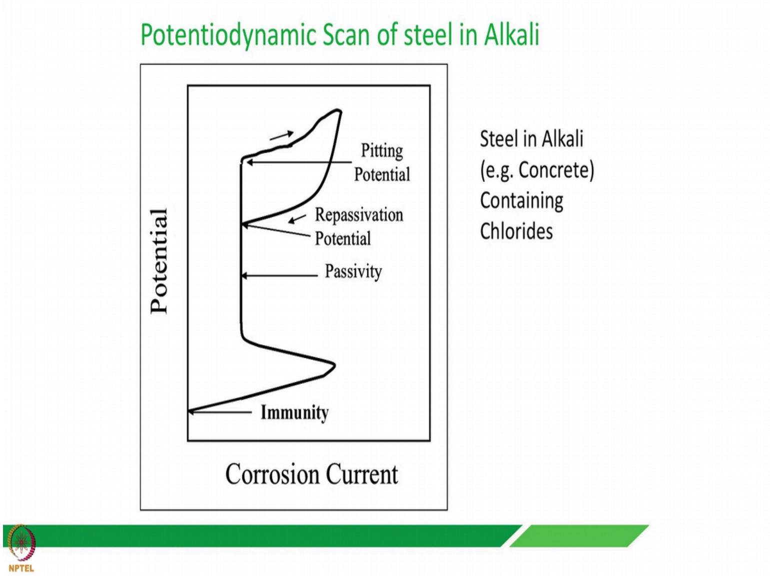

Potentiodynamic Scan of steel in Alkali

Steel in Alkali
(e.g. Concrete)
Containing
Chlorides

you to measure that. And this is the corrosion current.

So what you do, when you are applying a certain protection; this is the current that you apply to oppose the anodic reaction. When you are dropping your corrosion current to a lower value and you are pushing the potential lower.

Now let us not confuse our potential with the corrosion potential. It is a different potential, it is a force potential. So it does not mean that it is corroding more because the potential is lower. It just means that you are now protecting it.

You can apply a larger current and reduce the potential further, reduce the corrosion rate further. But the original idea was let us try and stop corrosion altogether. So we totally opposed the anodic reaction with enough current and now we get zero corrosion.

But to achieve that, it was seen that we actually have to produce a lot of current. A lot of current could also have side effects. First of all the anodes may not be able to do it. So you need to develop special anodes.

Secondly the structure itself, if it sees too much current, it starts to get a bit stressed and it may, may increase the porosity, so thankfully we realized that steel does not actually behave. So we do not need to go down to immunity.

And steel reinforcement in concrete actually has a shape like this which means it no longer goes straight up like that but one, at a potential, the potential, the corrosion current drops down to very, very low level.

And this because of the passivity that I talked about before. You have got hydroxyl ions there. They produce this oxide film on the surface. And therefore corrosion does not happen. But it is very, very small.

So what they then realized really was that to achieve cathodic protection you did not have to go down here where it is immunity but you could actually hold it somewhere up here. Now when you get corrosion, it means you have exceeded what we call the pitting potential of the steel reinforcement.

Once you have exceeded that you have to bring it back past the re-passivity potential which is lower than pitting potential and into this region here which is passivity. So bringing it from up here to here, it is much less work that bringing it all the way down here. So it requires less current.

So let us not bring it down to immunity. Let us just keep it in the passive region. Now there is another thing that we realized obviously is that as you increase the chloride content

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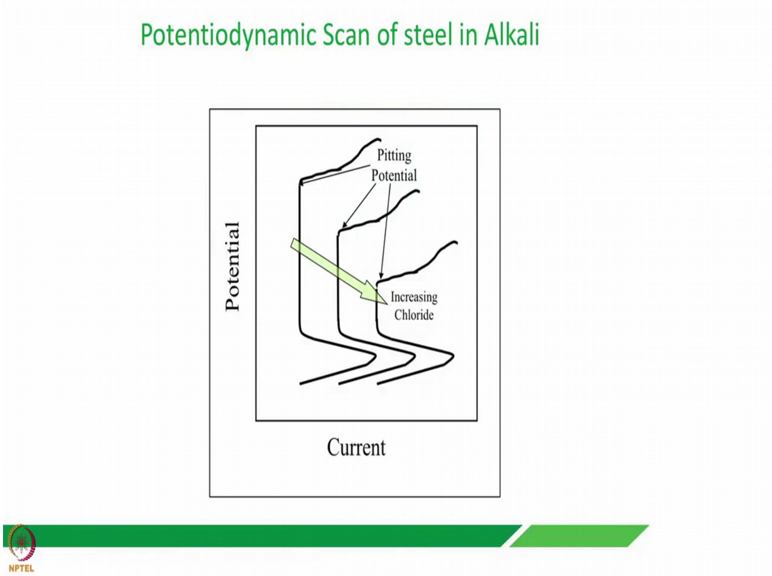

Potentiodynamic Scan of steel in Alkali

this pitting potential gets lower and lower.

So it means you got a smaller window where you can actually apply the current to achieve passivity and it gets lower and lower.

So you have to, the more chlorides, the more corrosion, the more current you have to apply to bring it lower down. But if corrosion is not very much then you do not need much current at all.

So the current that you apply relates to the level of corrosion that you have in the first place.

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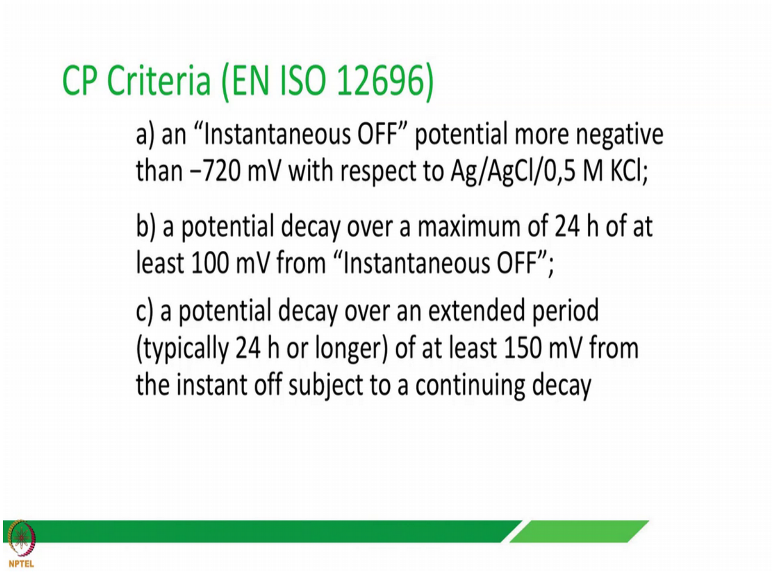

CP Criteria (EN ISO 12696)

a) an "Instantaneous OFF" potential more negative than −720 mV with respect to Ag/AgCl/0,5 M KCl;

b) a potential decay over a maximum of 24 h of at least 100 mV from "Instantaneous OFF";

c) a potential decay over an extended period (typically 24 h or longer) of at least 150 mV from the instant off subject to a continuing decay

Now people have come together.

They have brought about a standard which is a nice old standard, Clause 6 9 6 which is used throughout Europe and they try to encourage people to use this standard because they believe it shows you how you know that your system is working.

Now the first thing was that you need to reach immunity. Well, you do not need to reach immunity but if you do, if you apply current and you see that your potential goes to immunity which in this case is minus 720 milli Ohms then everything, you know that is working.

That can happen if you have a low availability of oxygen. And therefore you apply more current and somewhere the potential drops very, very low.

So it tells if it is minus 720, do not worry about anything else your system is working. But in most cases, that is not the case. There is plenty of oxygen available.

And so they suggest that you switch off the current and immediately measure the potential of the steel. You then wait 24 hours, go back and measure it again and the difference between the two, they termed the depolarization potential. And that depolarization potential needs to be 100 milli volts or more.

And then they give you another way out if you do not achieve a 100 milli volt through polarization. Then you wait longer. If it is saying 70, you say well, is he working, is he not working?

It can wait 2 days, 3 days, 5 days and that instance the potential needs to drop by 150 milli volts. So you need a depolarization potential of 150 milli volts. But in most cases, a 100 milli volt depolarization is majority used.

But what is this 100 milli volt depolarization actually based on?

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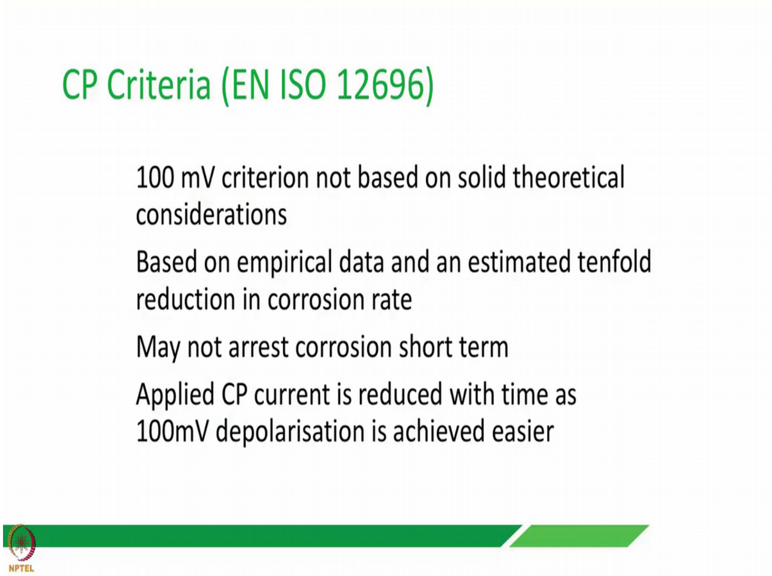

CP Criteria (EN ISO 12696)

100 mV criterion not based on solid theoretical considerations

Based on empirical data and an estimated tenfold reduction in corrosion rate

May not arrest corrosion short term

Applied CP current is reduced with time as 100mV depolarisation is achieved easier

In fact there is no solid theoretical background on this. It is more as an empirical kind of situation where you can imagine that 100 milli volt, if you look at the mathematics, know the rest of it; it is roughly a ten time decrease in the corrosion rate.

So if the corrosion rate is 10 milli amps per meter square and you bring it down to 1 milli ampere per meter square, that is fine. That is good enough. So roughly if you decrease by 100 milli volt, you decrease the corrosion rate 10 times and the corrosion rate is not enough to cause major problem.

There is (()) (26:02) ten-fold decrease in corrosion rate but it may not totally arrest corrosion. Most of the times that is not important because it is a low corrosion rate. And what we found is that with time it actually gets lower and lower.

When they go first time they adjust the current to get 100 milli volt depolarization. Then they have continually monitor that and then they see that depolarization after 2 months or 5 months is actually higher than 100, it is 150.

So they are encouraged to turn that down because they do not want the system to be overrunning. They bring it down so it is again 100 milli volt. And then they bring it down again, and again.

But that tells us something. It tells us that the corrosion rate must be decreasing. It must be doing something good to the steel reinforcement because it requires less current to achieve the required polarization.

So this also are the lessons that we have been learning over the years of collecting of this information. And there is additional information which I already talked about.

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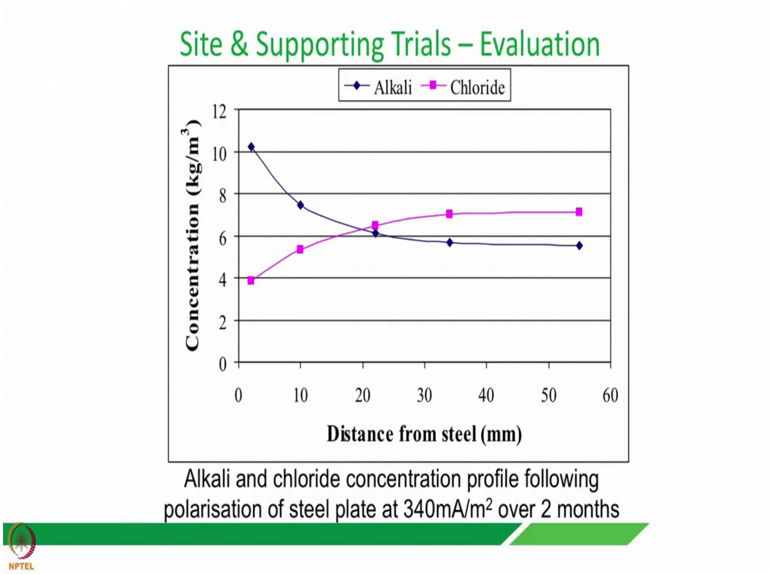

Site & Supporting Trials – Evaluation

Alkali and chloride concentration profile following polarisation of steel plate at 340mA/m^2 over 2 months

If you apply cathodic protection and then you measure the alkalis near the steel reinforcement, the chlorides you can see that it will actually increase the alkalis considerably when you reduce the chlorides from what it was originally which is the, this baseline.

So again that is another benefit. You are reducing chlorides, you are increasing hydroxyl ions. You are benefiting the steel. Corrosion must be getting lower. And that ties up with the 100 milli volt depolarization which is easier to achieve.

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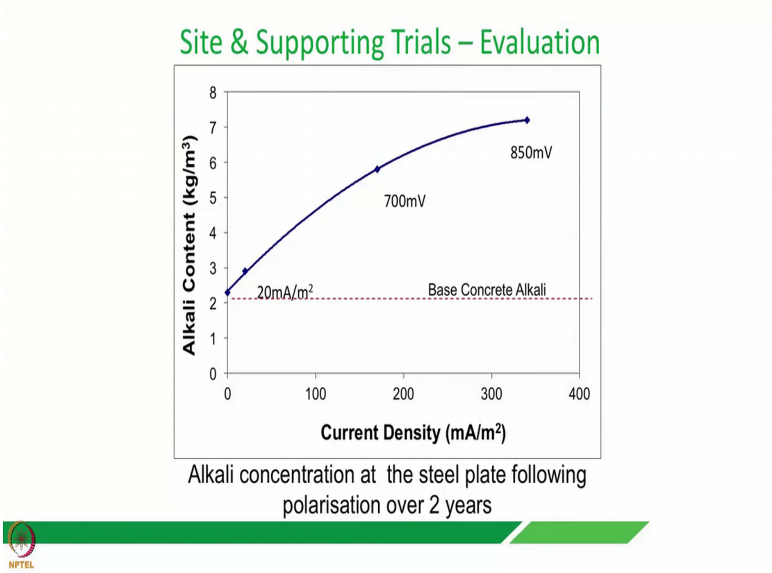
Site & Supporting Trials – Evaluation

Alkali concentration at the steel plate following polarisation over 2 years

At the University we were showing that. To reach immunity which was the original idea you would need to go this range of potentials and that produces a very, very high increase in alkalinity.

But look at the currents that we have to use to achieve that. We are going up to about 340 milli amps per meter square. That is huge, that is way too much.

Eventually we realized that we only need 20 milli amperes per meter square but even at 20 you are getting a significant increase in the alkali concentration. So that process is still happening. Ok so how will you...

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The case for Sacrificial Anode CP

Sacrificial Anodes – Cathodic Prevention

Now I am going to talk about the galvanic anode cathodic protection which is produced by a different metal. Now if you think of the electrochemical series, we have, at the very top we have gold. And then we have platinum and we have copper. And then we have iron and at the bottom we have zinc, aluminum, magnesium.

They are placed in the order because of their activity and if we imagine in nature gold is gold. You do not have to do anything with it. You find it and it is already gold.

But with the other metals you have to extract it from its ore. And the harder it is to extract, the more activity it actually has and it wants to try and get to back to its nature which is the ore, the oxide. So if we choose two metals that are of different activities.

So you have iron or steel and you have zinc which is much lower. You connect the two together; you are actually forming a battery. You have two half cells of the battery, one becomes the anode, the other becomes the cathode, and then current flows between the two.

And that is actually what batteries are. We have two half cells within a battery. When you connect them to something then the current flows and this exactly we are doing here.

We have zinc which lower down the electrochemical series, we attach it to steel which is higher up and therefore as soon as you are connecting together this current flowing.

And the current flowing is introducing electrons because it was zinc going to the solution produced the electrons, they moved towards the steel and that immediately becomes the cathode, there is no corrosion.

So you are actually protecting the steel with the zinc. But what is the side effect? You are obviously reducing the amount of zinc that you are having.

You are consuming it. And therefore it has got a finite life. But people have tried to, I have tried this idea of putting zinc on concrete, try and see whether it works. And it did not work.

The reason was that zinc can actually passivate itself when it is in contact with the concrete. And you need to have an alkali greater p H greater than 13 point 3 to maintain the activity of the zinc.

So what we actually managed to do here is to introduce very high alkali levels in the form of lithium hydroxide. If you have such a lithium hydroxide it goes at the very top of the scale of p H, it goes to 14 and a half.

So it is very, very alkaline but it is consistently alkaline because it such readily buffers the solution and you have a constant high p H in your environment.

That forces the zinc to corrode and protect the steel reinforcement. This surrounding mortar also has a high porosity.

And this high porosity allows the corrosion products that are formed by the zinc core (()) (31:48) which are in fact in this high p H that they are soluble and therefore they can migrate within the pores

And then when they reach super saturation they get precipitated out but they are away from the zinc and somewhere around the pore structure. So you need the porosity to contain all those corrosion products.

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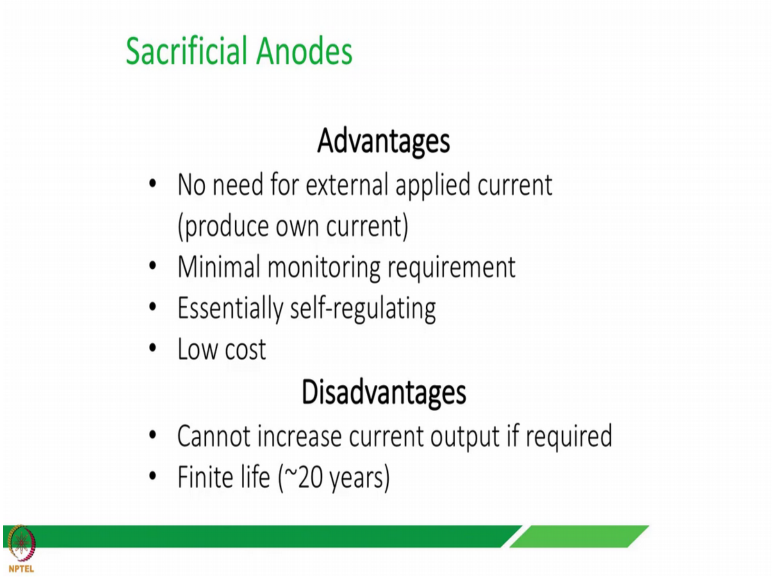

Sacrificial Anodes

Advantages

- No need for external applied current (produce own current)
- Minimal monitoring requirement
- Essentially self-regulating
- Low cost

Disadvantages

- Cannot increase current output if required
- Finite life (~20 years)

The advantage of using galvanic, or the protection of galvanic anodes, well of course there is no need for an external power supply so you do not need wires, we do not need power supply, it is quite simple. Users can attach the anode to the steel reinforcement.

Again having to monitor the structure when you apply the impressed current cathodic protection to maintain 100 milli volt polarization, to make sure the current is flowing, to make sure the system has not broken down, there is continuous monitoring involved over the number of years you actually have the system running.

But this one because it is self-regulatory, it just does what it does, it supplies current as long as the zinc is there, there is less requirement to monitor. You monitor only because you want to make sure that it is working and satisfy the client that it is working. Otherwise if you forget about it, it is still working.

So it is essentially self-regulating. What it means is that if the temperature goes high and the corrosion activity is high on the steel, so is the corrosion activity on the zinc.

So it produces more current. If the structure goes dry and there is no more need for the current to flow, well it does not. Because the resistivity increases so it just does what it does and it does it well.

And so, so relatively low cost compared to, depending on the size of the area you are protecting. If you are going to protect the small area like that there is absolute no sense in using an impressed current cathodic protection because you got the whole system to install to just protect the small area whereas here you put few anodes in, that is it.

The disadvantage is of course you cannot turn the current on and off whenever you want as you can do with an impressed current cathode protection and it has got a finite life. It can only last as long as the zinc is there. So if the zinc is consumed then that is it, it is finished.

Ok so after developing in the lab we tried out on a real

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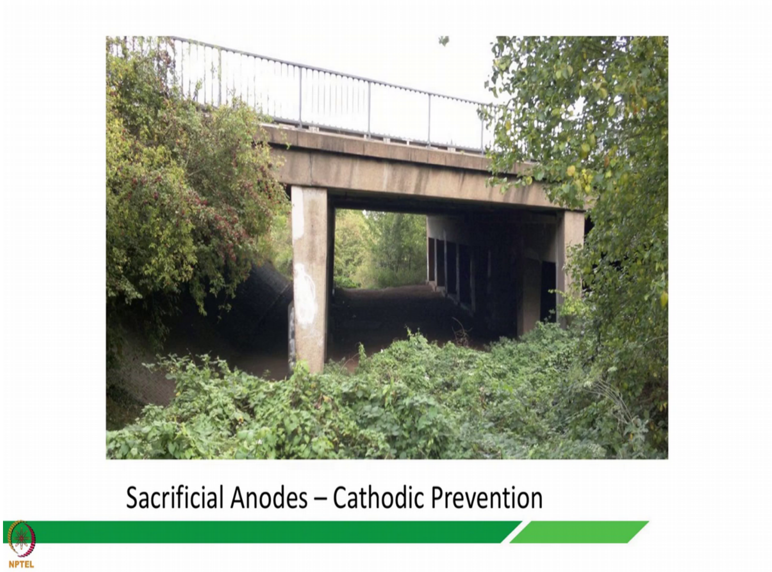

Sacrificial Anodes – Cathodic Prevention

structure to see how it works. This is quite a long time ago. This is the bridge in the U K that needed, basically a patch repair.

So we removed the concrete

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Sacrificial Anodes – Cathodic Prevention

that was contaminated and was causing corrosion of the steel reinforcement. There were cracks all along this section of the crossbeam.

We removed the whole concrete and then positioned galvanic anodes on the periphery over the concrete. One of the things that happens if you apply patch repair straight on without any galvanic anodes is that you are shifting the corrosion process adjacent.

The reason being is that you are cleaning the steel, you are making it absolutely cathodic. It is not going to corrode so naturally there is a tendency to try and form anode somewhere else.

And because the surrounding concrete is older, and may contain a few chlorides, it is a natural position for the anode to stop. So this was the problem that people were having when they were patching up the concrete, corrosion starts all around it.

So we thought Ok, if we put these anodes in there and we protect that small area around that steel reinforcement around the patch hopefully we will not see any corrosion.

And the fact that is exactly what happened. We did monitor instead of connecting as you normally do is that the zinc straight on to the steel, we connected it through wires and through junction box. And then back to the steel that meant we can interrupt the current and therefore measure it.

We could switch it off and measure depolarization and depolarized potentials. And the current, this is coming upto 20 years now, the next reading

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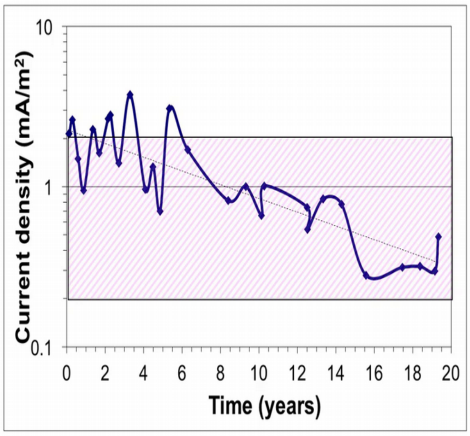

Current density output of galvanic anodes

we will take will be about April which will be exactly 20 years. And you can see obviously it is reducing.

The main reason why it is reducing is because you are getting less and less surface area of the zinc and it is getting smaller and smaller that is why it produces less current.

But there is also a small loss in the current because you are now beginning to fill up the pores with corrosion products and there is less electrolyte for the current to flow. But as long as we know that and we know the history, we have the history now of how the current drops with time we can design for that.

This is basically the peaks in the process related to temperature. It is amazing how much the temperature variation varies the current. So these were summer readings, these were winter readings and so also you can see that it was a very good summer, that was a very good summer etc.

So what we did, the polarization potential which tells you whether the steel is corroding or not

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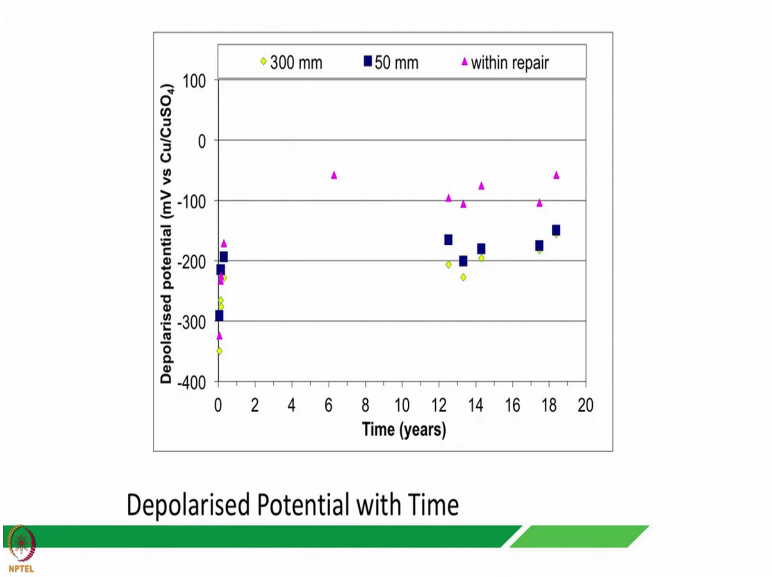

Depolarised Potential with Time

and the next time that tells us that if you potential with respect to copper sulphate electrode, which is a standard reference electrode that measures potential If it is less negative than minus 200 milli volts it means that your steel is not corroding.

We can see that earlier on the potentials were very low and therefore the steel was corroding but very quickly within the patch the potentials became extremely positive or less negative

And therefore were extremely passive which would of course actually a problem outside, because it would have been a potential gradient and that would have allowed corrosion to occur but because of the zinc the potentials outside the patch repair were also quite passive and therefore not corroding.

So the system has worked for 20 years now. There is no cracking. So we are confident that by doing that you are preventing problems that would occur if you just apply a passive (()) (38:39).

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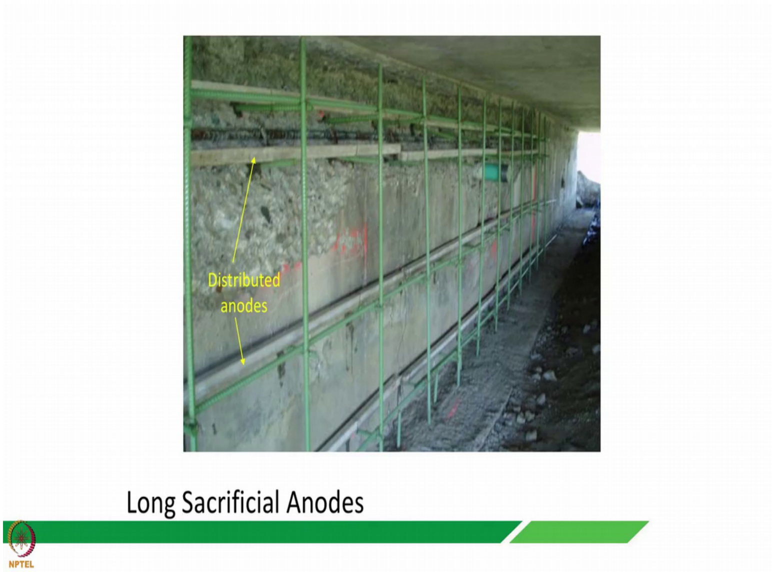

Long Sacrificial Anodes

But then we moved on from that and started to look at larger anodes.

And this is basically, it is the same kind of anode but in a long, long strip so you can actually put an anode right across the hole of the structure by increa (()) (39:00), because you are increasing the surface area you are also increasing the current output

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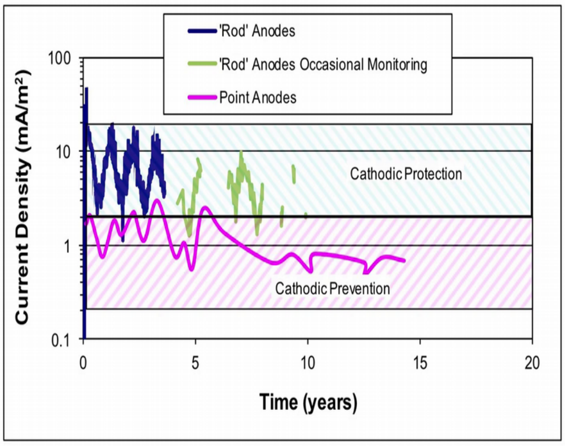

Current density output of galvanic anodes

And therefore it was the current of the previous one that I showed you. Comparatively speaking you have a 10 times increase in the current from these larger anodes and we are now talking about current densities are recommended for cathodic protection.

So we now realize actually we have large enough anodes that produce large enough currents we may be able to protect the steel completely in certain situations. So we started developing the other anodes that we could put into holes,

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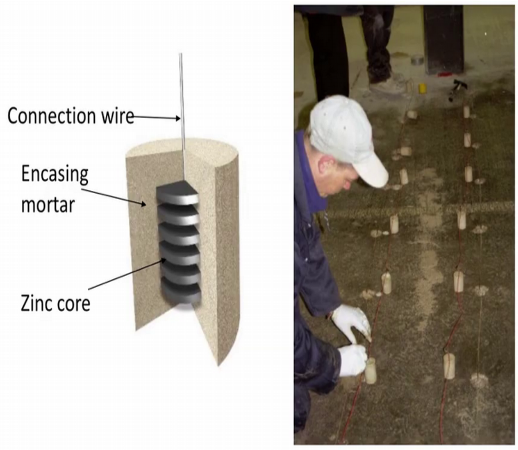

Sacrificial Anodes – Cathodic Protection by reducing corrosion rate

and drlll holes you can put in a grid formation like this. And that gives you a global protection.

This is for concrete that has shown signs of corrosion. It has got chloride contamination but there is no cracking yet. So it is quite easy to continue from there and say Ok, no more corrosion. So you attach these anodes to the concrete.

And this is the structure that was actually receiving both types of anodes. Where there was cracking

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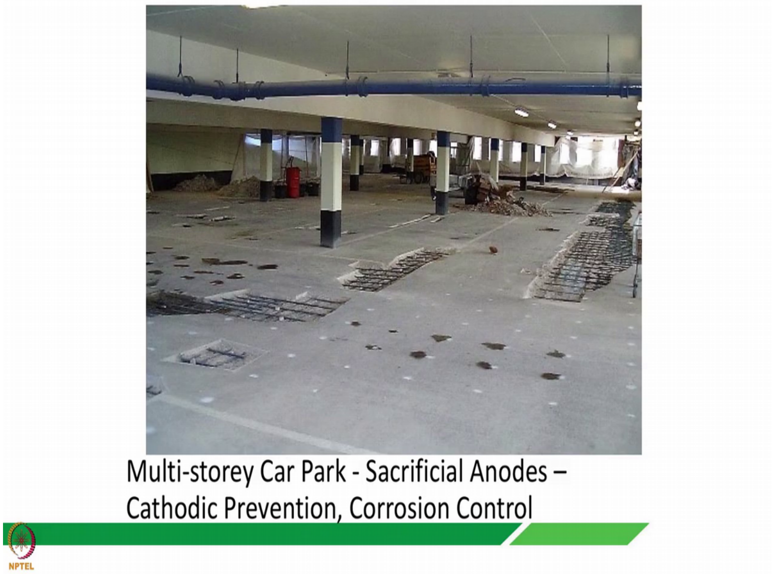

Multi-storey Car Park - Sacrificial Anodes – Cathodic Prevention, Corrosion Control

you do your patch repairs and you put your anodes around the periphery like here, and well there was not cracking you introduce your anodes into a grid formation.

But we have to learn more lessons. You know we cannot just stop here. We have done something Ok, fine.

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Anode Installation South Clatterbridge

We introduced galvanic anodes into the process. It has got its limitations. People are still not 100 percent happy with it. So we carried on learning from that

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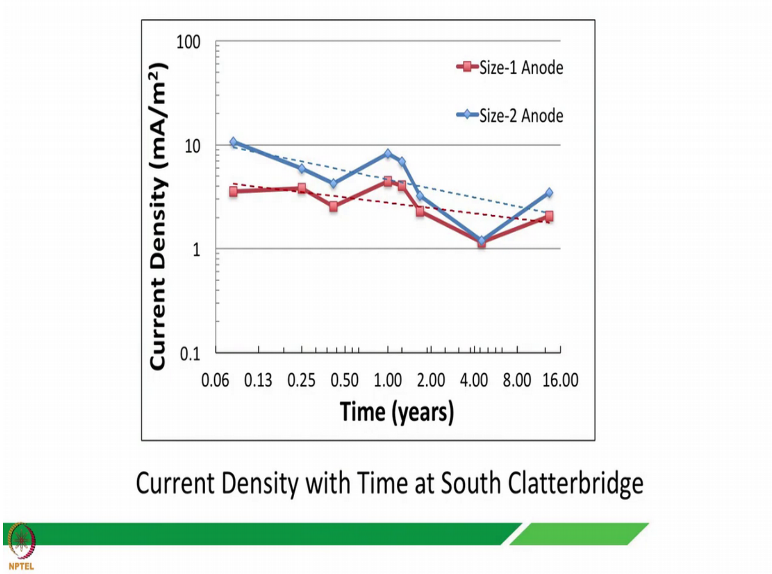

Current Density with Time at South Clatterbridge

and we have a couple of structures that we will be monitoring. That has taught us quite a big lessons.

This particular one, it was two structures very close to each other on a what we call in England, a motorway. It is a road basically, heavy, heavily used road and the road is above here and like we said before they used the icing agency in the U K, and the cause was splashing of these chlorides on to the bottom of the structures.

So we decided to put some anodes there. There was a slight difference in the two. So we decided to put larger anodes in the one and the smaller anodes in the other just to see, study the difference basically.

And this is the current output that we are getting. So the size 1 which is the smaller anode was producing a lower current throughout but they were both decreasing in the same kind of rates. Anode 2 was always producing a high current density.

Up to about 15 years which is what how old the structure actually is, now working the system is.

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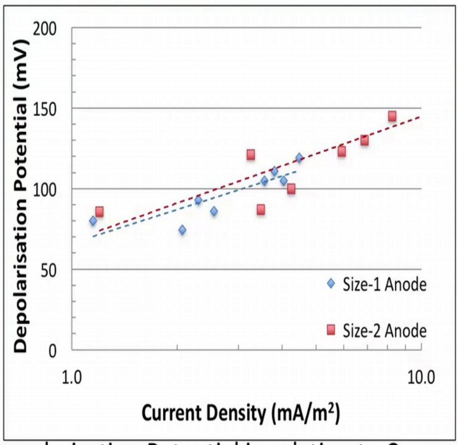

Depolarisation Potential in relation to Current Density at South Clatterbridge

If you remember depolarizations when you switch it off and measure the potential and measure again at 24 hours how much does it depolarize

What we found is quite a good relationship between the current density that we were getting from the anode and the amount of depolarization that we are getting.

And it all sits on a pretty good straight line even though the anodes were different sizes, you can just put one line through that and it will represent both of them.

And when we measured the corrosion rate we saw that we were not actually reducing the corrosion rate, those kind

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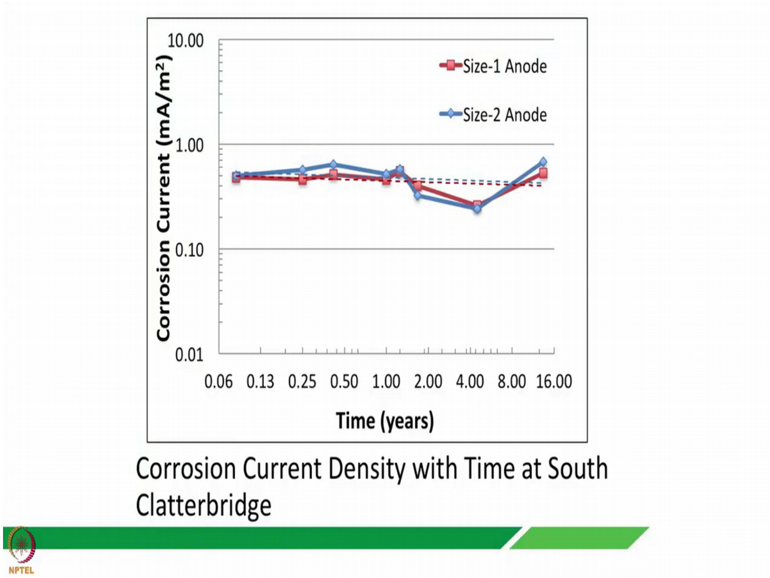

Corrosion Current Density with Time at South Clatterbridge

of depolarizations but we were controlling the corrosion. It was not an increase.

We were keeping it as it was, which means that there was not going to be any, any damage.

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Corrosion Control at Ivy Street- Galvanic anodes at 300mm centres

This one taught us even more, this other structure.

Again we put anodes throughout this apartment but we separated in two zones where we were monitoring the current and the potentials to understand what goes on. And what we had obviously here is again the expansion joint here, chlorides get down, run down the wall.

They penetrate the wall but they do much more damage down the bottom because they concentrate on the ground and they start seeping up into the concrete.

So zone 2 was corroding more than zone 1. But we said Ok, we will use the same anodes in both cases just to learn. And we did so. Even though the anodes were the same we get the different level of current.

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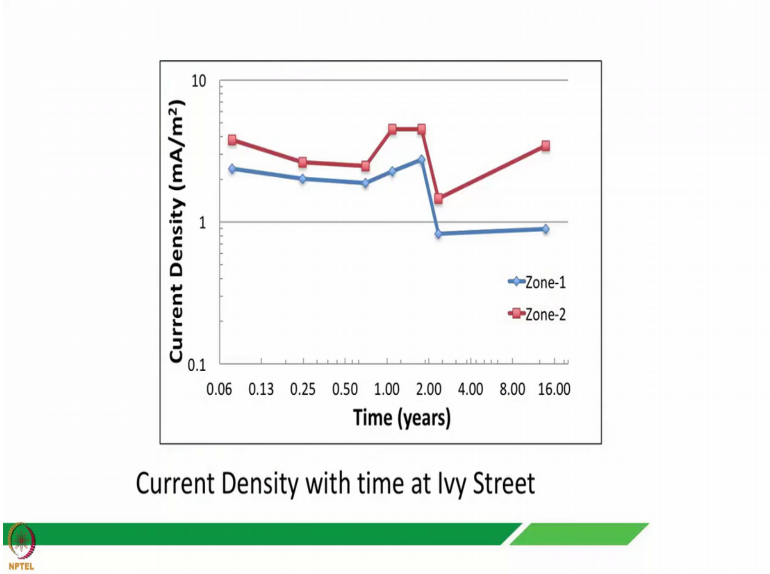

Current Density with time at Ivy Street

Zone 1, remember was the one that was corroding less. Zone 2 was corroding more.

So the area that was corroding more was recieving more current. And we explained that by the resistivity in the concrete. Because when we have more chlorides the resistivities reduce and therefore more current is able to, to get into the steel. So again a kind of self-regulatory way of working.

But what was even more

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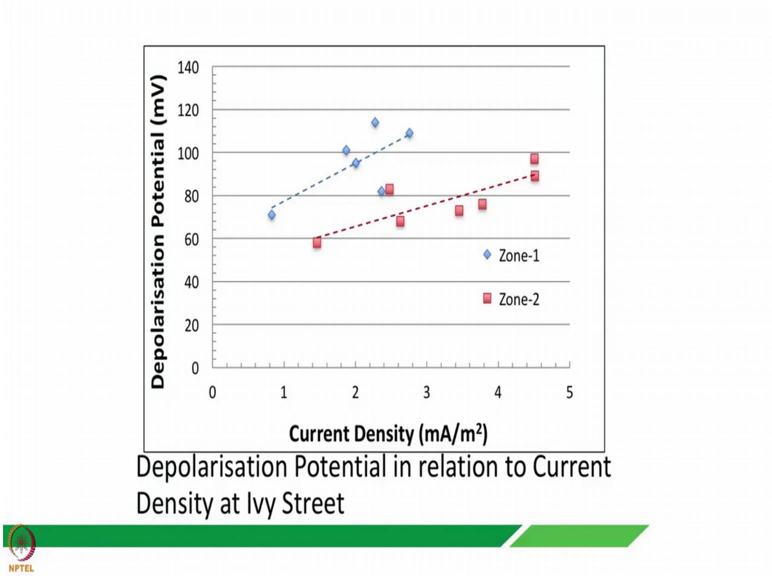

Depolarisation Potential in relation to Current Density at Ivy Street

important for us was this relationship between current density and depolarization potentials clearly very distinct in this way.

We had zone 2 which was corroding a lot. And it was struggling to get a high depolarization potential even though you, we could get up to 4 and half milli amps per meter square we still were not reaching the 100 milli volt depolarization.

Whereas in the lower corroding area, we were reaching the 100 milli volt depolarization quite easily even with less than 3 milli amps per meter square. So it told us that in a almost direct way, look, depolarization depends on the current density.

For any level of corrosion that you were achieving or you are suffering you will get a particular depolarization level if you apply a particular current density.

So we looked into the background of that. One another thing that we learnt from this was actually that the corrosion rate was being diminished in zone 1 which was the lower corroding one.

So we were applying enough, enough current to be actually reducing the corrosion rate, not just maintaining as it was. So again the other lesson was, can we stop corrosion If we apply enough current?

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$$i_{\text{corr}} = \frac{i_{\text{app}}}{\left(\exp\left(\frac{2.3\eta}{\beta_c}\right) - \exp\left(\frac{-2.3\eta}{\beta_a}\right)\right)}$$

where

i_{app} = applied current density

i_{corr} = corrosion rate

η = electrode potential shift

β_a, β_c = Tafel slopes.

Butler Volmer Equation

So we looked at the Butler Volmer equation which describes the anodic, cathodic reactions in, in the system and we could see that we could actually find a relationship between the applied current that we have and the depolarization potential. Everything else you can keep constant.

These are the Tafel slopes that they do not change. So you can determine the corrosion rate by knowing what your current you apply is and relating it to the depolarization potential.

But what you can actually do is draw a chart of this sort

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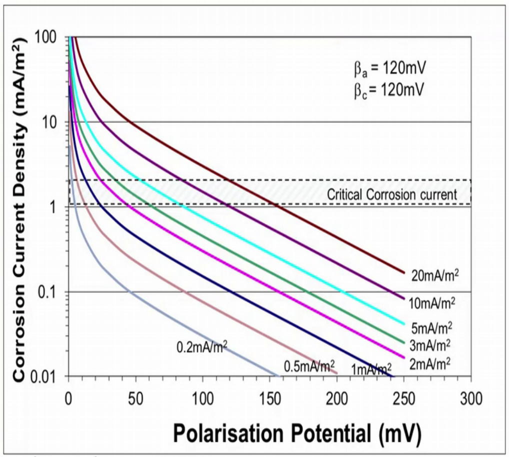

Butler Volmer Equation

So for every current density you would have unique line, so point 2 milli amp per meter square is that one, 20 is up here, and all the others in between.

So you can look at how, polar (()) (46:53), the corrosion current density determines what the depolarization potential you get according to how much current you can apply.

So if we look at 100 milli volt depolarization which is what the standard tells us, does it actually mean a lot? Because if we got low corrosion you do not need very much current to achieve it.

If you apply 200 milli amps per meter square you are actually not stopping corrosion you may be reducing it but you are above the critical level which causes cracking.

What the very, very important thing that we realized was that even at 20 milli amps per meter square, this is from historic data, I told you before that depolarization that was getting larger and larger.

Well this is how it is explained. We have 20 milli amps per meter square that you are applying. Corrosion rate is quite high but with time this depolarization is increasing.

Ok they are bringing it down now, try and achieve 100 milli volt every time but if you let it run you will see that it will be moving along that line and eventually will get to a lower level of corrosion.

So not changing the current density, keeping it the same means that you reach a point where you can stop corrosion.

And that was really significant, significant discovery. We tested it out in the laboratory. We used

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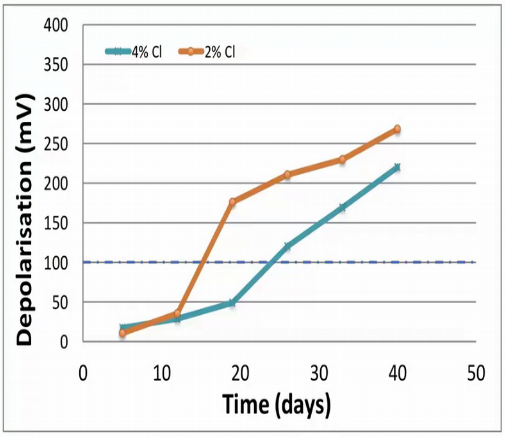

Change of 24 hr depolarisation with time with applied current density 50mA/m^2

specimens that contained various levels of chloride and this example we have 4 percent of chloride and two percent chloride, both high levels which cause corrosion.

So the samples were pre-corroded and then we try to apply cathodic protection. We tried 20 milli amps per meter square to start with but the corrosion rate was so high that we were really not achieving much depolarization. It was less than 50 milli amps.

So we thought Ok, let us increase it to 50 and when we increased it to 50, gradually we were getting more and more depolarization and to reach we were exceeding 200 milli volts depolarization. So it kind of proved the point that with time you are able to protect your steel better and better.

But even more significantly when you look at the depolarized potential which is the measure of corrosion actiivity we were seeing that early on, we were getting very, very negative potentials, very highly corrosive potentials but with time, just look what happens.

We have reached in this case, around minus 200 which is now passive, it is not corroding anymore. And we changed the measure here. We thought Ok, time does not mean a lot. It must depend

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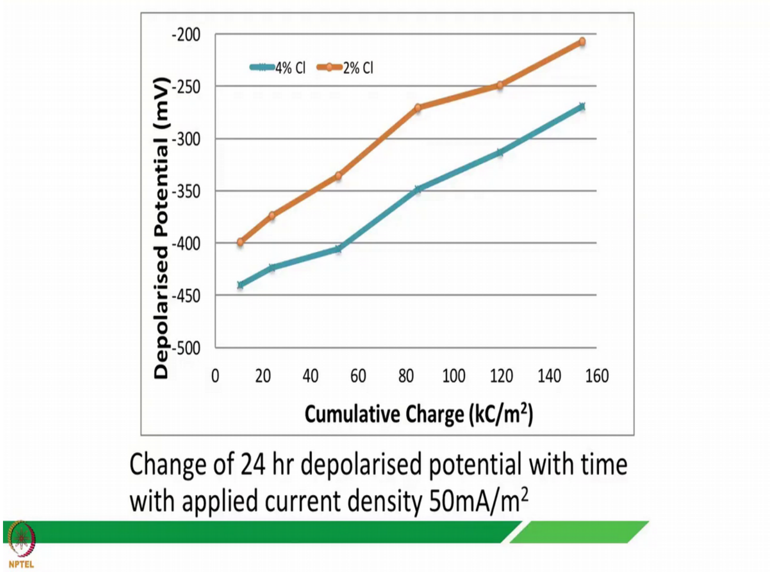

Change of 24 hr depolarised potential with time with applied current density $50 mA/m^2$

on the current density as well.

So we changed that to total charge delivered to this steel reinforcement, charge being the current times the time that you apply it for. So it is amps times second is Coulombs and here we got kilo Coulombs per meter square of steel.

So when we applied 150 or so kilo Coulombs we see that we were getting to a situation where we were starting to stop the corrosion.

We continued with that to see, to prove that we cannot stop corrosion and this is a sample which is 3 percent chloride,

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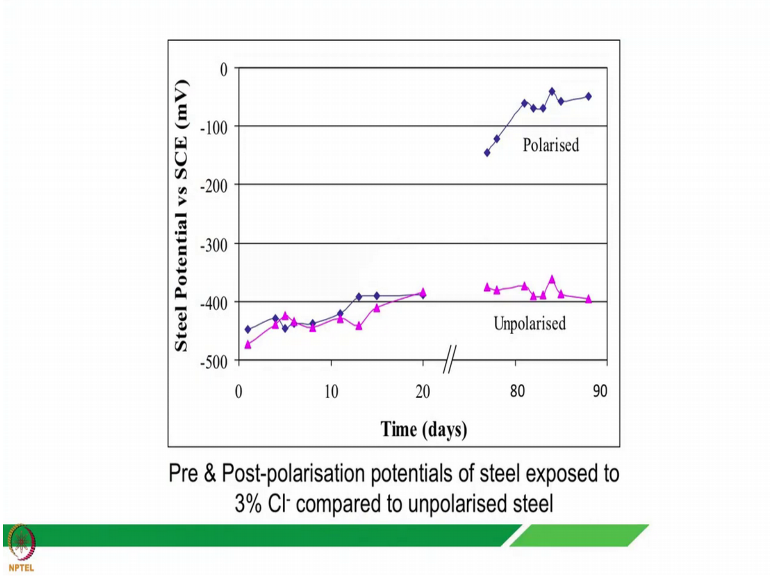

Pre & Post-polarisation potentials of steel exposed to 3% Cl^- compared to unpolarised steel

both samples

corroding but then on the one sample we applied polarization and we see that we stopped corrosion. On the other sample which is continued without polarization and still corroding.

So that is quite a neat result that shows yes, we are able to stop corrosion. And then we looked at different current densities and different levels of chloride to see

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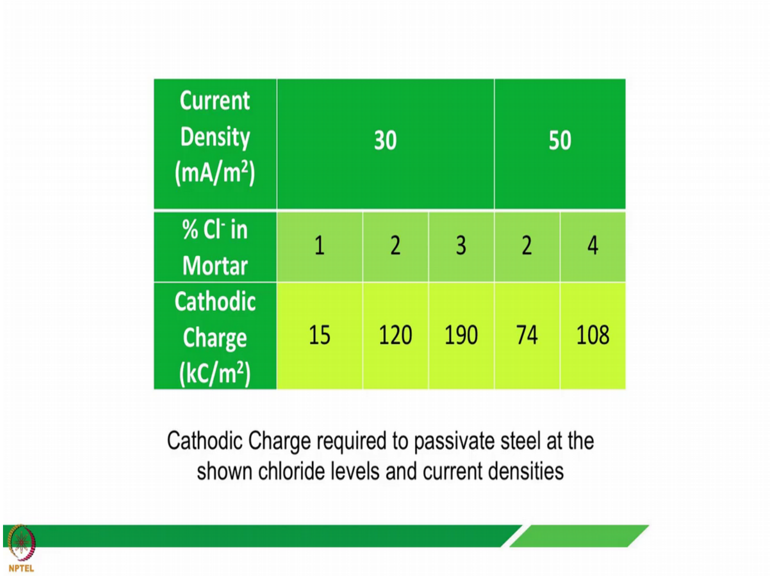

Current Density (mA/m^2)	30			50	
% Cl^- in Mortar	1	2	3	2	4
Cathodic Charge (kC/m^2)	15	120	190	74	108

Cathodic Charge required to passivate steel at the shown chloride levels and current densities

how much charge was required to stop corrosion.

Stopping corrosion was measured by the depolarized potential getting to 150 milli volts, minus 150 milli volts with respect to calomel electrode.

And what we found was that these are the values for 30 milli amps. If it was only 1 percent chloride, it was very relatively easy to stop corrosion.

But then at 2 percent we needed 120, for 3 percent 190, but if we increase the current to 15 for the same level of chloride we are requiring much less charge to stop the corrosion.

Even at 4 percent chloride that is lower than the 3 percent chloride at 30 milli amps per meter square so it also depends on how quickly we apply the charge, so on the current density basically as to how successful we are going to be in stopping corrosion

So that proved the idea of using a 2-stage cathodic protection method. So in stage 1

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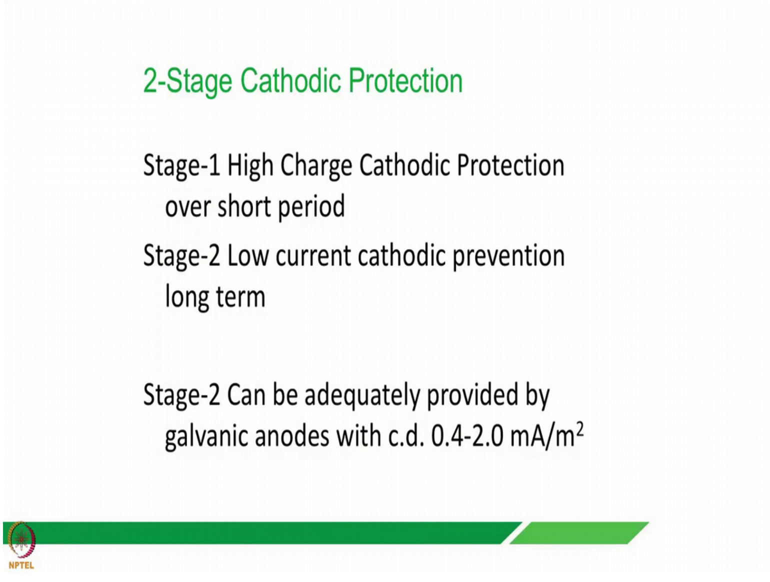

2-Stage Cathodic Protection

Stage-1 High Charge Cathodic Protection over short period

Stage-2 Low current cathodic prevention long term

Stage-2 Can be adequately provided by galvanic anodes with c.d. 0.4-2.0 mA/m^2

you apply very high current density or relatively high current density until you stop the corrosion.

Then once you stop corrosion you do not need this higher current density anymore. You can drop the current density considerably and the protection will continue to occur because of that cathodic prevention rather than cathodic protection, If you remember the patch repairs all we were trying to do was prevent corrosion from happening just outside the patch repair. So we needed quite a low current for that.

And of course stage 2 now can be provided adequately by the galvanic anodes. Because you that the galvanic anodes can produce current densities between point 4 and 2 milli amps per meter square. So we can have stage 1 high level cathodic protection, stage 2 low level cathodic protection.

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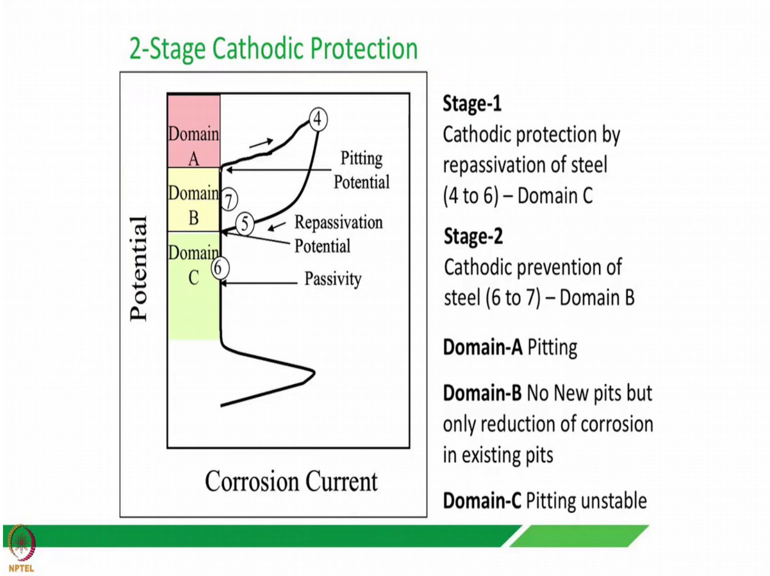

2-Stage Cathodic Protection

Stage-1
Cathodic protection by repassivation of steel (4 to 6) – Domain C

Stage-2
Cathodic prevention of steel (6 to 7) – Domain B

Domain-A Pitting

Domain-B No New pits but only reduction of corrosion in existing pits

Domain-C Pitting unstable

So going back to this polarization diagram this standard tells us and this is actually taken from the standard that if you, steel is corroding and they call that domain A so you are at 4.

When you apply cathodic protection you bring it down to either 5 which is reducing corrosion rate or to 6 which is re-passivating the steel stopping the corrosion.

So what I was always saying here is that we need to go straight down to 6, forget about 5 we need to go straight to 6 as quickly as we can, so we can stop corrosion.

And then when you apply a little current density it does not matter if that potential rises up to above here because it is still below the pitting potential. Once you repassivated it, the other path will be that way. So you can maintain passivity with a much lower current density.

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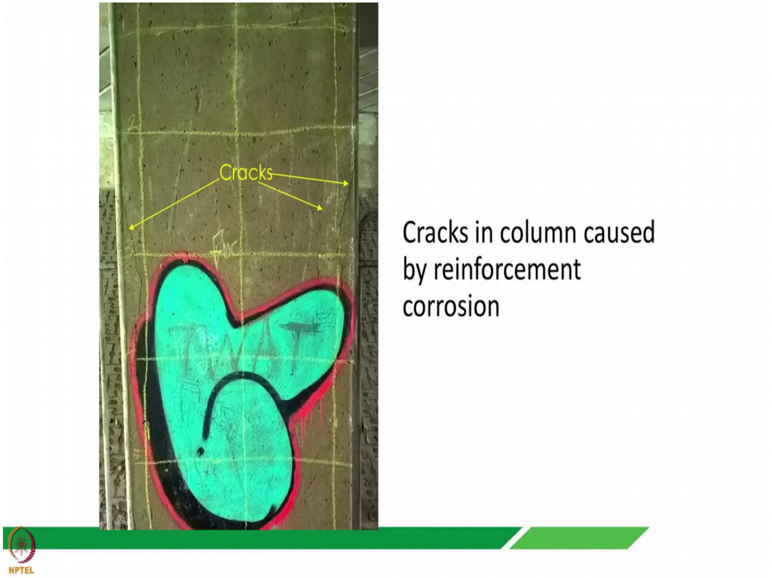

Cracks in column caused by reinforcement corrosion

Ok again you need to try that and see.

So we found another structure also suffering from corrosion. There were cracks on this side, not quite you can see them, I can see them (laugh).

They are here and we removed the contaminated, there was again chloride contamination. We removed all these cracks and then we installed these specially designed anodes.

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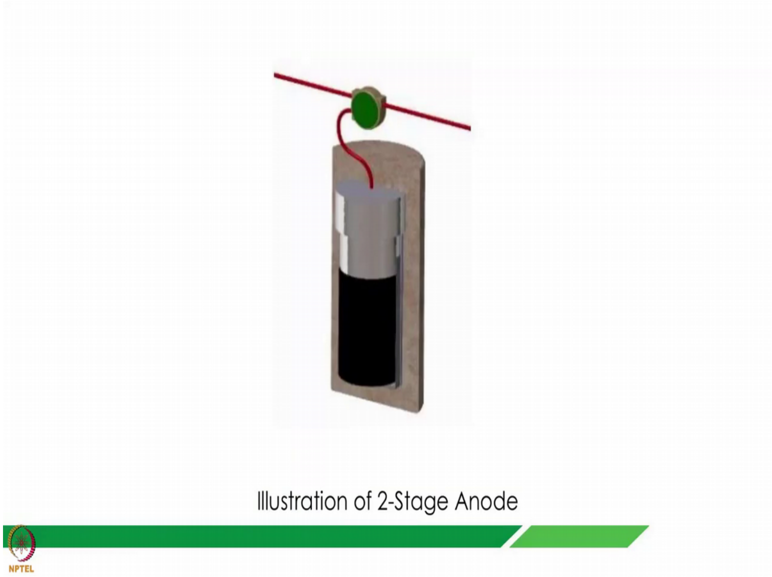

Illustration of 2-Stage Anode

They have actually got both stages in, within that system.

So you have an I C C P element at the bottom and the galvanic anode at the top and it switches from the one to the other. This is switching side allows switch over from one to the other when the I C C P has finished working.

So you can apply a high current density at the beginning and then a lower, subsequently. We installed in that way. It is quite easy to install. You just drill holes

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Installation of 2-Stage Anode

and bury them into the concrete. Originally we added 10

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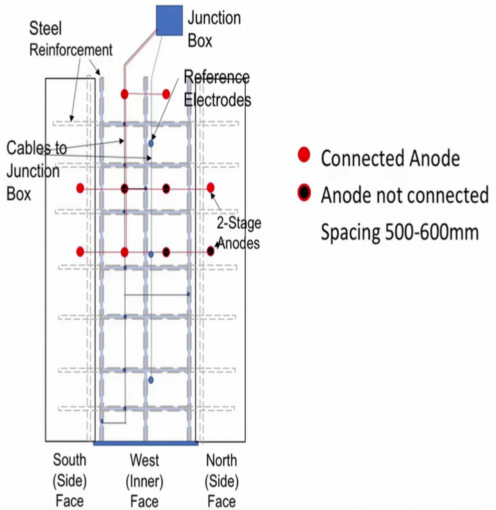

of these units into the concrete. And this was the spacings. But we quickly realized that it was producing too much current.

So we stopped three from working, the four from working and we ended up with just the six. And then we just monitored the current. This is the current that we were getting.

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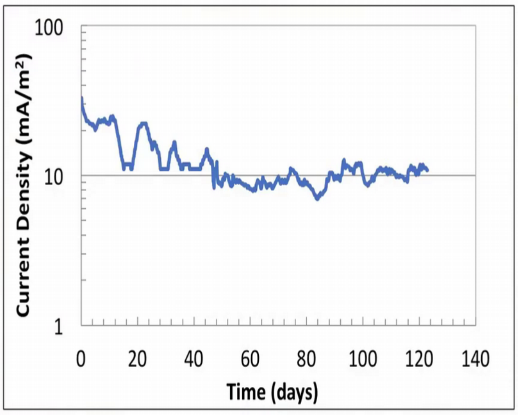

Current density applied to steel during Stage-1 with time

Very high at the beginning and then it gradually dropped and settled at about 10 milli amps per meter square. And we carried it on until 120 days.

Then

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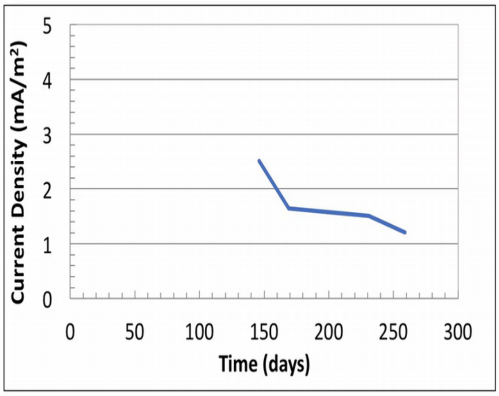

Current density applied to steel during Stage-2 with time

we switched over to the galvanic anode which was producing much less current obviously 1 to 2 miili amps per meter square.

But if we look at the what happens to the depolarized potential of the steel

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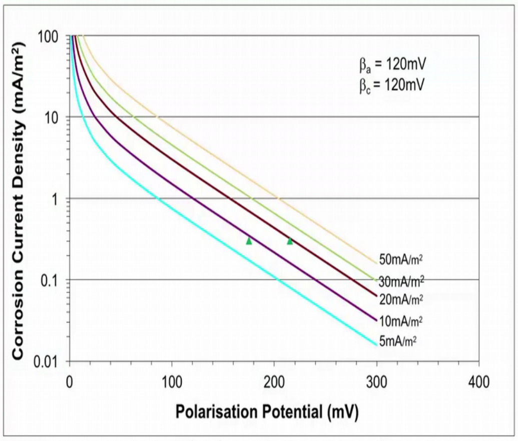

Corrosion current at Ref-1 from Butler Volmer Equation shown against relationship between polarisation potential and corrosion current density at 5 different applied currents

we can see that from a very negative potential, 450 or so

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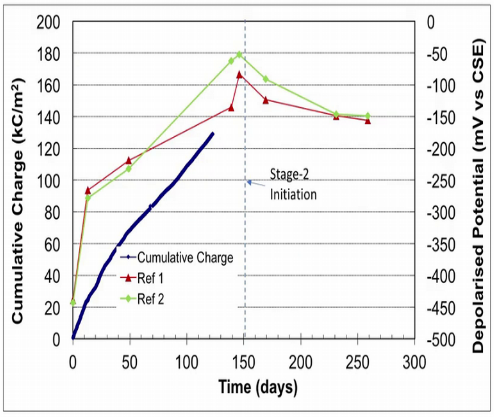

Cumulative Charge applied to steel during Stage-1 and the resulting movement of the depolarised potential towards passivity

it quickly rose up and became passive above here and then it remained passive even though the galvanic anodes were switched on, minus 150 is very passive potential. So it seemed that worked.

And this is the amount of charge that we delivered obviously with time. So within 120 days we delivered 130 kilo Coulomb per meter square

And you see for this structure that was adequate to stop the corrosion. So we continued to monitor that now and see whether the corrosion would stay low as long as the galvanic anodes are working.

So this is also a window into the future. We think that this kind of system would now become part of the wired cathodic systems that we were talking about. So I believe we should be re-evaluating the 100 milli volt criteria.

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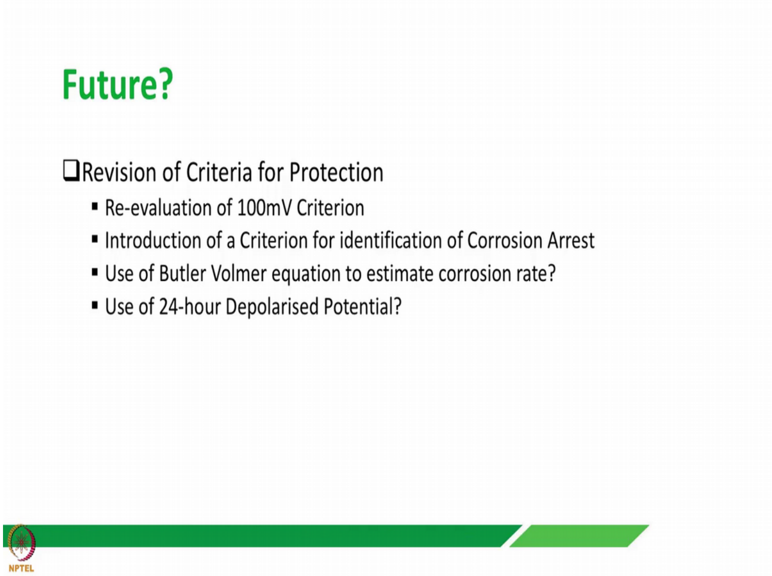

Future?

❑Revision of Criteria for Protection
  - Re-evaluation of 100mV Criterion
  - Introduction of a Criterion for identification of Corrosion Arrest
  - Use of Butler Volmer equation to estimate corrosion rate?
  - Use of 24-hour Depolarised Potential?

Because the way it is, we are not making use of the current that we are applying to the full. We are not trying to stop corrosion. We artificially trying to keep to a number that is empirical, it does not really mean a great deal whereas we are missing stopping of corrosion.

And we can maintain impressed current cathode protection for years and years, making sure this 100 milli volt polarization but we may not even stop corrosion, even as long as that.

So if the system goes wrong and stops, many, many, many reasons for that and then this is one of the problems I C C P anodes, I C C P systems is that there is problem is maintaining wiring, anodes, of power supplies, we got to make sure everything is working all the time, monitoring equipment get, you know become too old and computers, new computers do not work with older systems and so on, and so you lose, you lose important information.

You are no longer able to use the same systems. And therefore there is always a risk sometime the cathodic protection system would fail and this is what we have been finding in the U K, I am talking to engineers and to local authorities and they say, well I have I C C P system. I do not even know whether it is working or not. My boss left 5 years ago and I do not know how, how to monitor and so on.

So this is, so many problems with it. But if you can apply this charger early on and you are confident that within 2-3 months you stopcorrosion then you are just maintaining it, even if the system goes wrong you know at least corrosion has stopped. It gives you some time to try and plan ahead as to what next to do.

So I think introducing the criteria for identification of the corrosion arrest, when is that you actually achieved corrosion, that is an important parameter.

Have I actually stopped corrosion? And if I know I have stopped corrosion then I can be happier subsequently. And I think the use of the (()) (59:33) information may be used for that.

But also the depolarized potential it is hardly ever mentioned in literature. It is not mentioned in particularly, in the standards. Depolarization potential is the best parameter for knowing whether you stop corrosion or not. If your polarized potential is less, more negative, less negative than 150 milli volts it will definitely stop corrosion.

So why bother with anything else?

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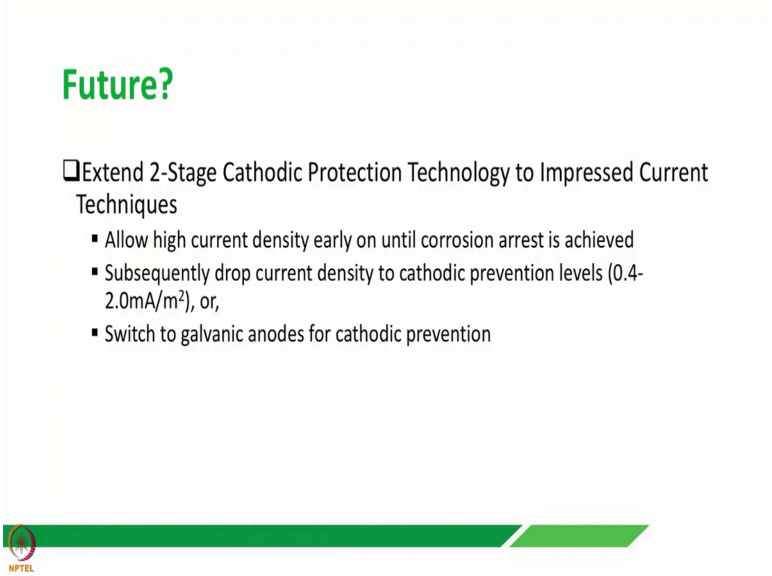

Future?

- ❑Extend 2-Stage Cathodic Protection Technology to Impressed Current Techniques
  - Allow high current density early on until corrosion arrest is achieved
  - Subsequently drop current density to cathodic prevention levels (0.4-2.0mA/m^2), or,
  - Switch to galvanic anodes for cathodic prevention

They are adopted by many more systems, even impressed cathodic protection systems, that is another area for work that we need to be doing to try and establish a way of doing it, by using whole variety of systems.

So we allow a high current density early on to stop the corrosion and subsequently allow the current to drop to lower levels. We can achieve that with galvanic anodes which are self-regulatory.

You do not have to worry about them,

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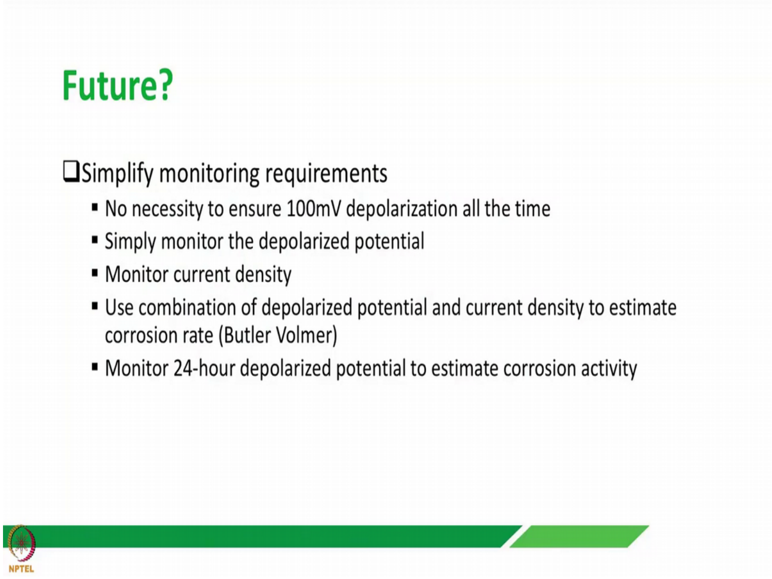

Future?

- ❑Simplify monitoring requirements
  - No necessity to ensure 100mV depolarization all the time
  - Simply monitor the depolarized potential
  - Monitor current density
  - Use combination of depolarized potential and current density to estimate corrosion rate (Butler Volmer)
  - Monitor 24-hour depolarized potential to estimate corrosion activity

is essential, you can get lower than 100 milli volt polarization sometimes and it is still valid that you are controlling corrosion so that with the values. In most case we are getting 100 milli volt but the corrosion current was maintained.

But we need to definitely monitor the depolarized potential, I already said that, and the current. Then use the combination of the two by using the Butler Vohmer equation to give you the corrosion current and monitor the 24 hour depolarization potential to estimate a corrosion activity.

And I leave it at that and let you to think about the future of cathodic protection. Thank you very much (Applause)

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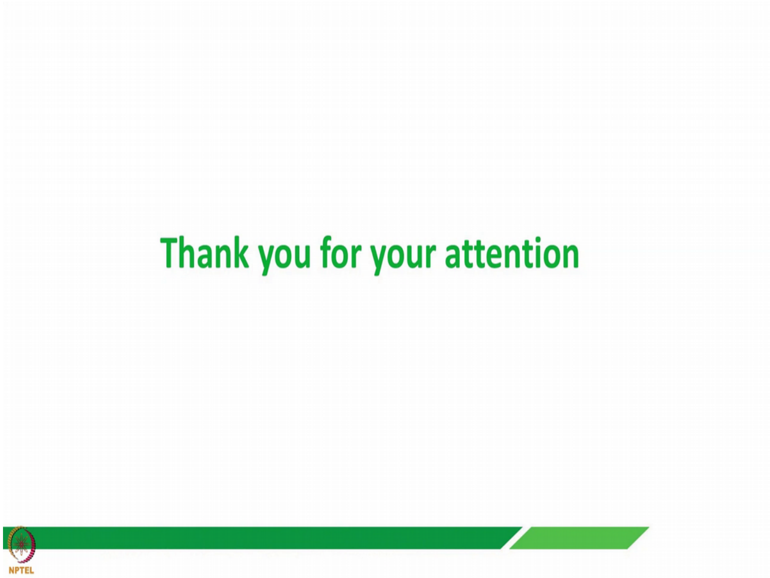

Thank you for your attention