# Transcript – ‘What we Know About Hydrogen Embrittlement’

*Disclaimer: Below is a full transcript of the podcast ‘What we know about hydrogen embrittlement’. While every attempt has been made to stay true to the audio, some parts have been edited for clarity.*

**(00:00:00) SH:** Good morning, and welcome to this episode of the ‘Engineering Undistilled’ podcast. I am Sophie Hobbs. I am the Library and Information Services Assistant here at The Welding Institute and today I am joined by Paul Woollin. Would you like to introduce yourself?

**(00:00:16) PW:** Thank you Sophie. So, I’m Paul Woollin. I’m currently Research and Quality Assurance Director at The Welding Institute. I’ve been here for 33 years and I’ve worked on various industrial applications where avoiding Hydrogen Embrittlement has been important, so I’m pleased to try and answer your questions.

**(00:00:40) SH:** So, today we are going to be having a brief look at TWI’s history with Hydrogen Embrittlement. It’s a long history, there’s about 80 years of it, so we’re going to go on a bit of a whistle-stop tour by looking at the publication history of TWI - some of the key papers and research that we’ve produced, and the developments in understanding that has come out of it. So, I think that we should just get started straight from the top. So -

**(00:01:09) PW:** Yeah, absolutely.

**(00:01:10) SH:** - Yeah. So, for the uninitiated, what is Hydrogen Embrittlement?

**(00:01:13) PW:** Hydrogen Embrittlement is actually a very common phenomenon. It’s been known for a long time. The early research goes back into the 1800s and it’s effectively any material – most materials – if you put Hydrogen into them – now you might say how does Hydrogen get into a material – but because Hydrogen is the smallest atom, if you can produce Hydrogen atoms it can diffuse, particularly into metals, quite easily and then the combination of the Hydrogen atom, however that’s actually formed within the metal, can interact with various microstructural features. And if you apply a load to the material then there’s actually a whole host of mechanisms by which you can get embrittlement or cracking. So, not surprisingly, when people have used metals in various environments where Hydrogen can be introduced, they found a number of cracking problems.

**(00:02:08) SH**: And what environments are – is – Hydrogen introduced to metals?

**(00:02:11) PW:** Ok well the obvious one will be – which is particularly relevant today - is the idea of a Hydrogen Economy where we might have houses heated with Hydrogen rather than the natural gas we couldn’t use, or in a vehicle where you might have Hydrogen in a fuel tank which is burned in a combustion engine or provides power through a fuel cell. So, anywhere where you have to contain Hydrogen. Now fortunately, Hydrogen molecules don’t easily dissociate so the Hydrogen doesn’t penetrate particularly easily into the material that’s containing it, but if you get dissociations you can get some of that – so particularly if you can get high pressure you can get some of the Hydrogen that will diffuse into the metal. The classic example is if you can get corrosion, so if you have corrosion processes like rusting of steel or corrosion of aluminium, you produce some Hydrogen in the process. And if that hydrogen tends to go into the material rather than bubble out into the liquid that’s causing the corrosion then you can get Hydrogen from corrosion and that can fuse into metal. In recent years, probably the biggest examples have been in the Oil & Gas industry and there’s two sources there. One is so called ‘corrosion in sour environments’ or so called ‘sour environments’ I should say. So this is where your Hydrogen Sulphide present. So, you typically have water, some sort of salt, and Hydrogen Sulphide. And what happens is you get corrosion and the effect of the hydrogen sulphide on the surface means that the hydrogen tends to diffuse into the material rather than bubbling off into the liquid. So when you have a sour environment you get a lot of that hydrogen from corrosion, goes into metal and that can cause embrittlement.

And the other one is a lot of subsea equipment, which has become very common again particularly in the Oil & Gas industry. But not only oil and gas but things, large structures, pipelines, on the sea-bed are typically protected from corrosion by attaching them to another material which is more susceptible to corrosion so it gives what's called 'galvanic protection'. So, you can attach an aluminium anode, the aluminium will [inaudible] corrode. But what that means is the hydrogen, you actually generate hydrogen on the surface of the material you're protecting, and again that hydrogen can diffuse in. So, either from corrosion or protection against corrosion, strangely in both situations, you get hydrogen which can penetrate into the material.

So there's actually plenty of ways, unfortunately, which industry can put hydrogen into a material.

**(00:04:43) SH:** And why do you think it is important to understand Hydrogen Embrittlement?

**(00:04:48)** PW: So my own experience has been I say with the Oil & Gas industry predominantly, so people trying to… People always try to push the boundaries with engineering structures. So my own experience it was people developing new oil and gas fields, deeper water further offshore meant that a lot of equipment went onto the sea-bed. So, huge engineering challenges and putting things into deep water to produce oil and gas in an environmentally friendly way so you don't have leaks. So that's a lot of effort gone in to provide you know the – ok we're now in a transition away from Oil & Gas – but it's been hugely important for the world to have these supplies of energy and it's kept the economy and the whole world going effectively for many years now, the Oil & Gas industry.

So when you have a failure in these, particularly pressure retaining systems like a pipeline network, if you have a leak however small you can't then operate the system. And so there have been a number of cases of Hydrogen Embrittlement leading to leaks in subsea and offshore facilities, and having a solution for that has been tremendously important. So finding solutions that are workable in industry has been massively important.

**(00:06:07) SH:** It seems that there has been an awareness of hydrogen embrittlement, as you said, starting from the 1800s. Sort of the 1870s. This was, of course, during the second industrial revolution, which saw the widespread use of steel being used for things like ships and things like this. However, at the time very little was known about hydrogen embrittlement. They were ware that it was happening, but weren't really sure why. Didn't really know what the mechanics were or anything like that and it wasn't until the 1940s that it really started to be understood because of the famous case of the Liberty ships. And I think this was when TWI – then known as BWRA – started to get involved in Hydrogen Embrittlement. Could you tell me exactly how BWRA-slash-TWI got involved in Hydrogen Embrittlement?

**(00:07:02) PW:** So you're absolutely right. One of the big drivers of industrialisation and mechanisation was say the use of steel and also the use of welding. So I need to bring in the welding aspect. So I say massive increase in manufacturing, particularly in the Second World War, a lot of push for new faster manufacturing methods for things like Liberty Ships. So by going from riveting to welding you can make ships I think an order of magnitude faster, so you can make ships in a few days. But the difference between a riveted structure and a welded structure was that the failure modes are different. And in particular one of the issues was that, if you make a long weld, you could find that you get a fracture right around the weld. And there are examples of ship hulls which fractured rapidly, and there are one or two iconic pictures of ships that have gone *[makes a triangular breaking motion]* to that sort of shape without really seeing what service. And this is a function of the fact that I say from a riveted structure you have a certain type of sort of unzipping failure between rivets, but with a long arc weld potentially you could get a crack running some distance. So, after the Second World War, the UK government set up a number of independent research and technology organisations, which were to assist the development of industry after the war, and one of them was British Welding Research Association which was established here in Abington in 1946. And one of... When you look back at the history, not everything, but one of the big issues of the day was how to stop fracture of welded structures. So, then there's... ok I didn't join TWI until the 1990's, but I say when you look back there are certainly a number of decades over which it was established that Hydrogen was a key source of problems with welds. And so earlier I mentioned sources of hydrogen from the environment passing into steel, but one of the issues about welds - particularly in the early days - was that people didn't realise that when you make an arc weld you have a... So you generate an arc which is high temperature so you can melt a material and stick it together but you have to have a protective environment around that and the quality of the protective environment determines how much of the outside air can get into the weld. So if you have a poor gas shield, or a - not a 100% gas shield because of course nothing is 100% - some of the air can get into the weld zone and then if you have moisture in that, that moisture can be picked up into the weld as hydrogen. So this actually took several decades to establish and really get to the bottom of. A lot of the early work at The Welding Institute, as I understand it, was related to simply trying to measure the hydrogen. Because I think there was an understanding that hydrogen was involved in the failure mechanism, but actually measuring hydrogen is somewhat difficult and in steels – Carbon-Manganese steels, typical steels – it's quite a difficult, elusive element to measure because it tends to diffuse away. So what happens if you like, with the example of a weld, you can make a weld and look at it, inspect it and it's fine; and then you come back the following day and you can find that it's cracked. And if you wait a week later you can find all of the hydrogen that was there that caused the crack has actually disappeared. So the... one of the challenges with hydrogen embrittlement is that you need mobile hydrogen, so if hydrogen doesn't move effectively that cures the problem. So hydrogen in material in its own right isn't an issue, it's when the hydrogen moves. So unfortunately welded steel is a particularly good example where I say if you don't have perfect shielding – which you typically don't – you get some hydrogen into the world, over time the hydrogen diffuses away and can cause cracking while it's doing that. I'd say over a day or two days sometimes. But if you wait long enough the hydrogen's gone. And also hydrogen being very light and mobile is a difficult thing to pin down and actually measure. So I suspect it was several decades before it was even possible to measure how much hydrogen was in a weld. Again, you're looking at small zones of material. That's one of the other challenges with hydrogen embrittlement is that it's typically a localised effect where you have a certain microstucrture. So in a weld you can get whole range of structures from the different thermal cycles, you get hydrogen diffusing and if the hydrogen happens to diffuse to the - if you like -the wrong region whilst you have… You don't even need applied loading you can just have the residual stress in the weld then you can get these spontaneous cracks. So it actually took several decades to establish reliable measurements methods so you could measure how much hydrogen was in a weld, to come up with then with methods for controlling the hydrogen. And I think it was the late '60s early '70s before there were standards which effectively are a set of algorithms or rules on how you stop hydrogen embrittlement just in carbon-manganese steels. So it's… Yeah, it was a problem that took several decades to come up with a real reliable solution to, and BWRA - which became The Welding Institute - played a key role in a lot of that; and one of our roles was in developing the hydrogen analysis methods.

**(00:12:44) SH:** One of our earliest papers that we have available in the [TWI] Digital Library - as you said - was by B A Graville in 1967. And he did exactly what you said, sort of trying to measure hydrogen and how it affects hydrogen embrittlement. And I think it is quite characteristic of those decades, trying to figure out what it is, how it works and everything like that. And you find evidence of it in all the literature where they're going "we don't know what this is, how does it work" and I think it is sort of typical work-

**(00:13:19) PW:** Yeah

**(00:13:20) SH:** -of BWRA at this time.

**(00:13:23) PW:** Yeah [inaudible] The BWRA was set up specifically to help industry, and the model was if you can get some… Basically if you can get a pound from industry the government would match it with a pound, so that was the original model. So it always had to be applied research and so I say trying to find pragmatic solutions to hydrogen embrittlement was particularly challenging and that was particularly our niche so I'm sure there were many people around the world studying hydrogen embrittlement, but our role particularly was trying to find pragmatic solutions for welds.

So two key things were the creation of hydrogen and measurement methods. Which typically, in the early days I think, involved submerging a weld in a liquid which was typically mercury and then collecting the bubbles of hydrogen that slowly diffused out of a sample and then measuring the volumes of gas that were collected; and then tracing that back to how much metal there was and then you could work out what the concentration of hydrogen was. So that was a really key piece of Work around developing measurement methods.

And the other thing is – and I don't actually know who did this, I should do – there was also the development of things called nomograms which were effectively 3-dimensional graphs, expressed in 2-dimensions, which allow you to look at - once you have a weld with a certain amount of hydrogen in - well, how do you control that? And there are two basic control mechanisms.

The first, you can stop the hydrogen from getting in there in the first place, but as I mentioned that's… It's challenging to avoid all hydrogen getting into a weld so you typically have some hydrogen. So then the trick is about how you let it dissipate before it can cause a problem. So this led to rules around pre-heating so basically making sure that you weld things while they're hot so they.. One of the other factors is that, particularly in steels, hydrogen embrittlement typically happens when things are cold. So if you keep them hot it means that they're less susceptible to the hydrogen and also the hydrogen diffuses out faster; so by controlling the thermal cycle during a weld and effectively keeping it hotter for longer you can let the hydrogen escape. And again the nomograms that were produced by BWRA were absolutely critical in establishing the standards for avoiding hydrogen embrittlement in practice. So those are the two things that we worked on extensively and really had a key part to play in.

00:15:51 SH: This sort of early characterisation, application, everything, really sort of paved the way for most of our research afterwards and it's kind of in the 1990s that we really pick up on what it is and how we can really finesse our way through, and we really start to properly understand. The industrial applications as you said, like it's a solution to a problem and P M Hart in the 1990s points out that in the '70s and the 20 years proceeding it that cases of hydrogen embrittlement did reduce as a result of BWRA's work and everything like this. He says that it was attributed to developments in steel production as well as the procedures and everything like this; and I was thinking, as we look to manufacturing new alloys and metals and work with different types over the years - so 1970s onwards we've looked at steel then it went into stainless steels, vanadium alloys, all of this sort of stuff – I was wondering if hydrogen embrittlement is a cyclical area of work, as it's the same problem occurring in different things as they develop. Is that how you see things or…?

00:17:14 PW: Yeah, it's a good question, whether it's cyclical or linear or quite what it is but… So just to touch on Hart, I actually used to work with Peter. Peter was the head of department when I was a younger age than today, let's say, working in the materials department. And he did a... There was a publication looking at the sort of economic impact of hydrogen embrittlement and I think that when you look back to those early days of liberty ship failures and things it effectively… A lot of those early failures were attributed to hydrogen cracks which formed in welds. And ok it didn't always cause – well - the hydrogen crack doesn't cause the structure to fail, but if the hydrogen crack is big enough then it could lead to failure of the whole structure.

So there was another piece of development work which again The Welding Institute was very actively involved in and that was what's called 'Engineering Critical Assessment' so this is if you get a hydrogen crack or any sort of crack in a weld, how does it then behave in service. Can you accept the defect or do you have to remove it or repair it or what's the best way forwards. So this is a sort of mathematical solution, based on a thing called Linear Elastic Fracture Mechanics. So this is a science or theory that, as long as you make certain assumptions about linear elastic behaviour, if you have a defect of a service size you can calculate how it will behave in a structure. So Peter did this work which shown the importance of the hydrogen in hydrogen embrittlement forming cracks in welds and how things subsequently behaved.

As you mentioned, steel improvements, lowering carbon levels, hardness - effectively making the materials less susceptible to hydrogen embrittlement, as well as another number of other mechanisms which we won't touch on today but there's several cracking mechanisms - and steel manufacture, steel chemistries, and welding consumable chemistries, came on leap and bounds in those decades. And the materials became much more resistant to forming cracks in the first place in a weld. But one of the other things which has happened is that the constant development of industry is that the way to succeed is always to be pushing the boundaries. It would be very nice if human endeavour meant that you didn't have to constantly challenge the boundaries, but the reality is that everything is being challenged. So as you mentioned, if you take the example of oil and gas, if you try and put some sort of the very corrosive liquids that come out of the ground when you're extracting oil and gas, if you put them through a carbon steel then you get unacceptable rates of corrosion and the pipe will fail relatively quickly. So people moved to stainless materials and materials with chromium in which are more resistant to corrosion and will last longer. People have moved to higher strength materials. So high strength means you can use less material and get the weight down so if you're - let's take an example - again a deep water development where you're trying to put something in the sea bed, the lighter you can make it the better. So there's a general trend towards high-strength materials; and not just there, in aerospace in every industry you can think of – Space - you're using less material. It makes things cheaper, easier to move. So, there's a general trend towards high-strength, and what tends to happen also is that people tend to look at different classes of material. So in the high strength materials there was a trend towards duplex, so called duplex and superduplex stainless steels, which are higher-strength than normal austenitic stainless steels, and as you push the boundaries with strength of course the stress on the structure tends to be higher. Then there's also, for some very high-strength applications, people go to nickel alloy, precipitation hardened nickel alloys, and you start to get very high strength materials. And as strength levels are pushed up and stress are pushed up there is an increasing tendency to get very localised what's called plastic strain, so you can actually get deformation in some structures. And this is a basic principle of engineering practice that a little bit of plastic deformation is considered acceptable. But what we find is as the strength levels of materials have been pushed and the acceptability from a hydrogen embrittlement point of view is that has always been challenged. So I think you're right and let's say cyclic or linear as there's a general trend towards higher strength materials then there's a general trend of finding new hydrogen embrittlement mechanisms. So while each one is resolved, what I tend to think of it is as almost going up like a hill. The lower strength carbon steels arc welded has been resolved. Then issues came up with duplex stainless steels and superduplex stainless steels, maybe alloy 718 and as you go up that strength ladder then there's… the sad thing is there's nearly always thing to be a new hydrogen embrittlement mechanism that nobody quite thought of because I say every material really has some sensitivity, or most materials, so yeah. I see it as sort of going up a ladder and whatever engineering practice works ok then there's no problem then someone pushes the boundary a little bit further and find the next sort of chink in the armour and then there's a need for a new piece of research and a new industrial standard to overcome that one effectively. So I suspect it will carry on for some time.

**(00:23:07) SH:** In the same paper Hart points out that there is a new trend that saw the localisation of hydrogen embrittlement moving away from the heat affected zone and into the weld metal. This paper was published in 1999 and I think kind of starts to point out a clear path for research for the 21st century. And we do see this being studied in a handful of papers at the beginning of the early 2000s such as AJ Leonards 2000 paper 'hydrogen cracking of ferritic austenitic stainless steel weld metal' and your 2001 paper 'HESCC of superduplex stainless steels'. What's the significance of looking at weld metal instead of the heat affected zone?

**(00:23:57) PW:** Ok, I think the main significance is that… So again if you go back to my sort of early comments about hydrogen and how hydrogen might get into a structure, the early solutions were effectively around stopping bulk hydrogen getting into a structure. So the first issue's that you want to try and stop hydrogen getting into a material and then you won't have a problem, so you try and keep hydrogen out of it, however you do that, and then you have a material that's resistant to hydrogen. But then what you tend to get is that you get localisation. So firstly we have, if you like, welds or areas that you can get localised hydrogen from the environment. So hydrogen comes in and you get that in a particular spot; and I think the significance of the trend from heat affected zones towards weld metal was that heat affected zone cracking - so the problem with heat affected zones is that you have certain types of microstructure that develop. You typically have a stress concentration at a weld which increases the stress in the area of the heat affected zone. So by changing steel manufacturing practices you can get basically get more resistant heat affected zones that, even though there's a bit of hydrogen and you've got a stress concentration, you can cope with that. But then once you've fixed that what you're effectively doing for certain types of materials in particular, where there's a partitioning of hydrogen in between the steel and the weld metal, you find that effectively you solve a problem there but you sort of shove it into the weld metal.

So this comes back to the patterns about how hydrogen diffuses, which is related to face transformations and… So there's a bit of science behind where the hydrogen ends up. So I think that the point I would make is that hydrogen's quite mobile and what tends to happen, and in particular if you look at the more recent issues, there's a trend towards realising that it's a very local phenomenon. So some recent examples of being around, or more recent or not so recent, dissimilar joints between a carbon steel and another material - which might be a stainless steel - using a nickel based consumable, and you can get very localised microstructures on the interface which can be very sensitive to hydrogen, and actually very localised. So they're actually very small things that you're looking for; and also with some of the high strength nickel alloys the interaction - between the hydrogen and the microstructure – is on a very very local scale. So what I would say is that the significance of the transition from heat affected zone to weld metal is that you're always sort of chasing the hydrogen embrittlement problem-

**(00:26:45) SH:** Ah, I see.

**(00:26:46) PW:** -So you fix one bit and then it goes somewhere else so you tend to think you've solved the problem, but you never quite have. So I think that's the challenge that it can be a very localised phenomenon. So heat affected zone might seem quite localised but I'll say you're often looking at very fine microstructural features that can cause the problem. So that's arguably one of the biggest parts of trying to overcome it generically is it's always a very local phenomenon so it's difficult to exclude, particularly in large engineering structures where you might have a combination of hydrogen stress or strain and microstructure that together is susceptible to hydrogen. So I'll say it's this again it's symptomatic of the fact that hydrogen's very mobile and can find its way to little regions and then collect there.

**(00:27:42) SH:** Sort of a whack a mole

**(00:27:42) PW:** Yeah, you knock it down over there and it pops up over there. *[points across the room]*

**(00:27:47) SH:** As we're looking at the 2000s I think there are three papers or books that were published in 2004 that I think are quite notable. The first one we have is Norman Bailey et al's 'Welding steels without hydrogen cracking' which summarises quite a lot of what we knew at the time already and was a culmination of a lot of our previous work. At the time of writing Bailey states that the exact mechanism for HE – hydrogen embrittlement – was not known. Have we come any closer to understanding this precise mechanism, why or why not?

**(00:28:28) PW:** I think the challenge is that there are a number of, a very large number of mechanisms and arguably we – I say as we push the boundaries of engineering – we create new mechanisms or find new mechanisms. I think there are two fundamental theories of why hydrogen embrittlement can take place. One is called – well they have abbreviations, and I'm probably going to get them wrong – but one is around hydrogen enhanced local plasticity I think it's called, which is about the fact that if you've got hydrogen and the high stress the hydrogen can actually encourage plastic deformation in the material so movement of the dislocations.

So there's a sort of general group of mechanisms which come under that heading and there's another one which is called 'hydrogen enhanced decohesion' which is where, if you have hydrogen where two phases are present in contact, then the hydrogen effectively gets into the interface and then can encourage decohesion of those two things. So those tend to be the two sort of dominant theories or maybe mechanisms if you like. But if you choose a whole range of different materials, I say like the engineering world is constantly coming up with new alloys, then those mechanisms can have different manifestations if you like and dependant on the alloy and the application. So we do sort of understand it. It's funny I know a chap called Harry Bhadesia, who's been very at the forefront of a lot of work on hydrogen embrittlement and steels in particular and he lectured me when I was an undergraduate; and if ever I talked to him he says "well, we understand the theory so how come industry has these constant problems?". So it's not for a lack of understanding the theory it's how to overcome it on a practical basis -

**(00:30:25) SH:** I see

**(00:30:25) PW:** - Given that, although we'd like to think everything in industry is 100 percent controlled of course it isn't. So it's always- what is it? Maybe it's one of those unknown unknowns that you're never quite sure when it's going to crop up next. So I say a bit like your 'whack a mole' we're always closing down one manifestation when another one appears.

**(00:30:47) SH:** The second paper we have is Richard Pargeter's 2004 paper 'Evaluating necessary delay before hydrogen crack inspection' which discusses a need to wait a certain amount of time before looking for hydrogen embrittlement cracks and things. I think you mentioned a little bit about this before, but why is a delay necessary?

**(00:31:11) PW:** Yeah so this comes back to the fact that hydrogen is mobile. So when you make a weld - as you might expect - the hydrogen that's going from the environment is effectively trapped within the weld, or very close to the weld, but if you wait a day or two that hydrogen slowly diffuses away. So if it happens to diffuse to a point where maybe there's a high stress concentration or some other type of flaw – maybe a lack of fusion features, or solidification crack – if the hydrogen can then collect at some other feature… And I also mentioned earlier that unfortunately whenever you make a weld it's impossible to avoid residual stress. So you might think when something's just manufactured and sitting on the floor it doesn't have any stress on it but it doesn't have any applied stress but it has locked in stress from the fact that this has been very hot and then cooled down while it was surrounded by colder material, so you inevitably get localised stress. So it's just a function of the fact that hydrogen can unfortunately diffuse to a susceptible area over a certain period of time and then could cause a crack. So I say if you look immediately the weld might be perfectly sound, but if you wait and come back the following day you could find that you have cracks - and that's related to temperature. I think people have had experiences where they're more susceptible to hydrogen cracks in the winter than they are in the summer and so it can be, what you would think are relatively minor changes, you can find that cracks appear over a period of time. But then eventually, you give it long enough the hydrogen disperses from steel and you don't have a problem. Now the issues unfortunately with other materials are that sometimes hydrogen doesn't diffuse away very quickly but it's typically – if the hydrogen is either locked in forever or diffuses away very quickly and there's no problem. It's the things that are in the middle where you have to wait a while and that's why the significance of the work that Richard did is really quite important.

**(00:33:06) SLH:** Last but not least on this list of 2004 papers is your OMAE paper 'avoiding hydrogen embrittlement stress cracking of ferritic austenitic stainless steels under cathodic… cathodic?

**(00:33:20) PW:** Yeah it's cathodic

**(00:33:20) SH:** Cathodic protection' which sought to define the factors controlling the sensitivity when exposed to cathodic protection. What is cathodic protection and how does it affect the sensitivity

**(00:33:35) PW:** So cathodic protection is actually one of the things I mentioned earlier on which is typically if you have a steel pipeline that you want to put in the sea and you don't want it to corrode one of the things you can do is attach a piece of aluminium, so this is what cathodic protection is. And it's called cathodic protection because it has an electro-chemical effect where it changes – it changes the electro-chemical potential in a cathodic sense. It doesn't really matter what that means, but effectively that's what cathodic protection is. So it's a bit like galvanised steel. When you have a galvanised steel the zinc coating corrodes preferentially to the steel underneath and actually forms a protective layer; so it's a type of protection where you put something on a steel to stop it corroding so that's what cathodic protection is and what it does is it changes the electro-chemical potential so that the steel doesn't corrode. But the issue is in moving the potential sufficiently far so that it doesn't corrode what you tend to do is stimulate hydrogen generation. So anyway just onto that paper because I would say was the most significant paper of the year. Well a) for me it was quite significant because it was the culmination of a piece of work that had gone on since about 1996. So we'd been aware of issues in industry with duplex stainless steels since about 1996 and there was a series of research projects which looked at the microstructural sensitivity, the effect of stress and in particular looking at the coarseness of the microstructure and how that affected hydrogen embrittlement. And so this tended to happen at welds because there's a stress concentration in a weld, but wasn't necessarily associated with the actual – well it wasn't hydrogen from welding per se. So it sort of naturally gravitated to The Welding Institute to look at the problem and we worked with a lot of end-users, material producers, and other research laboratories, including DNV we worked with afterwards, to create a new standard – well I call it a standard, it's actually a recommended practice – DNV RP F112.L. So this was a new philosophically – in my head – a new way of avoiding hydrogen embrittlement in materials and this time it looked at trying to control stress or strain so we realised that duplex stainless steels, if you get sufficient hydrogen into them are inherently susceptible to cracking. You can't let the hydrogen diffuse away in this particular situation because that's just impossible, in fact what tends to happen is you get more and more hydrogen over time. You can't really stop the material from being sensitive. You can reduce sensitivity. So you've got a situation where you can't get rid of the hydrogen and you can't really make the material resistant so the approach taken was to control the stress. So it was a new way of controlling stress through design to make sure that you never get plastic strain and that for me is the critical feature that previous engineering designs have always assumed – well I believe – or was assumed that a little bit of plastic strain was acceptable in structures. Now ok applied loading should always be made maintained well below yield but there's an implicit acceptance that will always be little bits of plastic strain at a weld so for example. But this standard basically said under circumstances that's not acceptable so you have to avoid plastic strain at all costs; and I think when you look at the remaining hydrogen embrittlement issues we've come across, they typically associated with plastic strain in some form or another. Only localised, so we're not designing structures beyond yield which nobody would really advocate, but locally you get this plastic strain. So for me that was a, let's say in terms of philosophy of design against hydrogen embrittlement that was a new step that hadn't been taken, so from my point of view that was particularly important.

**(00:37:48) SH:** – Nice.

**(00:37:48) PW**: As well as being the culmination of a piece of work I'd been involved in for a long time.

**(00:37:51) SH:** Did you find anything specific when you were tests and things that helped form the procedures? Or…?

**(00:37:58) PW:** The funniest lesson I always remember is we – so when we started doing the early work there was a lot of pressure to get results quickly because there were oil and gas fields, one in particular, which was being delayed specifically because of this issue. A lot of subsea equipment was installed and then they found out they had a leak before it was even operating so when they pressure tested the system and found it was leaking and found it was this hydrogen embrittlement problem. So, there was a huge amount of pressure on us as a testing laboratory to a) diagnose the mechanism and b) really prove that we knew what was going on. So we were asked to do some tests to basically replicate what had happened to prove our understanding. So I always remember there was one project meeting I went to for this oil and gas field and the chap who was the project manager asked me what tests we can do and I said “well, there aren’t really any standard tests”. So he said “well what could you do?” I said, “Well, there is something a bit similar which is a test that’s used for looking at cracking in sour service.” I said “we could use that test, you know something like that, we’ll just change the environment and use the cathodic charging rather than sour environment.” So he said “Fine.” I said “those tests last a month.” So he said “What can you do in two weeks?” So we set off trying to do a series of tests and I don’t know how long it was I always probably over-exaggerate it in my head, but it was about 9 months later, we hadn’t got anything to crack in the way that the thing had cracked in service. So, we were always doubting ourselves about whether we really understood it or not, and what we were doing we were putting samples in to bending so effectively you put a rectangular specimen into a jig and you tighten up a screw underneath it and it bends it and these things just flipping things just wouldn’t crack. So for some reason somebody came up with the idea that we should move to tensile specimens and I honestly don’t know – I can’t remember the reason – why. So, instead we started doing tensile specimens - effectively you had a weight hanging on the end of a specimen and pulling it - probably because those were the machines we happened to have available.

So we started doing these tests and I said we had months of things not cracking, and I remember one of the technicians ringing me up. We put the tests on and that same afternoon he rang me up and he said “the specimens are cracked” I said “Well, it can’t have cracked” I’m not expecting anything to happen for months. We went and looked at them and lo and behold they had cracked, so that was a real key moment that we realised the difference between applying a load in bending and applying a load with a hanging weight was that if you bend something it can actually sort of *[shrugs shoulders]* relax. So you hold it in a certain position, but it can actually sort of relax a little bit so the stress actually reduces, whereas when you’ve got a hanging weight it can’t relax. So what tends to happen we found a thing which is called low-temperature creep, which we weren’t expecting, which is actually this type of steel – duplex stainless steel – undergoes continuous plastic straining over a period of time. So, if it was Carbon steel and you hung a weight on it, it would stretch a little bit and then it would sit there, but the duplex stainless steel just tends to keep on creeping over time. So we discovered there’s this low-temperature creep phenomenon which none of were particularly aware of I don’t think – there were a few papers. But that was the key difference, you had to avoid this low-temperature creep which was related to a certain type of loading which, again, philosophically is quite challenges because engineering design isn’t doesn’t recognise any difference between how the load is applied and doesn’t recognise low-temperature creep. So that was a key finding, and again that was one of the things – I’m not trying to claim the recommended practice as perfect – but that’s one of the key steps in that design procedure was that we produced it so that you couldn’t have any plastic deformation from low-temperature creep. Which means it’s quite conservative which I know creates issues, but it does… it addresses that issue for the first time in a design standard, so, again from my point of view that’s significant philosophically.

**(00:42:07) SH:** With the standard and the findings from this paper, how do you think the industry has benefitted from this research, has there been any sort of demonstrations or…

**(00:42:19) PW:** Failures of that type are much less likely. I don’t believe there has been any significant ones in recent years but obviously not everybody is as entirely open about things that fail in industry so there may be things that have happened but as far as I’m aware that type of failure is now effectively eliminated. So it means that the structures are much – it’s not actually safety so much as making sure that you can.. you know they’re still operating. You don’t want leaks because, particularly with remote offshore oil and gas fields, if you have a leak they can be, you know from an environmental impact that can be huge. But also from the point of view of the operation of the company you can have huge losses if you can't supply your customers with the oil and gases that you promised them. So a big impact there that that issue for duplex stainless steels has effectively gone away. I think the opportunity is to maybe improve the standard over time so there's a little bit less of conservativism – with standards there always tends to be a degree of conservatism in so you're comfortable that it will do what it's intended to do. So yeah those types of failures don't occur anymore.

The thing is on the back of my mind is, that I think was maybe hinted at in one or two of your questions, is sort of 'what next?' really you know what… So from my perspective there's still a number of people researching hydrogen embrittlement mechanisms like I say in different materials and I know nickel alloys are one particular class where there's interest but there's a number of other types of material. And in fact interest has probably extended increasingly into effects of permeation of hydrogen but also other species into polymers. So one of the things that we see in recent years is a move towards polymers and composites increasingly in high integrity structures. So in the past probably most high integrity structures – basically things that you need to stay in one piece, particularly for pressure retaining purposes so things like nuclear reactors and pipelines – tend to be made out of metallic, typically steel but there's increasing interest in industry in what you can use polymers and composites for. What we find is polymers and composites, hydrogen actually doesn't tend to have much effect on most of them because actually, polymers and composite structures are more open than metal that the hydrogen can actually pass through it quite easily without causing many problems. But there's a number of other species that can get in so water, carbon dioxide, hydrocarbons, can permeate into polymers. So there's a range of mechanisms there which again so I would say there's still an evolving science of when one species permeates inside another how does that affect integrity?

And the other thing which I think needs to happen someday – I'm not quite sure when or will it be any time soon – is I mentioned earlier on Engineering Critical Assessment. Which is this idea that things that have defects in them can be considered safe by doing a calculation showing that the defect is of an acceptable size, and that works on the principle of linear elastic fracture mechanics. But there's a need to try and take that technology into the hydrogen embrittlement space because I would say most attempts so far to use a measurement of fracture toughness in a material that contains hydrogen, and look at the effect of hydrogen on the behaviour, hasn't really managed to.. What's the word… the overlap of the two, the calculation and the testing, hasn't really come up with a standard method for how you could do an Engineering Critical Assessment in a material when it contains hydrogen. So, material without hydrogen you can show that a defect is fine, and material with hydrogen you can show that a defect won't initiate, but when you already have a defect and you have hydrogen there's something there that's not quite right. And various people have tried to do this including TWI, we've done a number of JIPs (Joint Industry Projects) all of the people have worked on this topic. So there's something that we don't quite understand about how defects extend when there's hydrogen in the material. So if you ask me what my sort of what my two topics are for the future are 1) the wider topic of how permeation of anything into a second material affects the integrity. And I say that the other issue that still needs to be addressed is how can you stop hydrogen embrittlement when you have a defect, a pre-existing defect? Now we know you can, there'd plenty of experience which shows I say from a purely human experience point of view how to do it, but from the point of view of our understanding and doing a calculation to show that things are safe it doesn't seem to work very well at the moment. So in terms of the future those are the two things I think need to be done.

**(00:47:35) SH:** So we're going to jump to the 2010s. So the 2000s saw a little bit of research into subsea and sort of deep sea applications but it was in the 2010s that we really had a spike in it here at TWI

**(00:47:56) PW:** Ah ok, in terms of publication?

**(00:47:48) SH:** In terms of publication but also -

**(00:47:59) PW:** It's probably catching up on all the work that had been done

**(00:48:02) SH:** Possibly, yes. But, there were 9 papers in between 2009 and 2013 alone. What was happening in industry at this time for there to be this need for subsea [inaudible]

**(00:48:19) PW:** I think probably those papers reflected the activities of the previous ten or fifteen years. I think there had been a lot of work going on at TWI and elsewhere, lots of other people, recognising the different manifestations of hydrogen embrittlement and how it could impact on industry. Probably from the 2010s onwards what would I say was the different… there were certainly… oil and gas prices I think were on a fairly steep rise so there was a push towards more so-called deep water exploration. So the oil and gas companies, you could imagine you know look at the middle east, there's a lot of oil in particular available on land - and in other parts of the world as well - but there it's more visible. The oil is on land fairly low, shallow, beneath the surface so easy to get out. Then if you look at the example of the North Sea the UK North Sea and Norweigian sector, there was a sort of move offshore in the 70s and 80s to build structures – platforms – which typically might be in water that was only a few hundred feet deep. And I think what was really happening in the 2000s and the 2010s, this push into deep-water explorations. So there was a huge drive to go to deeper and deeper waters to find bigger reserves. I think at the time there wasn't much of a thought of maybe a greener future, this was sort of before that sustainability and climate change had really caught hold. So there was a huge push towards deeper and deeper water development which meant more equipment on the sea bed , so more equipment that was hydrogen charged, having to make things stronger, lighter weight, so you can get them out and store them. Very long pipes. So TWI did a lot of work over a number of years looking at the fatigue of these pipes because of they're undergoing fatigue loading - so cyclic loading - and getting hydrogen charged, that created a whole set of challenges and we did a lot of work looking at the pipes. So I think it was that drive for further oil and gas expansion and probably if there's been a little bit of decline in recent years it's probably been since 2015 or so, there hasn't been that push purely for out and out deep water oil and gas. Now, there were developments in and again back to the sort of on shore developments in some countries which sort of continued to push for oil and gas, but that push to deep water and more and more challenging from an engineering point of view oil and gas applications has gone down. So I think that's probably why in the 2010s there was a real push on what more can we do and how can we overcome hydrogen embrittlement.

**(00:51:13) SH:** Two of these papers published in the 2010s, Amir Bahrami's 2010 paper 'Assessing integrity of subsea dissimilar joints' and Mike Dodge's 2014 paper 'fusion zone microstructure and subsea joint embrittlement' both examine subsea welds under cathodic protection. Dodge's paper notes that there were three specific microstructural features that appear in hydrogen embrittlement while under cathodic protection. This was the coarse-grained heat affected zone, a feathery martensitic band, and a featureless planar region. However Bahrami's study points out that it is the latter two that dominate the facture path that occurs in a weld. Why?

**(00:51:56) PW:** If I knew the answer to that I'd be a richer man. Yeah. I think going back to those publications reflect work that have been going on for a number of years and I think particularly the dissimilar joints challenge, what we found was that there was a number of big failures. When I say big I say as in the impact was big. One in particular in the gulf of Mexico, again a bit like the one I talk about earlier for duplex and stainless steels, was a new development being put together and found leaks very early on. And some of the parts were brought back and I remember looking at some of the pieces here and it was very clear that there was a very close adherence of the fracture path to the interface between a carbon steel and a nickel weld metal. And let's say as mike points out – Mike Dodge – that the crack has a tendency to run in those regions that are very close to the weld. So there's been a whole lot of characterisation done by people with Mike Gittos, Lee Smith - probably others that I've forgotten - over a number of years. And they found a very close correlation between these features and I think it was over time that the sort of leaning quite towards where the cracking started, moves towards this featureless zone and this feathery zone. So they're a little bit… again this hints at the problem we have with the localisation of hydrogen embrittlement specific microstructures. So these features, let's say you have a carbon steel and you another material and you have a weld that's made with a nickel consumable and the compositions of the nickel consumable and the steel are very different. You have a, when you make a weld you always have a sort of stirring actions, that's what tends to happen. So the thing's… You've got liquid metal next to very hot steel, the two things have different solidification temperatures and quite what happens at that interface is actually quite difficult to envisage, so I don't think anybody really knows quite what's going on when it actually freezes. So you get these funny features which I think some of them are little bits of material that get sort of sucked in just as it's freezing. So you get these funny features and of course material scientists such as me and my colleagues love looking at these strange features and giving them names and descriptions and things and analysing them under the microscope. So yeah it's just an evolution over time that where we think the cracking started which is in these – typically it's in the bit you don't really understand – which is where the problem arises.

**(00:55:00) SH:** And so does understanding these features and this path help understand how we can prevent hydrogen embrittlement at all or is it still a mystery?

**(00:55:11) PW**: Unless you understand how things form you can't really stop them, I think is the challenge. So there's.. so this actually comes to another point about what was BWRA and then The Welding Institute's role been in all of this work? One of the things that we have striven to do – if that's a word – is to create understanding. So one of the great advantages I've had, I always feel working at The Welding Institute, is you work with different companies who can have different experiences of the same phenomenon so you get inputs from different.. from materials producers, manufacturers, end-users regulatory bodies, all sorts of people have perspectives on a different… different perspectives on the same issue. So it's, yeah, this ability to have multi-disciplinary inputs helps you to develop the understanding of quite how something takes place. And I know you might say "why does it matter?" you know what does understanding really mean? I always think what it is it's understanding which factors are the critical ones that have to come together if something's going to happen because if you really understand that you can then say "well ok, if we just stop one of them, we can stop the whole thing." So it's.. the understanding really comes down to essential variables which is a common theme through quite a lot of the work at The Welding Institute, establishing what are the essential variables and which bits you need to control to implement a pragmatic solution is really key. And again, just one of my other things I find quite interesting is sometimes it takes decades for a new set of rules which are effectively, you know. We talk these days a lot about algorithms, but effectively you can develop an algorithm to stop a particular type of industrial failure, industrial problem. I say it can take you decade sometimes, although hopefully things are getting faster these days, but it can take a long time to develop the algorithm that overcomes a problem and to develop the algorithm you need to understand what the essential variables are. And then you need to understand how they relate to each other. So you need to understand that these conceptually, if not mathematically, what the relationships are between things between things. You know if this is a straight line or whatever it does that *[makes a back and forth gesture]* you know so you need to understand the form of the mathematical expression so… and like you say we are particularly fortunate here because we get different perspectives from so many different angles.

**(00:57:47) SLH:** Oh definitely. So, all of the subsea research culminates in again Dodge's two part paper 'weld cracking in subsea oil and gas systems'. Has the research in oil and gas contributed to, we've mentioned it a few times as we've been just talking, the hydrogen economy?

**(00:58:10) PW:** Yes.

**(00:58:11) SH:** And in what ways?

**(00:58:12) PW:** So I think one of the big challenges for – well I'm sure there's numerous challenges for a hydrogen economy, not least of which will be the cost and you know how much it will... how much investment it will require to enable this and whether it can compete with alternative sources of energy. But what I would say is that a lot of the work on Carbon-Manganese steels, which dates back to the oil and gas industry and sour service has informed what people are trying to do in terms of carbon-manganese pipelines for hydrogen. So there's a lot of interest in whether you can have hydrogen pipelines on a large scale and a number of people are going ahead with those sorts of things. So a lot of the learning that's come from the sour service hydrogen embrittlement problem has been put into the designing a safe hydrogen transport model. Probably the most obvious thing there's a tendency towards limiting strength because there's a realisation particularly in sour service – this is where it's come from – that if you keep strength or its proxy hardness at a certain level then that material is effectively immune to hydrogen embrittlement so you don't any. Although sometimes when you make a weld that's not quite true. But there is this rule of thumb that if you control strength and hardness then you stop cracking. So that's the main one that's been built into the standards that people are currently looking at. But my own perspective is that that's probably quite conservative and that the strength limits can be pushed. And I know there are a number of people who are working on that so that's not just my idea. So there are initiatives underway to push the limits of what's possible from a strength point of view. But that would be the main one I think that that learning from Sour Service and oil and gas will be effectively used directly in any hydrogen transmission lines in the future.

**(01:00:17) SH:** Fantastic.

**(01:00:18) PW:** Although they're probably made too expensive if you follow them, so you will have to put the higher strength steels in but that's a different issue.

**(01:00:26) SH:** The hydrogen economy itself has been sort of emerging since the early-mid 2000s. R Hammond, considered the material needs in 2007 including a need for safe storage and transportation, as you've mentioned before, I was wondering if the needs have changed in the twenty-years-ish since that paper was published?

**(01:00:52) PW:** When was that one?

**(1:00:53) SH:** That was 2007.

**(01:00:53) PW:** 2007, yeah. So TWI built its first hydrogen testing facility. We had hydrogen sulphide testing facilities for the oil and gas industry for a number of years but we're going back to the 80s at least - maybe the 70s – certainly the 80s. We built our first proper mechanical test facility for hydrogen in the early 2000s and that was actually backed by the

Japanese government who were looking at hydrogen powered cars. So there was an initiative whose name I can't remember now… Might have been NEDO or something but I might have got that wrong. Anyway there was this initiative to develop hydrogen test facilities and we built a laboratory which allowed us to do fracture and fatigue tests in hydrogen up to 1000-bar. But most of the interest at the time then was on hydrogen storage in a vehicle. So it was mostly about stainless steels and that was the material that was being tested then as it evolved that laboratory was kept busy. So you might say that the hydrogen economy's quite a new thing but there's been a lot of work around rocket propulsion as hydrogen is a fuel in some rockets and that continues to be the case. So there's been people interested in… I don't know exactly but they were certainly high-strength alloys so probably mostly nickel alloys and I haven't been involved in enough of the project to know exactly what materials were looked at but it was I say a bit of an evolution of the stainless steel side towards higher strength corrosion resistant materials. Typically the issue with a rocket, certainly in those early days is that they were probably only single-use-

**(01:02:37) SH:** Mm… definitely.

**(01:02:37) PW:** -So you don't need to use them multiple times whereas cars hopefully last a bit longer. So there was a bit of lean in there towards stainless steels and nickel alloys and as we've come into recent years I say the interest has definitely moved towards carbon-steel pipelines and the large scale transmission of hydrogen. Now I think that there was a UK government initiative - and I'm sure there's been a number of others around the world - to look at putting hydrogen in the gas mains for powering domestic central heating. I think at the moment the commitment to that is not clear, I think it's unlikely to happen in the short term. But there is greater commitment I believe towards having a… I think it's called a sort of hydrogen spine, a sort of gas transmission network which will be used to help decarbonise heavy industry and I think some transportation that's difficult to decarbonise through electric vehicles. So I think the general trend seems to be – there is definitely interest in hydrogen powered cars. Electric vehicles seem to have the upper hand in terms of the market at the moment. Whether hydrogen powered cars will become economically feasible in the short term I don't know but there's definite interest I say in heavy industry and I think transport and vehicles, trains, trucks, they're the most towards hydrogen. So I think for the time being hydrogen in the gas mains is unlikely but I think some sort of industrial hydrogen transport network based on carbon-steel pipes is very likely to go ahead, and some of that is certainly going ahead. I don't think the UK is particularly at the forefront of that other countries are a little bit ahead but we're.. we've certainly got a lot of work going on in the UK to establish the safety and look at what's possible.

**(01:04:28) SH:** How is our understanding of hydrogen embrittlement impacting the development of the hydrogen economy?

**(01:04:36) PW:** Well, I say if you talked to Harry Bhadesia, he would say "hydrogen embrittlement's been understood for many decades so why doesn't industry sort its act out?" - And I'm probably paraphrasing what he would really say. But I think in terms of basic understanding it is all there. It's the constant shifting of industry and new applications where I think these… there are particularly for high strength materials there are still Hydrogen Embrittlement issues which are difficult to avoid through standard design practices. So, I think our understanding is good. I think as the world continues to move design practices will continue to be challenged. I think the big opportunity, and I know there's a lot of activity in universities to try and move towards more modelling and simulation to try and take the fundamental understanding which I say is there in industry. And I say this is what Ali would say, that the understanding is there but to really try and translate that into industry I think that's the piece of the jigsaw that's missing. And given the complexity of the issue I think that eventually modelling and simulation – and again these effectively developing more sophisticated algorithms through coding and software - that it might be that there has to be a move away from reliance of just a published standard - where you know you have written instructions on what to do - towards software. I suspect that will be the way that I would see things going, and that's the way to deal with the complexity.

**(01:06:15) SH:** We are halfway through the 2020s and

**(01:06:18) PW:** Well on our way to Net-Zero targets.

**(01:06:20) SH:** Oh hopefully.

Some of the latest developments in studying hydrogen embrittlement have been. Stephen Grigg's 'use of acoustic emission sensors to monitor hydrogen embrittlement' and Dorothy Winful's work on additive manufactured alloys such as Inconel 718. Does additively manufacturing materials alter how hydrogen embrittlement works in these materials? And if so, how?

**(01:06:55) PW:** Yeah so there's two separate issues there. One's around additively manufacturing which I'll start on and if I forget the other one do remind me I shall also touch on monitoring. So firstly if you take additively manufactured components, so metallic components, you're effectively… What you're doing is putting little blobs of molten metal down in a very structures sequence to build a component up and what that is effectively is many hundreds or thousands of welds on top of each other to produce a structure. So one of the real challenges is understanding the defect distribution in that. So when you know we've worked on arc welds which are typically *[makes V gesture]* this sort of shape, and we understand how flaws can form along the edges between passes and within passes. So there's a very good understanding of defect formation mechanisms and how they then affect ultimate integrity and performance of a component. I think the challenge with an additively manufactured part, I say where you may have hundreds or thousands of beads is that you could in theory have hundreds or thousands of defects. Now, ok these won't be as big as – or hopefully they won't be as big - as long as you control the process but with anything as big as they might be with an arc weld but there will be a distribution of defects. However well you do it, there will always be defects. Quite what you classify as a defect is another question. The most obvious thing is that you could have two pieces of metal that have come together that haven't actually – they're not actually - stuck, as in melted together, fused together. They could be just touching, so you could have some sort of interface that isn't fused. So that's the most obvious type of defect. But you also… We've started... I suppose over the years we've developed this idea that certain types of microstructure can be effectively 'defects' because they're weak spots or brittle spots. So there isn't the experience or level of understanding of what constitutes a defect in an additively manufactured part. There isn't particularly good understanding of what the essential variables are.

So I know one of the challenges that companies have is if you have your own additively manufactured machine and it's over there and the same chap always operates it and you always use the same software you tend to get the same result out of it. But if you want to go to a supply chain and buy from a range of suppliers then it's different operators, different software, and we don't have as good of an understanding of essential variables as we do for arc welding. So control of defect populations is a real challenge. So if you're looking at hydrogen embrittlement as I said earlier one of the remaining challenges, in my head at least, is how you manage the interaction of hydrogen with defects because that's not a particularly well understood phenomenon. You can stop defects – new defects – forming but how manage the interaction of hydrogen with an existing defect is tricky. So that’s all around additively manufactured parts, there just isn’t that much experience and I know there’s a huge amount of work being done but you know the industrial experience is still only years or maybe a decade old, so there just is a limit to how much shared industrial learning there’s been. Some companies I’m sure are very good and know exactly what they’re doing but like I said the shared and the breadth of knowledge isn’t there.

So there are challenges about additive manufactured parts, not just with hydrogen embrittlement, any degradation mechanism could be influenced by defects. But the other part, just to touch on monitoring. So effectively when you look at making a safety case or trying to demonstrate that any engineering structure is fit-for-purpose the welders tended very much to rely on codes and standards and human experience – we know this works, and that doesn’t work, and this is all written down. And as long as you follow the standard everything will be fine - But there is an evolution, and not just recently probably the last 50 years or so – towards calculation. So rather than having to rely on grey-haired people from many years ago telling you ‘this is how you do things’ that you actually calculate from those principles.

**(01:11:14) SH:** And this is where the modelling comes in.

**(01:12:17) PW:** Yeah the modelling and simulation. So there’s these two basic ways you can make a safety case. One is calculation and the other one is to rely on experience who’d done it before or people who’d done it before and have written a standard. So if you like you’ve got standards and you’ve got software. And this is a broad approximation but those are the two main methods. And then what the trick is with most things is then learning from experience, so if you’ve got an aircraft, a car, a nuclear reactor – whatever it is – you need to keep looking at it to see how it’s going. So where you’ll see this most commonly is in – certainly if you’ve got a reasonably modern car – with all the warning lights on the dashboard. So there’s lots of things monitoring how your car’s going over time and telling you when you need to get it serviced or you need to stop driving it and go and get something fixed. So there’s this concept of monitoring has been coming in for some time but it hasn’t found its way into large scale engineered structures and particularly difficult failure modes. So I don’t actually know how this monitoring works on your car, but I’m sure part of it is looking at your breaks and looking at the thickness of the break pads, or measuring tyre pressure. So these things are relatively easy to monitor without wishing to… I’m sure there’s a lot of effort gone on, I’m not suggesting it’s easy - but relatively easy. Whereas when you look at monitoring of engineered structures, say nuclear reactors, things on the seabed, it could be in extremely deep water and hostile conditions so monitoring there can be very difficult, and particularly if you’re trying to look for hydrogen embrittlement in a sub sea structure – that’s huge – with a sensor that will survive. So there has been you know a lot of interest in sensors and hydrogen embrittlement. So, again, I think… Just back to my… so there’s two ways. You can follow what’s gone before and works well and you can do a calculation, but you have to keep monitoring. And particularly as people want to do newer and newer things the push is away from what’s gone before and towards the new. So people want to be able to do calculations, they want to able to do real-time monitoring so they get that learning. So you do the best calculation you can at the start. Typically what that means is it’s very conservative but then you want to be able to monitor during service so you can get data. So, the kind of monitoring work that Stephen and others have been looking at is particularly around the hydrogen embrittlement phenomenon and actually again is it almost like a philosophically new way of trying to deal with hydrogen embrittlement. Rather than assuming you can design it out at the start actually just looking at the thing throughout its life and spotting when there’s a sign of something happening and then intervening to overcome this.

**(01:13:58) SH:** With all of this in mind, what developments do you think there will be in the future or should be in the future?

**(01:14:05) PW:** Well I think I mentioned some of the existing challenges so I say that the underlying challenge is that, you know the world's economy, all the pressures on us, demand continual development and improvement and we've got… There's all the stuff that's going on with Space, there's all the stuff that's going on with energy, all transport, there's a lot of pressure around defence. Security of supply - you know national security. So there's a whole host of challenges ahead of industry which will push it towards using new design practices, new materials, new manufacturing methods like additive manufacturing. So there's all these pressures to change and constantly evolve and my gut feeling is that although we do fully understand the basic mechanisms of hydrogen embrittlement that the industrial application will continue to be a challenge. And I – as I mentioned earlier – I think that there'll be a shift in philosophy to how people seek to avoid hydrogen embrittlement and I say monitoring is likely to become increasingly important. As it is with other mechanisms, modelling and simulation are likely to be increasingly important, so digital methods and taking advantage of the computing power that's out there. So I think there'll be philosophical shifts. I think there is this overriding challenge that we need a way to do an Engineering Critical Assessment of a structure with a defect in to comprehensively allow for the effects of hydrogen. So that's my one sort of holy grail. When do I think that one will be fixed? Probably no time particularly soon but that's the real challenge I think that still exists. But also, as we've mentioned a number of times, as people move to different materials there'll always be different manifestations and it's not just hydrogen in metals, it's also permeation of other species into polymers and composites. SoI think it's actually the evolution of the science into the effect of permeation onto integrity is what we'll see happen over the future.

**(01:16:25) SH:** And lastly, to finish off this fascinating talk: it's evident that we have been at the forefront of research and development as evidenced by these papers and by the JIPs and the projects we've worked on. As things continue, the developments you've mentioned, why do you think people should come to us to understand hydrogen embrittlement?

**(01:16:52) PW:** Yeah that's a good question. I would say we've got a variety of people at The Welding Institute who have worked on this for a number of years. We have a network of people who are now retired but still work with us and we've got a large pool of knowledge to draw on. We've got various testing facilities - which other people do I'm not… Obviously other people have these. I think the thing I would say is if you look at the mission of The Welding Institute it's to enable others to achieve their purpose through welding and joining and allied technologies. So effectively it's to help other people who have welding problems to fix. That's really why the place was set up. And that remains our purpose, so our purpose is to help others. We have this ability as an independent to convene different people and points of view so if I think about my own personal role I think bringing people in to share experiences and work together is a key part of what we do. So that's… and I know obviously industry can't share everything and there's things that remain confidential but that ability to come together and share with others what they're willing to share I think that is. Like I say we've got facilities and we've got other people that we work with so I think we've got that ability to bring people together to try and address the most difficult challenges. And also we've got the modelling and simulation people and software. So, yeah *[nods].*

**(01:18:38) SLH**: Amazing. Thank you very much. Thank you.

**(01:18:39) PW:** Thank you

**(01:18:44) SH:** The papers mentioned in this podcast will also be available on the TWI-Global website or the TWI Digital Library, which is an exclusive platform for our Industrial and Professional Members. So if you're interested in reading any of these papers or would like to do a bit of research on your own then these are the platforms where you can find our expertise and everything like this. Thank you very much.