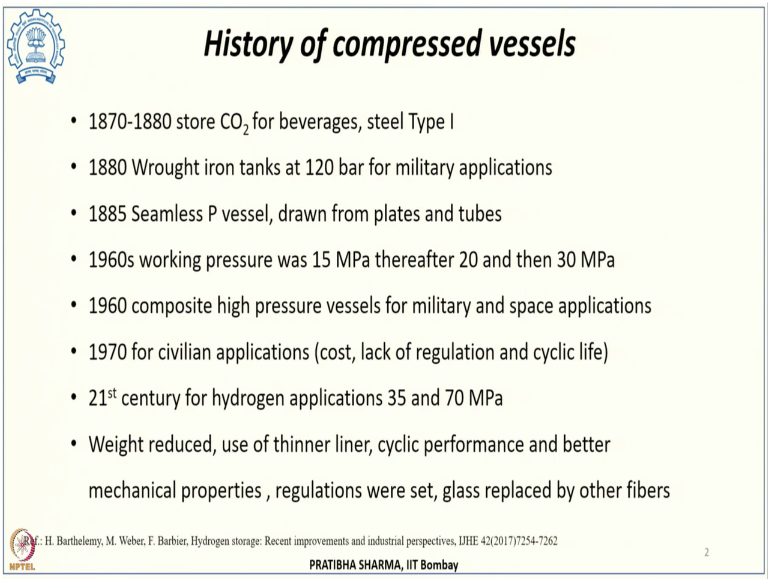
Hydrogen Energy: Production, Storage, Transportation and Safety
Prof. Pratibha Sharma
Department of Energy Science and Engineering
Indian Institute of Technology, Bombay

Lecture - 40
Compressed Hydrogen Tanks

In the previous classes, we have seen the Thermodynamics associated with hydrogen compression. We have seen the different types of hydrogen compressors and now, once we have compressed that hydrogen, we have to store it. For that we require compressed hydrogen tanks. So, in this lecture, we are going to learn what are the different types of compressed hydrogen tanks available; what are their design, concepts and what are the different safety parameters; what are the challenges which are associated with these compressed hydrogen tanks.

Just to look at the history of these compressed vessels, the oldest pressure vessels, these date back to the late 19th century. It was in somewhere in 1870 to 1880 that the steel type I tanks were used and these were basically used for storing carbon dioxide and that use was for beverage and at that time, started the use or the business of industrial gas.

(Refer Slide Time: 01:33)



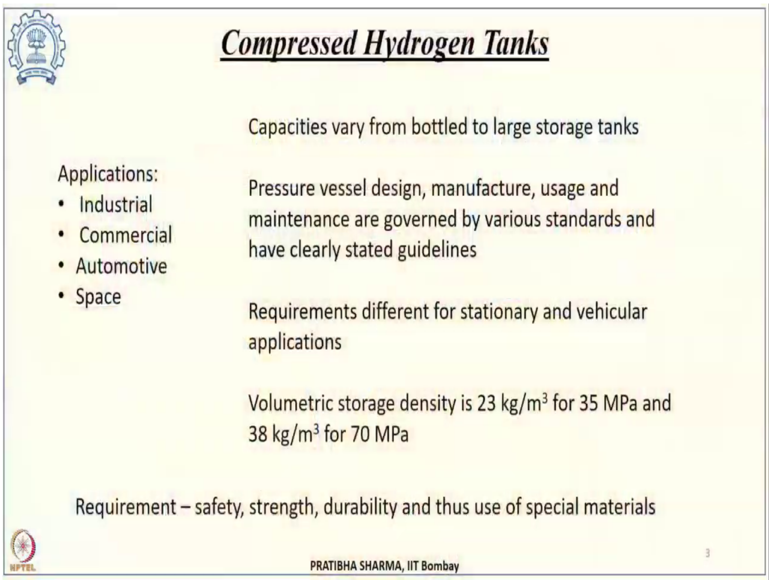
Thereafter, in 1880 hydrogen, it was stored at 120 bar in Wrought iron tanks and this was for military application. In 1885, the use of seamless pressure vessels which were in fact drawn from plates and tubes that came into existence. However, it took a pretty long time to increase the pressure to 15 MPa. So, in 1860s, the working pressure was 15 MPa. However, thereafter, it increased to 20 and then, 30 MPa.

Now, in 1960, the composite high pressure vessels, they came into existence and they were basically used for military and space applications; but then, there were challenges at that time associated because of the cost because of the non-existing regulations because the cycle life as such when they came for civilian applications in 1970s, there were very few in numbers which were available in the market and those also were specially designed for that particular application.

It was in 21st century, this composite high pressure vessel which could store hydrogen at 35 to 70 MPa came into existence. Now, there were several improvements in the design; there were several improvements in these high pressure vessels in terms of weight reduction, use of a thinner liner, increase in the cycle life performance, getting better mechanical properties. Then, there were regulation that were set on these pressure vessels, the glass which was used for wrapping that was replaced by other fibers that could increase the strength of these cylinders.

So, there were several advancements that they have experienced over a period of time. If we look at these compressed hydrogen tanks, then they can be used for a wide variety of applications.

(Refer Slide Time: 03:44)



They can be used for industrial applications, for commercial applications, for automotive onboard hydrogen storage in different FCEVs, for space explorations and for all these applications, the capacity can be very small. These can be available in the bottled hydrogen cylinders to very large scale storage tanks are available at different locations.

Now, it is very important to look at the design of these pressure vessels, their design, their manufacture, their usage, at the point of usage and during the maintenance all these are governed by various standards now which are in place and there are clearly stated guidelines and protocols that needs to be followed.

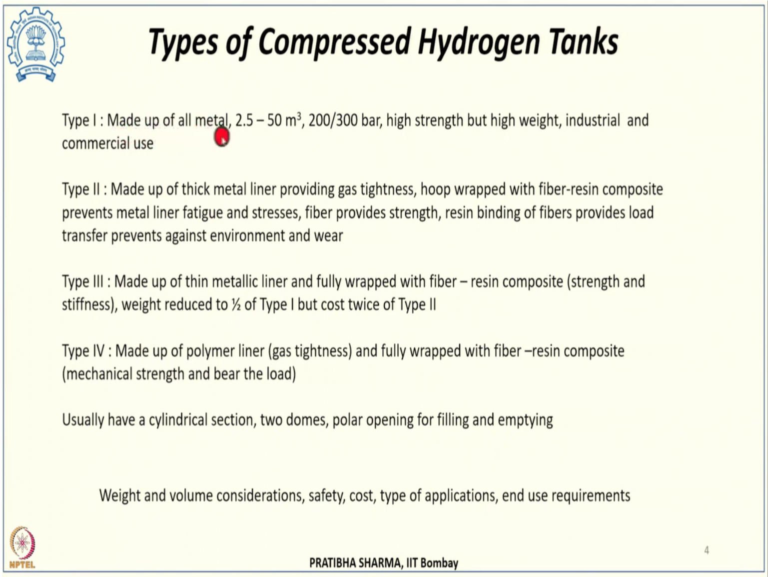
Now, if we see these applications, their capacity that varies and the requirements from these storage tanks is very different. Like the difference is drastic when it comes to either stationary or vehicular application; the weight and volume is a bigger constraint, when it comes to vehicular application as against when it is used for stationary application.

We have learnt in the earlier class that as we compressed gas to higher pressures, the volumetric energy density increases. Now, the commercially available tanks which are meant for like vehicular application, they can store hydrogen at 35 MPa or 70 MPa. Now, as against the hydrogen under normal temperature pressure condition, where the density is 0.8 kg per meter cube; the density increases when it is compressed to 35 MPa to 23 kg per meter cube. While when it is stored in a 70 MPa tank, the density increases to 38 kg per meter cube.

So, when we are using these compressed hydrogen tanks, there are several requirements which are in terms of safety while being used. The strength of these tanks, durability of these tanks and as such requirement is of special materials which could sustain such high pressures. Hydrogen, we knew that it is a peculiar molecule, it has a very high diffusivity, it is the smallest molecule.

So, there are several challenges associated as well while storing hydrogen. Now, there are different types of these compressed hydrogen tanks, these can be categorized into four categories; type I, type II, type III and type IV.

(Refer Slide Time: 06:27)



The first category which is type I tank, these are completely made up of metal and since these are made up of metal, they have very high strength. They can store hydrogen at a pressure of 200 to even 300 bar. But the maximum sustainable pressure can go as high as 500 bar. There are tanks which are available in different sizes, which can be from 2.5 to 50 meter cube. They have very good strength; but the major challenge is the weight.

Weight associated with these metal tanks is very high. The reason being as we go for higher pressures in order to have a high strength, the thickness of the wall of the tank increases and that adds up on to the weight. So, the cost is lowest for type I tank; but the weight is highest and these tanks are basically used for industrial and commercial purpose.

The second category is type II tank and these are made up of an inner metal liner which is a thick metal liner. This liner its purpose is to provide gas tightness so that there is no gas leakage. However, the hoop of this thick metal liner is wrapped with fiber resin composite. So, this is partially wrapped onto the hoop with a fiber resin composite and the use of this fiber resin composite that provides resistance towards metal liner failure, its fatigue and also against the residual compressive stresses.

The presence of this fiber, it provides strength to the tank while the resin which is there in the composite that helps in binding of these fibers. At the same time, that provides load transfer and prevents any sort of wear or failure from the environmental conditions as well.

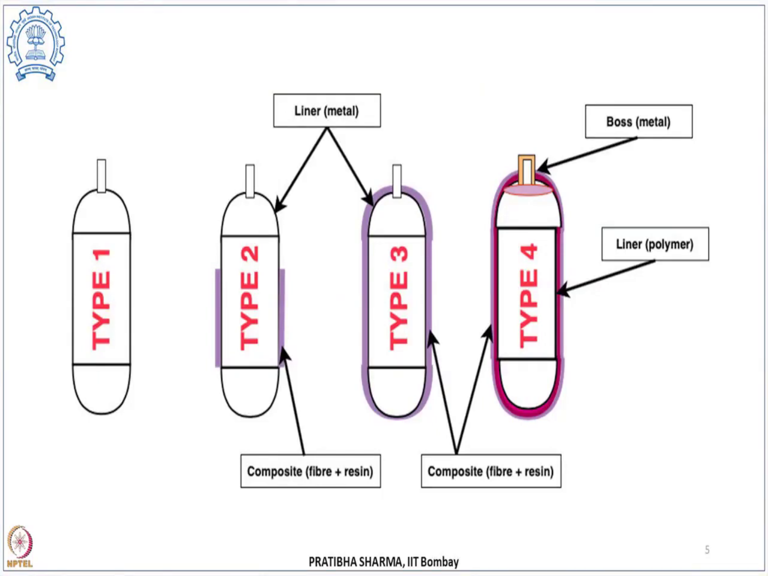
The third category is type III tank which is again made up of a inner liner which is metallic; but a thin inner metallic liner and instead of partially wrapping with the fiber resin composite, it is completely wrapped with fiber resin composite. Now, again the liner provides gas tightness, while the wrapping of this fiber resin composite that provides strength and the required stiffness. When we move along from type I to type II to type III and later to type IV, the weight of the tank reduces; but the cost increases.

So, if we see type III tank, their weight is half of that of type I tank; but the cost is twice that of type II tank and that is the major drawback. The next category of compressed hydrogen tanks is type IV tank. So, these are made up of polymer liner. So, instead of metallic liner which was in case of type I, type II or type III tank, the liner is also made up of polymer and that ensures gas tightness. The wrapping is complete. So, it is fully wrapped with the fiber resin composite and that wrapping provides both mechanical strength and also, it bears the load.

Usually, these tanks they consist of a cylindrical section and then, two domes; there is an opening, a polar opening. This could be one or two depending upon the application and that opening is provided for filling of the tank as well as emptying the tank. Now, when selecting which tank we are going to use, all that depends upon what is the weight and volume requirement for that application; whether it is meant for stationary application, then then we are not much worried about the weight and volume.

But if it is for portable application, then the preferred would be type III and type IV tanks because their weight and volume requirements are lower. Safety, the associated cost, what is the requirement of the end use application and what is the type of application we are looking at all that we will decide which tank will be used for these applications.

(Refer Slide Time: 11:20)

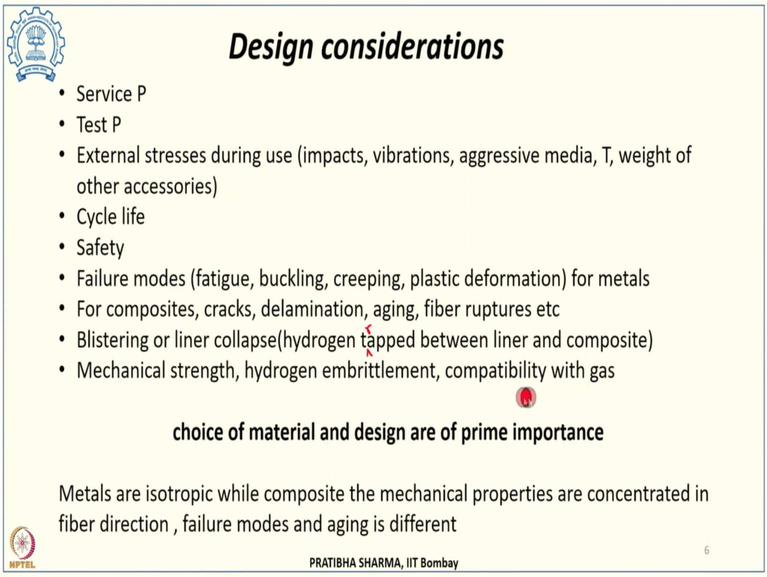


Just to show you how these tanks are. So, type I tank, this is a completely metallic tank with one port being shown here. This is all metal tank and this is highest in weight, but lowest in cost. Now, the type II tank, this is again a cylindrical structure with there could be 2 domes on the other side and only the hoop is wrapped. So, this is the hoop wrapped with the polymer reinforced; this is fiber and resin composite.

Type III, where instead of having partially wrapping, it is completely wrapped. But the inner liner still remains metallic. So, inner liner is still metallic in type III tank; but it is thin inner liner and then, completely wrapped with the fiber resin composite. Now, type IV, the difference is the inner liner is also made up of polymer instead of metal and then again, it is completely wrapped.

Now, when it is completely wrapped, the port which is required for filling and emptying purpose, then that interface the junction of the liner and boss that should be leak free. That is another major challenge in designing such tanks.

(Refer Slide Time: 12:44)



Now, when we see the design of such tanks, this is complicated. They are designed in such a way so that they should hold that pressure that is one is a service pressure. By service pressure, we mean like the type III tank, this could be for 350 bar and that they are going to operate and they are going to hold that pressure throughout their life. So, that is their service pressure. However, the test pressure, when they undergo a testing that could be 1.5 times more than the service pressure. So, they are designed to bear both; the service as well as test pressure.

At the same time, there could be external stresses that could be unavoidable during their use, there could be possible impacts with the other structures, there could be vibrations during their usage, there could be exposure to aggressive media, external temperature could be high or low and then, there could be other connectors, connections which could add to the weight. So, the weight of the other accessories and all these stresses, these are meant to bear. They should have a very high service life or cycle life. So, number of cycles, they can be used for.

Operation should be safe, they should be designed in such a way that we can avoid these failure modes like in case of metal, the possible failure modes could be fatigue, buckling, creeping or the plastic deformation. While when we are considering the composites, there could be challenges like cracks appearing, there could be delamination, with time there could be aging which could be experienced, there could be fiber ruptures and all these considerations should be given while designing such tanks. So, as to have that much strength and stability and durability.

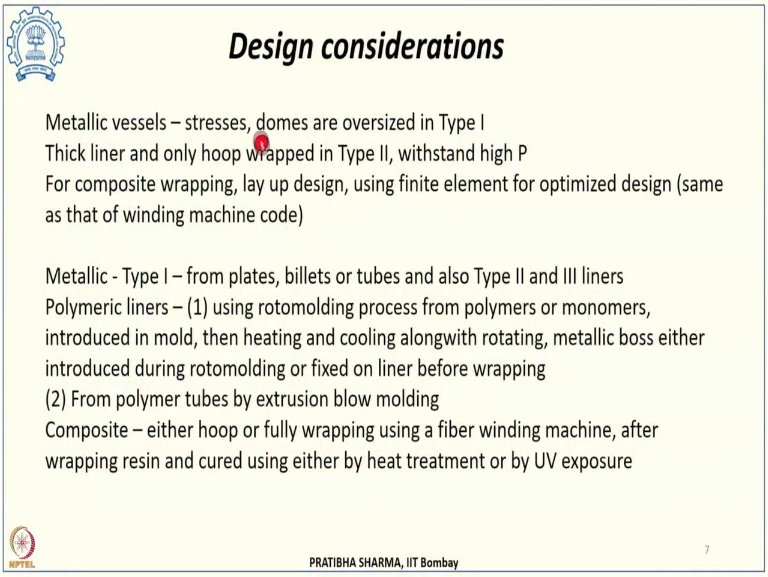
There are other challenges like blistering or liner collapse and that could specifically occur when hydrogen can get trapped between the liner and composite. And this can occur at the time when we are emptying or filling the tank and then, there is a pressure difference. So, the service pressure and the tank pressure which is the dynamic pressure that may change and that could lead to liner collapse at times.

We have to also consider that the tank should have a good mechanical strength; the materials which are used should not undergo hydrogen embrittlement which is the biggest challenges in devices, systems that store hydrogen; the accessories through which hydrogen is being transported. At the same time, whatever gas we are storing in the pressure vessels, it should be compatible; the tank should be compatible with those gases.

Now, all these requirements that need to be met that poses a very important restriction in terms of the choice of material that we could have and the design of the tank. Now, if we consider the metallic tanks like the type I tank, the metals they are isotropic throughout; but if we see the composite tanks whether it is type III or type IV, the mechanical properties these could be different.

This is these are anisotropic and these mechanical properties, they may be different in the fiber direction depending upon how the wrapping is being done; whether it is hoop wrapping, whether it is polar wrapping and then, also between the metals and composite, the failure modes, how the aging will take place all these are different and while designing the tanks all these also need to be considered. Now, when it is up to metallic vessels, the type I tank, then usually these are having a cylindrical section and then, there are two domes.

(Refer Slide Time: 17:09)



So, these are designed in such a way the domes are oversized so that the stresses could be reduced in type I tank. In case of type II tank, there is a thick inner liner and only hoop area is being wrapped and this hoop wrapping is done so that this could withstand higher pressures. But for composite wrapping, it is essential that an initial calculation, a simplistic calculation has to be done.

So, as to come up with the layup design and then, a detailed finite element analysis has to be done so as to come up with a correct and optimized design of such tanks and that is very important; how that wrapping will be done and this design which we come up with it has to match, it has to be coherent with the winding machine code as well.

Now, if we see how these manufacturing of these tanks is done; the type I tank or the all metal tank, they can be made from plates, billets or from tubes. Now, if they are to be made from plates, in that case these plates are deep drawn so as to get the cylindrical section and then, these are hot spinned so as to get the neck region.

Now, that hot spinning is done so as to get the neck region and the extra metal that is obtained that is machined to get the port; for port or connection for the emptying or filling. Now, same could be done with the billets. So, initially, they are heated up so as to draw them into the required shape and then, the same procedure is followed as with the plates and same is done with the tubes as well.

So, this is when it is the metallic tank or the metallic liner in case of type II and type III tank which is used as a liner material. Now, if we want to make the polymeric liner, in that case the process is different. Now, these polymer liners can be obtained from either polymers or monomers and these are introduced into a mold and the process which is being used is a rotomolding process. Now, when these polymers monomers are introduced into a mold which has a shape which is identical to the final cylinder that we want then these are heated and cooled along with rotating.

So, along with rotating, the process is done is of heating and cooling so that it could reach the fusion temperature or the temperature of polymerization. Now, once that has been done, then either there are two ways that the metallic boss which is the port, it could either be introduced during this process itself, the rotomolding or it can be fixed onto the liner before the next layer, the wrapping of the cylinder is being done.

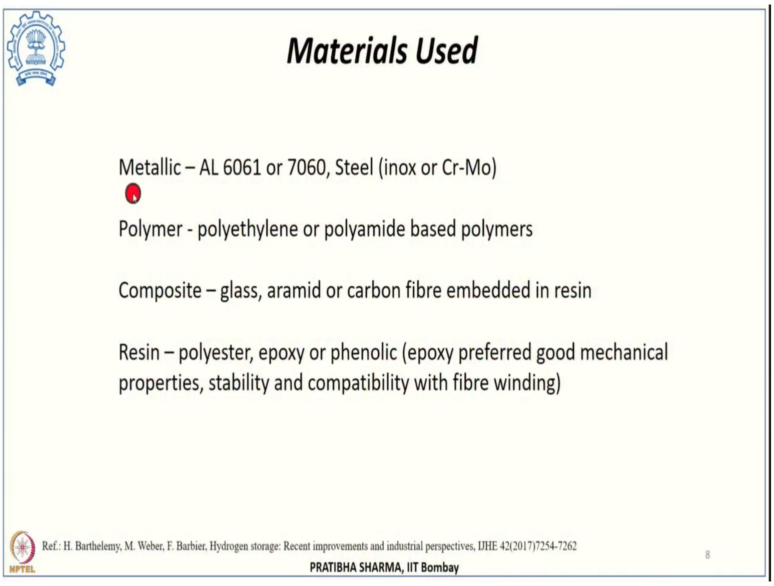
The another way to have the polymeric liner is we can make it from polymer tubes and that could be done by means of extrusion blow molding. Now, after the liner which is either like if it is type I, then it is all metallic; type II and type III inner metallic liner; if type IV, then polymeric liner. The next layer comes is that of fiber resin composite.

Now, for the composite, what is done is either we know that if it is type II, it is hoop wrapped. If type III and type IV, then it is fully wrapped with the fiber resin composite. So, first of all, in having that layer fiber is being wrapped and there are different ways, different orientations in which the fiber can be wrapped. It can be hoop wrapped, it can be polar wrapped and that is done through a fiber winding machine.

After that fiber winding is carried out the resin is introduced and that has to be cured and that curing of the resin so as to form the binding with the fiber that can either be done at an appropriate temperature heat treatment in an oven or it can be done by means of UV exposure. So, that is how the liner, then the fiber resin composite is done in case of different tanks type I to type IV.

Now, we have seen that there are several problems or challenges associated with these tanks. They have several requirements as such the materials which can be used for these tanks are also very specific.

(Refer Slide Time: 22:37)

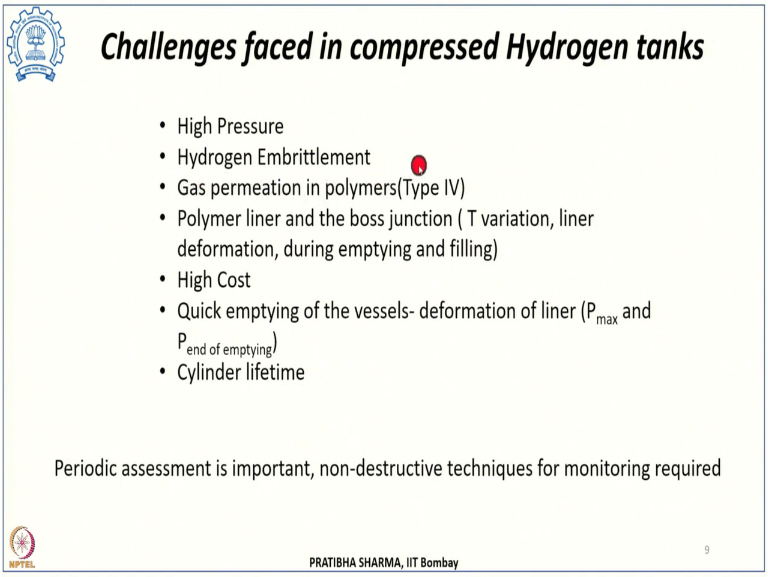


For example, the metallic portion or the metallic liner or the all metal tanks, they can be made up of either AL 6061 or 7060. It could be steel (inox or the chrome molybdenum). It the polymer which is used as a liner in case of type II, type III and type IV tank could be either polyethylene or polyamide based polymers. Now, again, the water content in these is important. So, while drying you have to consider that. So, polyamide, they have a higher wet water content; polyethylene have a lower water content.

The the fiber that could be used can be earlier in earlier pressurized vessels, glass was used and then it was replaced; however, glass is still more economical. But when it comes to higher pressure operations 35 MPa or 70 MPa, then carbon fiber is used. So, the options could be either glass, aramid or carbon fibers and these could be embedded in the resin and then, there are choices for resins also. These could be polyester, epoxy or phenolic.

However, the more preferred one is epoxy resin and the reason is they have very good mechanical properties, they are stable and they have a compatibility with the fiber winding. So, the fiber resin composite which could be a carbon fiber and epoxy resin is used in type IV cylinders. But the major challenges in designing in the materials selection in a compressed hydrogen tank are since we are dealing with very high pressures that too with hydrogen which is a very small molecule diffuses very fast. So, the choice of materials, the design of the tanks becomes very important.

(Refer Slide Time: 24:43)



At the same time hydrogen embrittlement, we know is the biggest challenge when dealing with hydrogen; then, we are using polymers like in type IV tanks gas permeation is another important factor that we need to consider. Now, gas permeation takes place in polymer and that is because of the diffusion that could occur and dissolution that could occur and this gas permeation should be as low as possible.

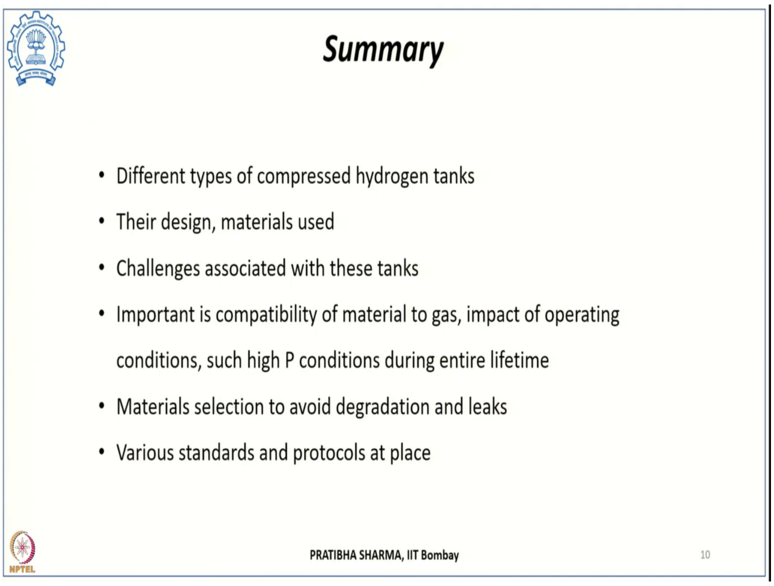
So, a proper testing of these tanks is essential to know the gas permeation and this should be as low as possible in these tanks, then the another important point is the place, where the polymer line liner is integrated with the boss. So, that junction the polymer liner and the boss junction. Now, this is a very important point and we can get leakage at this point, if there is a temperature variation.

For example, when that emptying of the cylinder takes place or when the filling up of the tank takes place, there will be a temperature variation. This we have already seen that the compression and expansion thermodynamics of hydrogen subjected to that temperature variation, there could be changes at this interface. There can be even liner deformations when such changes occur during emptying and filling of the tank. If it is done very fast, this emptying or filling of the vessels is done very fast that can lead to a substantial deformation of the liner.

So, we have to consider what is the maximum pressure which was filled in the tank and what is the pressure at the end of emptying and that needs to be monitored in such tanks. Cost of these tanks like specifically type III and type IV tank is higher. So, that is another challenge and the lifetime of the cylinder, again requirement is it should be high. For all these challenges, it is essential that a periodic assessment of these tanks should be done.

There are different ways of doing that visual assessment, then acoustic assessment is also being considered; but the important requirement is that there should be non-destructive techniques to monitor these tanks continuously.

(Refer Slide Time: 27:30)



To summarize the part on the compressed hydrogen tanks, we have seen today the different types of compressed hydrogen tanks; what are the possible materials that we can use; the design considerations; what are the challenges associated with these tanks and important is that while selecting the material, while selecting the design, we have to consider that we are considering hydrogen as the gas.

So, the compatibility of gas with materials plays a very important role and there is an impact of the operating conditions what is the temperature, what is the pressure and at such high pressure conditions, these will be throughout their service life. So, the operations will be at such high pressure conditions during the entire lifetime that also needs to be considered, while considering the materials as well as design.

So, the material selection should be such that there should not be any degradation or leak from these tanks and for that, there are various standards and protocols at place that needs to be followed.

Thank you.