Hydrogen Energy: Production, Storage, Transportation and Safety
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Lecture - 58
Hydrogen Transport via Road

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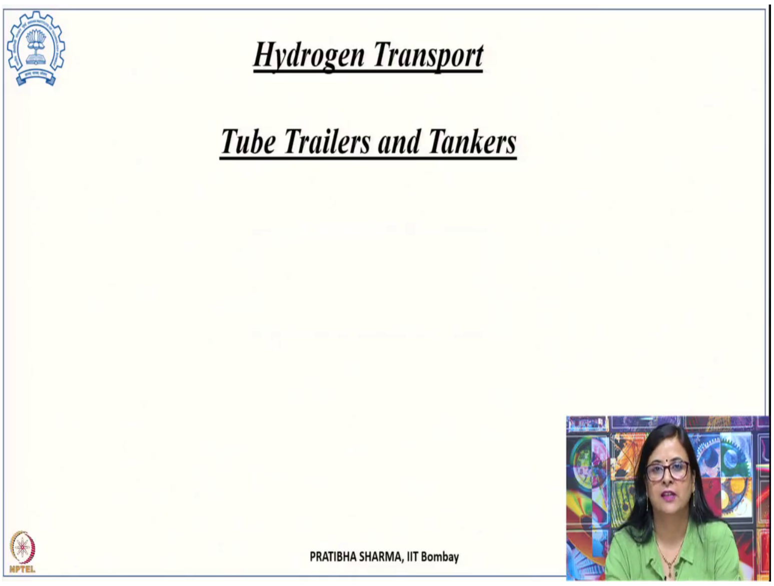

We have seen hydrogen transport via pipelines, liquid organic hydrogen carriers or using ammonia and that was meant for large volumes and long distance transmission of hydrogen.

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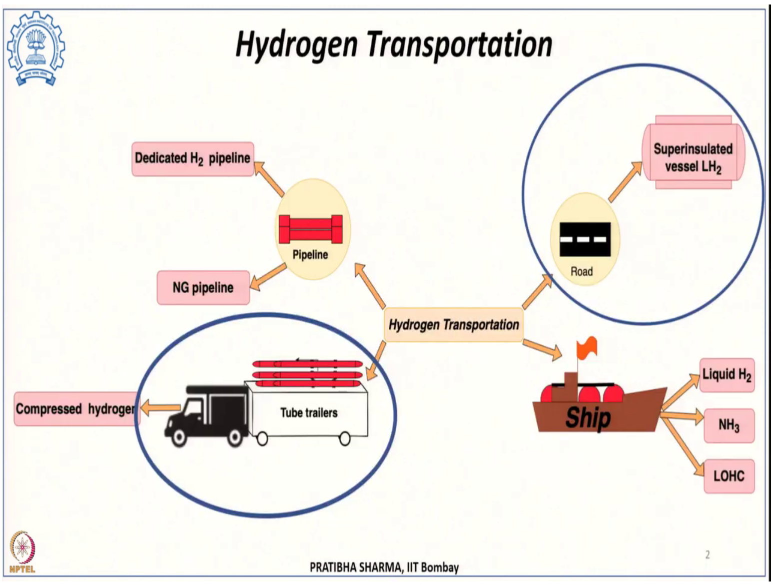

Now, let us look at some of the other methods of hydrogen transport like, transportation via road as compressed hydrogen in tube trailers or transportation via road in super insulated vessels.

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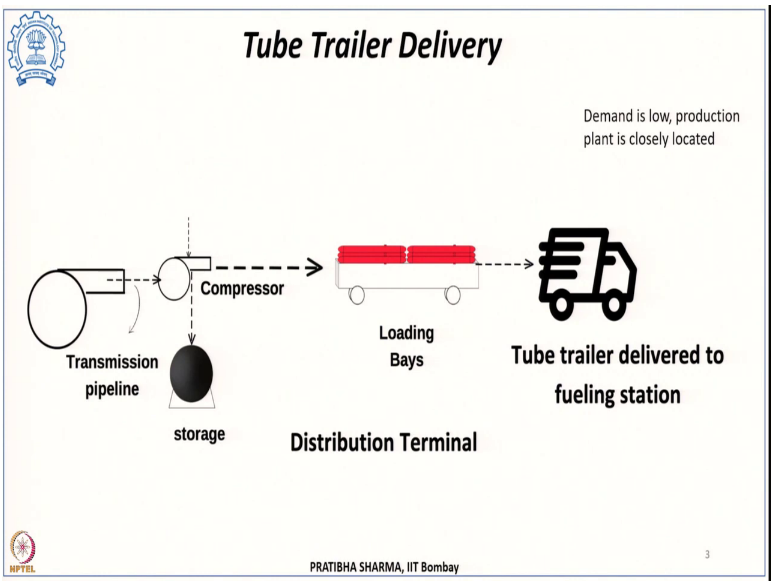

Now, if the demand of hydrogen is low and the production plant it lies in close proximity of the to the distribution terminal or the gas terminal. In that case transport of hydrogen via tube trailer could be more economical. Now this production could be either central production plant from there hydrogen could be taken via transmission pipelines to the distribution terminal or it could be a semi central production plant where, the production plant is co-located with the gas terminal.

So, therein the hydrogen will be compressed from the production pressure or the transmission pipeline pressure to the pressure required for tube trailer or the pressure at which the tube trailers will be filled. And that is compressed loading bays are there and then there is an interface with the tube trailers; however, there will be storage so as to address the demand variabilities.

So, now, these tube trailers these loading bays they have pressure vessels, which are loaded onto the tube trailers and then these tube trailers deliver hydrogen to the hydrogen refueling station.

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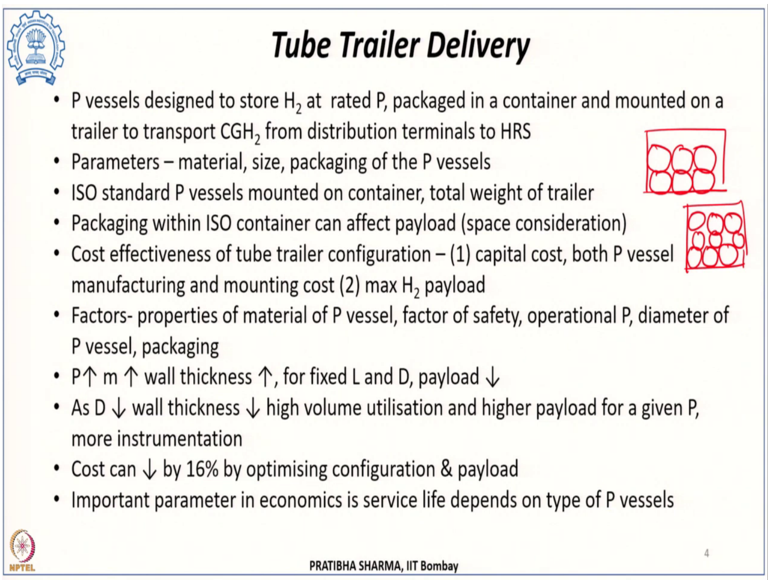

Now, when we consider tube trailer delivery by tube trailer, we mean that there are several pressure vessels that are meant or they are designed for certain pressure rating they store hydrogen, they are packaged together into a container and that container is mounted on a trailer to transport the gaseous hydrogen from the gas distribution terminal to hydrogen refueling station as compressed gaseous hydrogen.

Now, in this tube trailer delivery there are several important parameters that needs to be considered. Like these pressure vessels what is the material of these vessels, what are the dimensions of these vessels, what is the pressure rating of these vessels, how these pressure vessels are packaged together. Now there are different ISO standards which determine or which limit the weight of the tube trailer what will be the dimensions of the vessels that are to be mounted onto the container.

Now when these pressure vessels are mounted onto the container they can be packed in a certain way. For example, if we see they can be packed in such a way that they lie one above the other and so on. Or there could be wherein they are packed together in such a way. So, depending upon how they are packed together the total weight of the trailer, the hydrogen payload, that they can carry that may differ, but there is a restriction to the total weight of the tube trailer.

So, the packaging is going to affect the payload and that becomes more important when there is a space constraint compared to the weight constraint. So, they have to be effectively packaged together in such a way that volume is effectively utilized. Now this packaging, the cost effectiveness of the tube trailer configuration will depend upon parameters like, what is the capital cost. This capital cost includes both the pressure vessels, their manufacturing and the mounting cost.

At the same time how much hydrogen payload they are able to deliver. So, that optimization is essential in terms of cost per unit the payload or the capital cost per kg of the payload being delivered. Now, this cost is going to be determined by several factors like, what is the material of which these pressure vessels are made up of, what is the properties of these materials like what is the tensile strength, how much is the factor of safety that we are considering, what is the operational pressure, what is the diameter of these vessels and how they are packed together.

Like let us say for example, if we take a pressure vessel of a particular length L and diameter D and if we want to increase the payload or the mass of hydrogen that it is going to carry. So; that means, we have to increase the pressure. Now, if that pressure is increased; that means, the wall thickness has to be increased. Now if wall thickness increases; that means, the weight of the vessel will increase without even hydrogen and that will further decrease the payload.

So in fact, it becomes ineffective or counteractive if we increase the wall thickness to increase the mass that is being stored. Now, another option could be we can decrease the diameter. So, if we decrease the diameter; that means, we can decrease the wall thickness and in that case we can have higher volume utilization.

So, we can have smaller vessels which are loaded onto the tube trailers and then we can have higher volume utilization and for a given pressure this will give rise to a higher payload. But again the challenge would be now when we have smaller vessels the number of vessels will increase because the diameter has decreased wall thickness decreased.

Then in that case the number of vessel will increase and because of that there will be more instrumentation requirement, these instrumentation will come along with like the requirement for piping's then there will be number of walls that will be required will increase. So, all that cost will increase. Now it has been demonstrated that if we optimize the configuration and payload in such a manner.

So, as to decrease the cost then a proper optimization can result in decrease of cost by 16 percent. Now other than the parameters that mentioned an important parameter when we consider economics of tube trailer delivery is the service life. So, the service life of the tube trailer and that will depend upon which type of pressure vessel we are using.

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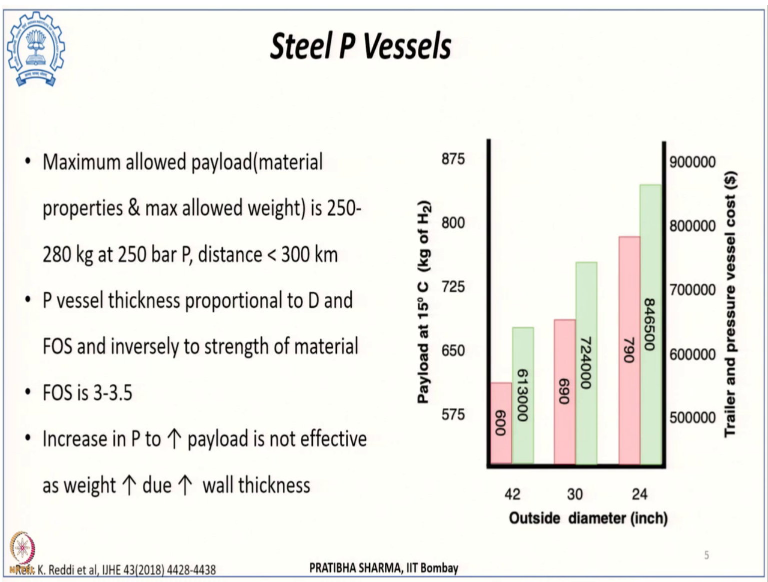

Now, there could be different type like these could be made up of steel. Now if they are made up of steel then depending upon the material properties we know the steel have a different tensile strength, it has different properties and then there will be standards limiting the allowed weight.

So, the maximum allowed payload when the vessel is made up of steel is limited currently to 250 to 280 kgs and these are holding a pressure of 250 bar and the maximum allowable distance with these steel pressure tanks is less than 300 kilometer. However, they have been lot of simulation studies that has been carried out like by the K Reddi et al, and they have seen that how to increase the payload, by say changing the pressure by how to change the payload by changing the outer diameter.

So, if we change the outer diameter then the payload could increase like from 40 to 36 it can store say 690 kgs of hydrogen or 24 inch it can store 790 kg of hydrogen, but we can see that there is a link between the cost as well. So, as the payload increases the cost of the trailer and pressure vessel also increases. So, the thickness of the vessel it is proportional to both the diameter and the factor of safety and pressure definitely.

So, this factor of safety it also plays an important role and this thickness of the vessel it is inversely proportional to the strength of the material. So, the thickness of vessel is directly proportional to diameter, factor of safety and inversely to the strength of the material.

This factor of safety for steel vessels this is in the range of 3 to 3.5 usually 3. Now as we have seen that if we try to increase the payload by increasing the pressure that is not effective because the wall thickness will increase, which will further increase the weight of the vessel.

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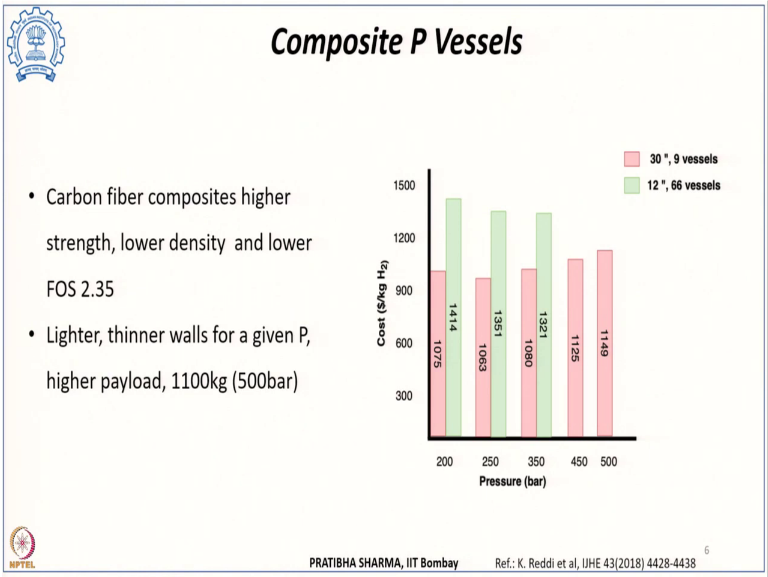

So, the other option could be to have composite pressure vessel and this we have already seen that different types of compressed hydrogen tanks like the type 1 to type 4 tanks, composite tanks we have seen type 3 and type 4 tanks. Now, when it is carbon fiber composites which are used we know that they have higher strength, they have lower density and thus because of the higher strength, the required factor of safety is comparatively lower than in the steel tanks.

So, for the composite pressure vessel the factor of safety to be considered is 2.35. Since they are lighter they may require their strength is more. So, they may require thinner wall for a particular pressure and as such the payload that they can deliver is higher. So, like at 500 bar the payload is 1100 kg. Now there has been studies being carried out to see the cost if we change the pressure.

So, for different say dimensions a 30 inch, 9 vessel container then the cost would be like different this is the peach 1, this is lower compared to 12 inch, 66 vessels at different pressure. So, at typical pressure of 500 bar we can get a achieve a payload of 1100 kg of hydrogen being delivered in such composite pressure vessels.

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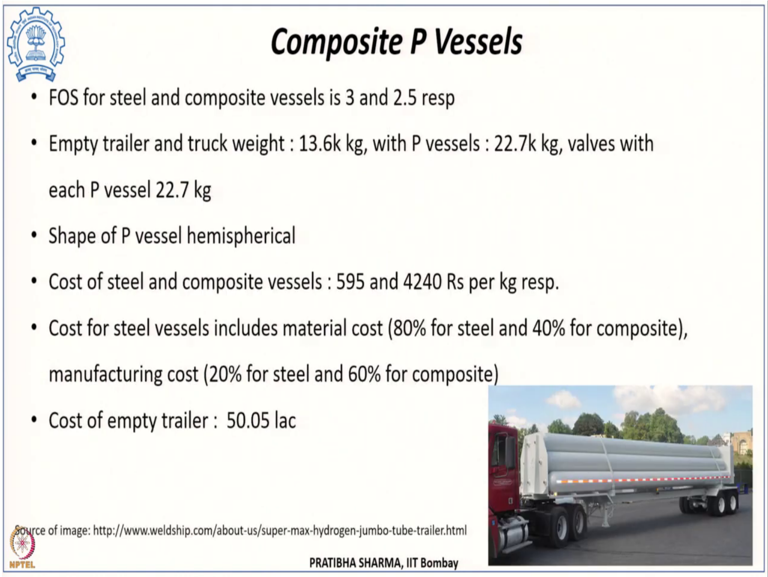

Now, this is a typical picture of how these typical tube trailer looks like, this is the source from which this has been shown. Now the difference is the factor of safety between the steel vessel and the composite vessel; for steel generally it is 3 factor of safety for composite it is 2.5, which is being taken. And then there are limitation on to the empty trailer and truck weight. So, there has been studies which has been carried out.

And then it has shown that the empty trailer and truck weight is like around 13600 kg with the pressure vessels it is 22700 kg even the valves, which are used that also has a like considered to be weight of say 22 kg for each of the vessels. Usually the shape is considered to be hemispherical and the cost associated with the material, the steel.

And composite vessels it is roughly about for steel it is 595 rupees per kg for composite vessel it is 4240 rupees per kg respectively. Now, among the materials cost if you see the breakup of these vessels it is material cost and the manufacturing cost. So, if we consider the steel vessels then the cost is 80 percent of that of the material that is the steel and 20 percent goes to the manufacturing cost.

If it is composite material, which is used for making these pressure vessels then 40 percent is for composite and 60 percent is for manufacturing cost that has been reported. The cost of the empty trailer it is roughly around 15.05 lakh; however, there may be variations to it as well.

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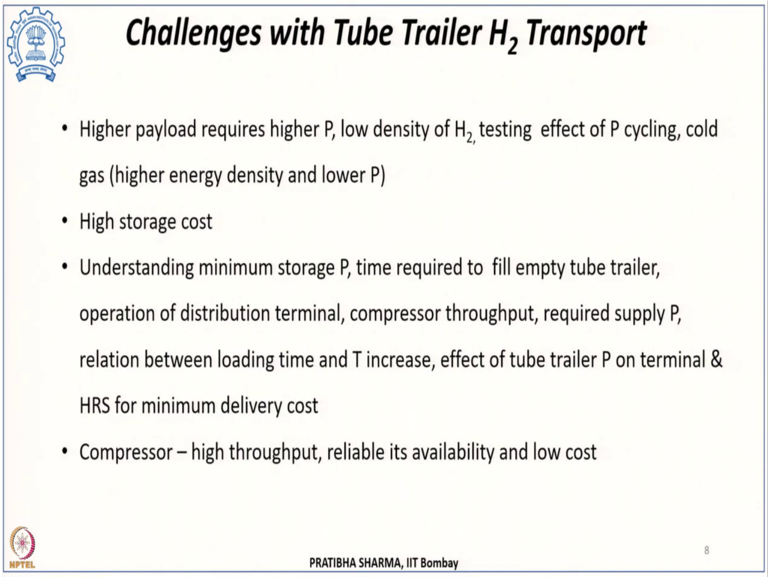

But the challenges that lies in transporting hydrogen via tube trailer is if we want to increase the payload because the density of hydrogen is low we have to increase the pressure. And if we increase the pressure we have seen that there is not much effective improvement in the payload because, of the higher weight of the vessels that will increase.

At the same time when it is a higher pressure we need to have testing being done we have to see what is the effect of repeated cycling on the vessels and that frequent testing will become essential. Now this improvement in the payload could be achieved if we store cold gas that is if it is cold and compressed then we can achieve higher energy density at a lower pressure. At the same time since there will be requirement of storage to meet the variabilities in the demand.

So, that also adds up to the cost with the tube trailer based hydrogen transport there are several features we need to understand yet. So, there needs to be studies to be carried out to understand what will be the minimum storage pressure.

So, when the tube trailer is emptied there will be still certain pressure about 50 bar that will be left out. So, what should be the minimum pressure at which it has to be returned back so, that the entire economics becomes more viable. How much will be the time required to fill the empty tube trailer, what will be the requirements for operation at the distribution terminal, how much will be the compressor output and how does it get affected by the different parameters, what would be the required supply pressure, when we do filling of these tube trailers.

During loading how fast we can fill without substantial increase in the temperature because during the loading there will be a dependence between the loading time and the increase in the temperature. What is the effect of these tube trailer pressure on the terminal as well as the hydrogen refueling station?

And what are the function, how does these vary with the delivery cost, all these needs to be well understood. Now compressors which are used at the gas stations at the distribution terminal it is required that they should have high throughput, they should be reliable, their availability and their low cost is required.

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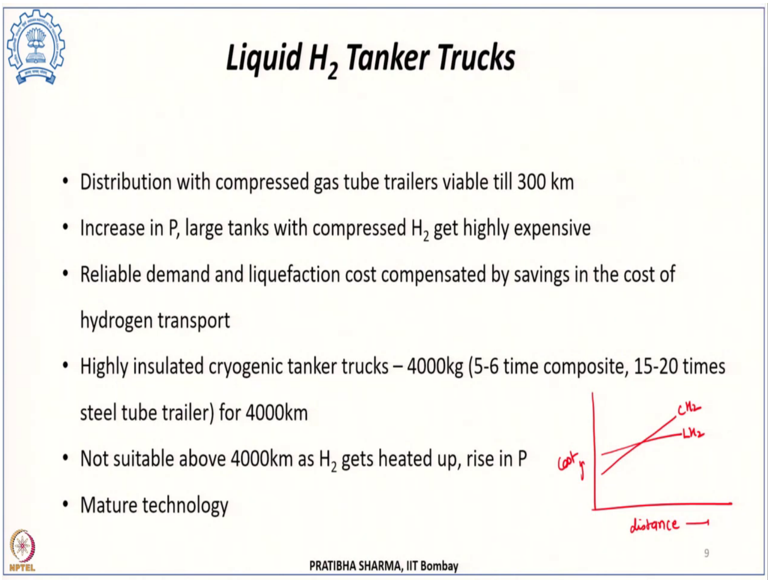

Now, the next method of hydrogen transport is in the form of liquid hydrogen using tanker trucks via road. We have seen that the distribution of hydrogen using the compressed gas tube trailers that is a viable option till a distance of 300 kilometers, beyond that economics will work more in favor of liquid hydrogen based transport via road.

Now if we see that there is an increase in the pressure required for compressed hydrogen transport via tube trailers the larger tanks with compressed hydrogen gets highly expensive. So, actually if we see the cost versus distance of transport curve then, in that case it is observed that there comes a breakeven point wherein the compressed hydrogen beyond a certain distance becomes more expensive than the liquid hydrogen transport. So, if we find that there is a reliable demand which will continue.

And if the liquefaction cost can be compensated by saving the cost in terms of hydrogen transport because liquid hydrogen transport carries a higher energy density or more quantities of hydrogen can be carried when liquefied. So, if that liquefaction cost can be off-settled by the savings in terms of the hydrogen transportation cost. In that case liquid hydrogen tankers or carrying liquid hydrogen through trucks would be more economical and viable and this can be done using highly insulated cryogenic tanker trucks.

So, these trucks can carry 4000 kg of liquid hydrogen over 4000 kilometers. Now this is roughly about 5 to 6 times that of the composite tube trailers pressure vessels and 15 to 20 times that of the steel tube trailers that we have studied, but above this distance of 4000 kilometers they may not be economically viable. Reason being beyond this long journey of more than 4000 kilometer hydrogen will get evaporated and it will get heated up there will be boil off losses there will be rise in pressure and as such beyond this it would not be viable and this is a mature technology.

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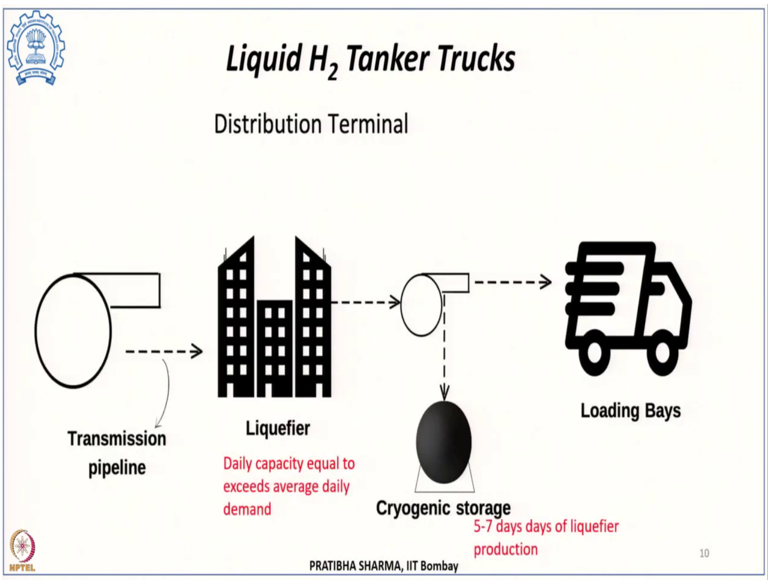

Now, let us see either the hydrogen can be transported via liquid hydrogen tanker trucks from the point of production to the point of end use via these trucks depending upon whether it is a centralized production plant in that case from the production plant hydrogen can be bought through transmission pipelines liquefied it could be stored.

In the cryogenic storage vessels could be pumped using cryogenic pumps to load onto the tankers or it could be a semi central production facility, where in the production and liquefaction is done on site both at the same location at the distribution terminal. So, what is required is the gaseous hydrogen is being transported, it is being liquefied using a liquefier, it could be stored in a cryogenic storage container it could be pumped to the using a cryogenic pump into the tanker at a loading bay. And then these tankers could carry liquid hydrogen to the hydrogen refueling stations or to the utility.

Now, these liquefiers which will be used for hydrogen liquefaction they usually have a daily capacity which is either equal to or that exceeds the average daily demand of liquid hydrogen, and the cryogenic storage facility which will be there at the distribution terminal that can store 5 to 7 days of the output from the liquefier. So, this is how a liquid hydrogen tanker or a filling or the distribution terminal for liquid hydrogen it works.

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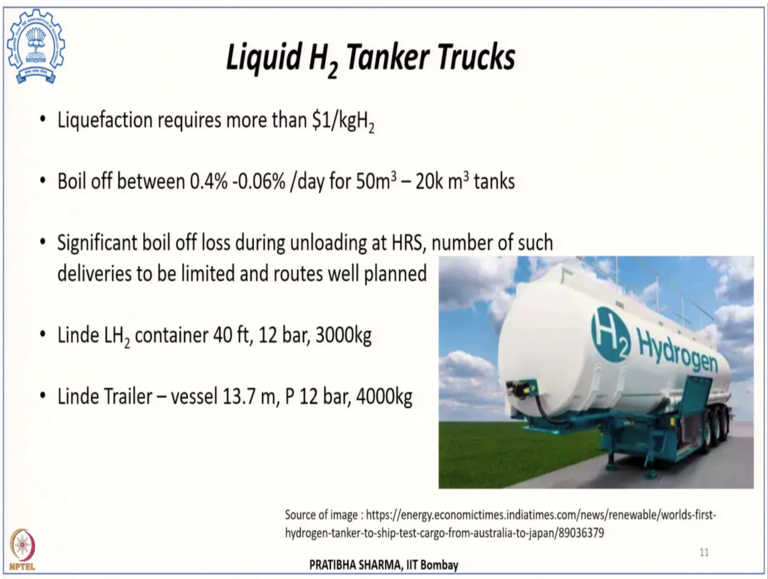

Now, this is an image showing a liquid hydrogen tanker the source of the image is mentioned below. Now we know that we have already studied that hydrogen liquefaction is an energy intensive process and then there are challenges like boil off. So, liquefaction in fact, requires more than 1 dollar per kg of hydrogen and then there are associated boil off losses depending upon what is the storage tank size.

Say for example, if it is 50-meter cube then the boil off rate is 0.4 percent per day if it is 20000-meter cube of tank then boil off rate is 0.6 percent per day. All this we have studied in the previous classes. Now, not only the boil off during the journey of the liquid hydrogen tanker truck, but there could be significant boil off losses that could occur during unloading at the hydrogen refueling station.

By unloading we mean that these tankers carry liquid hydrogen from the distribution terminal to the hydrogen refueling station. Now from here from these tankers liquid hydrogen is unloaded onto the cryogenic storage facility at the hydrogen refueling station and that also leads to at that point there are significant boil off losses. Now in order to optimize that the number of such deliveries needs to be limited, the route needs to be well planned.

And then there can be measures to reduce these boil off losses. Now there are several well-known liquid hydrogen companies, which have different tankers like some of the examples I can give here is Linde they have liquid hydrogen container which is 50 feet in length that can hold 12 bar of pressure and then it can carry 3000 kilograms of liquid hydrogen. Similarly the another vessel that is 13.7 meters in length can hold 12 bar of pressure and can carry 4000 kg of hydrogen.

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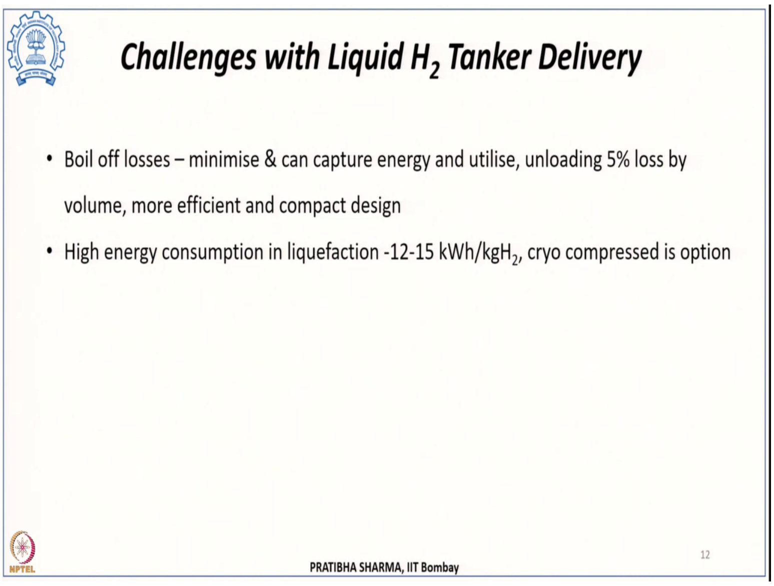

Now, if we see the major challenges that are there with the liquid hydrogen tanker based delivery; one is boil off losses are significant and what is required is to minimize these boil off losses either minimize or whatever hydrogen that is lost in boil off needs to be captured by certain means and then utilized. Not only the boil off losses during the journey, but during the unloading these are 5 percent losses by volume and this is a significant amount that also needs to be reduced and that can be done by designing such vessels.

In such a way that they get more efficient and compact. Other than the boil off losses the high energy requirement during liquefaction is another bottleneck because we know that 12 to 15 kilowatt hour per kg of hydrogen goes in liquefaction or about 30 percent of the energy content of hydrogen that goes in liquefaction. So, another option could be to carry it to transport it as cryo compressed hydrogen wherein we need not require 20 K temperature or very high pressures as well.

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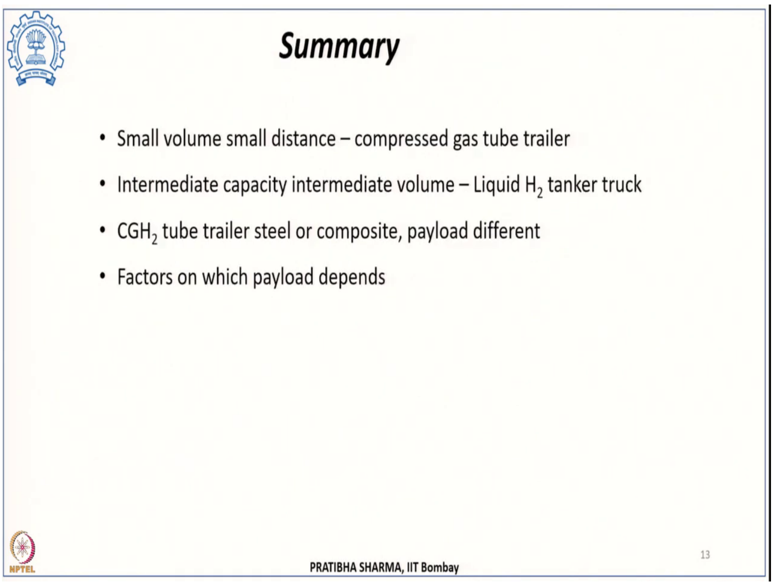

To summarize this part, we have seen that if we want to transport smaller volumes over smaller distances then the compressed gas tube trailers would be the preferred option. If the distance as well as the volume increases to intermediate capacity and intermediate volume 4000 kg, 4000 kilometers then liquid hydrogen tanker trucks will be more economically viable.

Now these compressed gaseous hydrogen tube trailers. We have seen that they can be pressure vessels could be made up of either steel or composite and depending upon several factors we have seen that the payload that can be carried using these tankers these trailers that will vary.

Thank you.