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

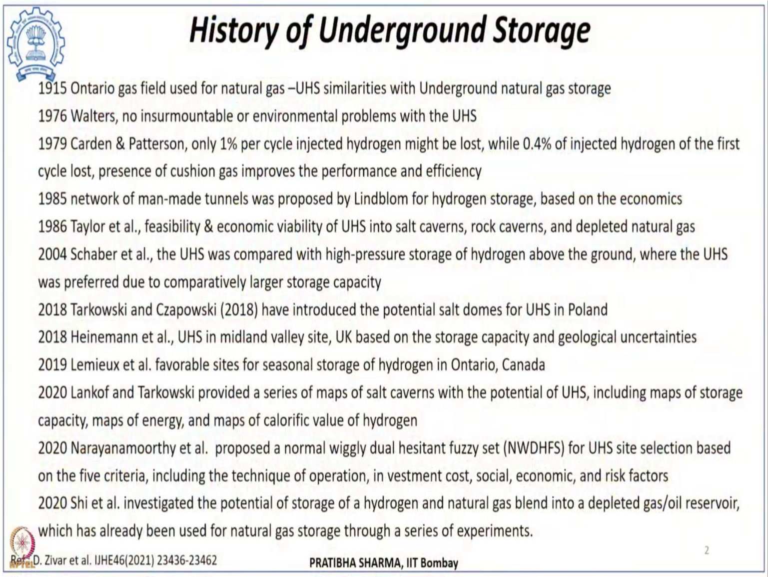
Lecture - 32
Underground Hydrogen Storage

The mismatch between the hydrogen production and consumption is the reason why we require hydrogen storage. The consumption varies with the demand; however, production remains almost constant. Now, in order to level these fluctuations in the demand at the same time sometimes when the demand surpasses the production. So, in order to level that hydrogen storage becomes essential.

Now, one of the method for storage is underground hydrogen storage, we have seen in the earlier class that there are different methods using which we can store hydrogen. However, the low density of hydrogen low viscosity and high diffusivity are the major challenges and that makes it difficult to contain or store hydrogen. and the mid or the long term storage at the same time large scale storage of hydrogen is the biggest bottleneck.

Now, underground hydrogen storage this has the advantage that we can achieve larger capacity of storage, at the same time this is a safer method of storage compared to the above surface storage. This is the reason being in underground storage it is less exposed to or the absence of atmospheric oxygen makes it a safer method of storage.

(Refer Slide Time: 01:51)



Now, looking back into the history of underground storage, it was in 1986 when Taylor was the first who identified that hydrogen can be stored in geological structures in a cheapest or the most cost effective manner. But the history of underground gaseous storage goes even way back to 1915 when in the depleted natural gas fields natural gas was stored first in Ontario gas fields that was in Canada.

In fact, the underground hydrogen storage has many similarities with the underground natural gas storage and there are many experiences from natural gas storage which has been utilized for hydrogen storage. There are many similarities at the same time there are differences as well. Now, these similarities are used not only in the ongoing projects, but in the future planned projects.

These are used for site selection, for monitoring purpose, for like life cycle assessment and considering the economic viability. And at the same time there are differences also between the underground natural gas storage and underground hydrogen storage. Like the differences lies because of the physico-chemical property, differences between natural gas and hydrogen.

For example, like if we see in terms of physical properties, the diffusivity is different, the viscosity, the densities are different as such in the similar volume we can we have to store like less amount of hydrogen compared to the natural gas or we have to go on to higher pressures to store equivalent amount of hydrogen. Then there are problems like leakage. So, that needs to be monitored.

At the same time there are differences in the chemical properties like hydrogen is more reactive. So, it can undergo or it can participate in different chemical reactions, various biochemical reactions, various bio microbial reactions wherein that can lead to loss of hydrogen. So, although there are similarities with the underground natural gas storage, but there are differences also.

So, later on in the year 1976, Walters he has found that there are no insurmountable or environmental problems which are associated with storing hydrogen in these geological structures in the underground hydrogen storage methods. In 1979, Carden and Patterson they identified they have studied that how much is the loss of hydrogen when we store hydrogen in these underground structures.

And he found that only 1 percent of hydrogen per cycle of the total amount of hydrogen which is injected that might get lost in the operational processes, while 0.4 percent of the injected hydrogen it gets lost in the first cycle. At the same time, he identified that if we have if we inject a cushion gas along before the hydrogen gas injection, that improves onto both performance as well as efficiency.

In 1985 a whole network of manmade tunnels was proposed for hydrogen storage by Lindblom and he also did a detailed techno economic analysis to show the viability of such storage. In 1986, Taylor et al they did a detailed feasibility and economic viability analysis of underground hydrogen storage into various geological structures like salt caverns, rock caverns and depleted natural gas reservoirs.

And they found that among these salt caverns are the most cost effective and better ways of storing hydrogen. In 2004, Schaber et al they compared the underground hydrogen storage facilities with the high pressure storage above ground and they were able to find and they reported that the underground hydrogen storage facilities they are more better or preferred compared to the high pressure storage and they are also economically viable.

Thereafter, there were large number of studies reported which identified the various sites for underground hydrogen storage like in 2018 Tarkowski et al they have introduced the potential salt domes for underground hydrogen storage in Poland. And they are out of 28 such salt domes they identified 7 as prospective sites for hydrogen storage. In 2018 Heinemann et al they did a detailed study on the site of midland valley site and they identified like what are the potential sites UK based in sites.

And that was on the basis of the storage capacity as well as considering the geological uncertainties. And they again mentioned that the salt caverns they are better in terms of capacity at the same time geological uncertainties. In 2019, Lemieux et al they studied the different geological sites for favorable sites for seasonal storage of hydrogen in Ontario in Canada.

In 2020, Lankof et al they provided an entire series of maps of salt caverns along with their potential for underground hydrogen storage. And this was an entire mapping which included the maps for storage with the capacity being included, how much energy that can be stored with the maps of calorific value of hydrogen.

In 2020, Narayanamoorthy et al they proposed a normal wiggly dual hesitant fuzzy set and that was for selecting a prospective underground hydrogen storage site and that was based on five criteria. These were like the technique of operation, how much is the investment cost, social economic and risk factors and then thereafter there were several active studies also based on the processes involved.

In 2020, Shi et al they investigated the potential of storing hydrogen and natural gas blend into a depleted oil and gas reservoir. And that reservoir was actually being used for natural gas storage and that was they have studied through different series of experiments. And they found that when hydrogen is blended with natural gas, the permeability reduces and then the losses also reduces the entire pore structure the permeability also changes when a natural gas and hydrogen blending is being done.

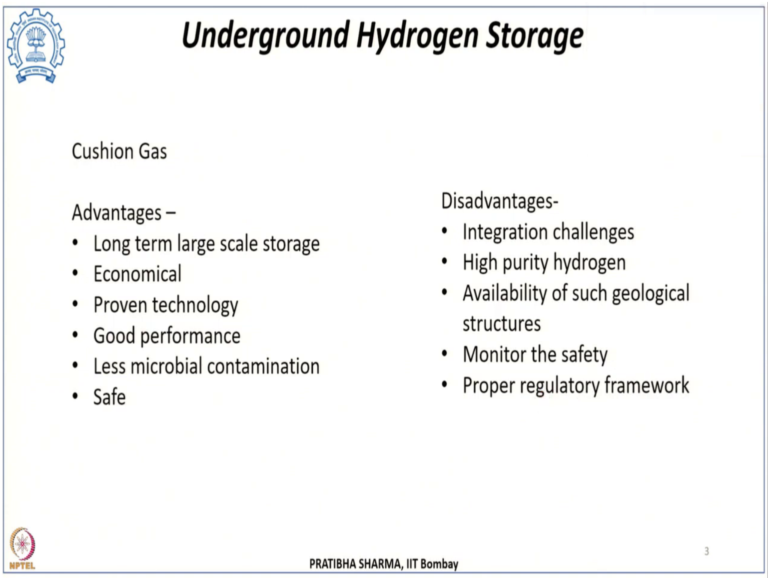
Now, if we look at the process of underground hydrogen storage a cushion gas is in fact, injected prior to the hydrogen injection. Now this cushion gas is actually a sort of permanent inventory which goes into the field, but which do not participate in the process. Now this cushion gas is required so, as to pre pressurize the geological structure or to get the desired pressure and deliverability rate from the structure.

And it has multiple advantages it can reduce the hydrogen losses and at the same time it can give the required pressures as well as flow rate. In fact, there are several series of compression and expansion cycles are performed in the whole process of geological storage wherein the injection as well as withdrawal of the gas is being carried out. And that finally, we could achieve the required desired pressures at the same time the desired flow rates.

So, this cushion gas is crucial and this can be any lower cost gas that could be either a town gas or carbon dioxide or methane or nitrogen. However, the disadvantage that lies is that it the hydrogen can get contaminated with the cushion gas and during the withdrawal cycle the cushion gas can also come along with hydrogen.

So, in that case we will have to do a proper separation and purification to get pure hydrogen. Now the underground hydrogen storage to several studies it has been found that these structures which store hydrogen they can be used for long term large scale hydrogen storage.

(Refer Slide Time: 10:51)



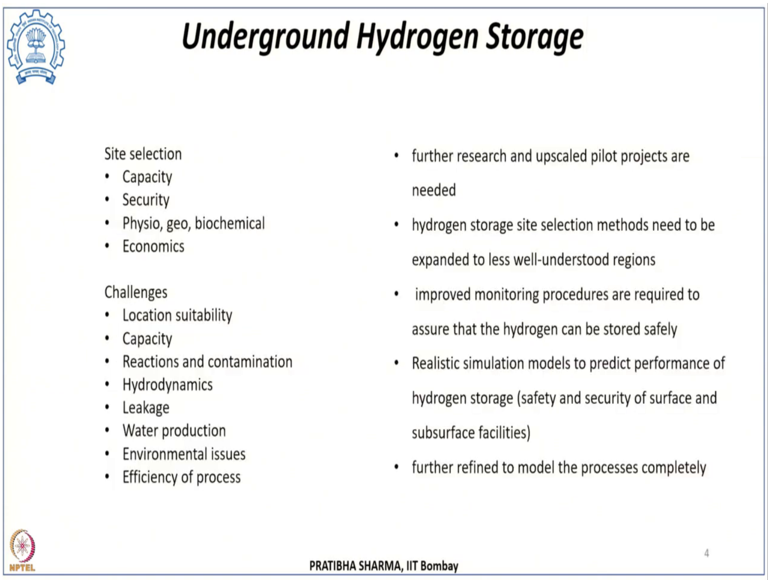
They are very economical because they can store hydrogen in very large quantities they are cost effective methods of storage. These technologies are also well proven technologies; they give good performance, they have a lesser microbial contamination depending upon which method we have used for storing underground in whether it is salt caverns based, whether it is depleted oil or gas reservoir or aquifer the contamination level may be different.

And at the same time they are even safer than the pressurized method of hydrogen storage. But in spite of these this list of advantages there are certain disadvantages also associated with underground hydrogen storage or these are certain challenges associated like there are integration challenges. Integration challenges in terms of when these are integrated with large scale hydrogen production then the injection the faster injection may not may be difficult to integrate with the underground hydrogen storage.

Or, the rate at which it is being produced we may not be able to inject at the same rate into the geological hydrogen storage. So, there could be challenges depending upon what are the production rate. At the same time some of the biochemical or chemical reactions or microbial reactions can cause contamination into the hydrogen stream which is being stored in the below the ground and that could lead to lesser purity hydrogen. So, the getting a higher purity hydrogen could be a challenge in some of the cases like in storing in aquifers or in case of oil and gas fields.

Besides that the major challenge lies in terms of availability of such geological structures. So, they should be close either they have to be in proximity of the hydrogen production plant or then we will have to also look at the transportation added cost which is due to the transportation. At the same time continuous monitoring is required so, as to ensure safe and secure storage of hydrogen in these geological structures. And we need to have a proper regulatory framework associated with storage in these structures.

(Refer Slide Time: 13:11)



Now, two different experiments lab scale experiments and several field scale experiments. It has been identified that underground hydrogen storage we can achieve very higher capacity and the site selection can be done in such a way so, as to achieve the desired capacities of storage these are even secure methods of storage safe in handling. They although they undergo physio chemical, geological or biochemical reactions below the ground and that can even lead to losses of hydrogen.

And also there have been several studies which has been done to understand the economic viability of this method of storage. However, the major challenges that remains in underground hydrogen storage are the selection of proper site or the location suitability to get a higher capacity geological structure. Then there are reactions because of all these physiochemical, geochemical or biochemical or microbial reaction and that can compromise with the purity of hydrogen and can lead to contamination of the hydrogen which is being stored.

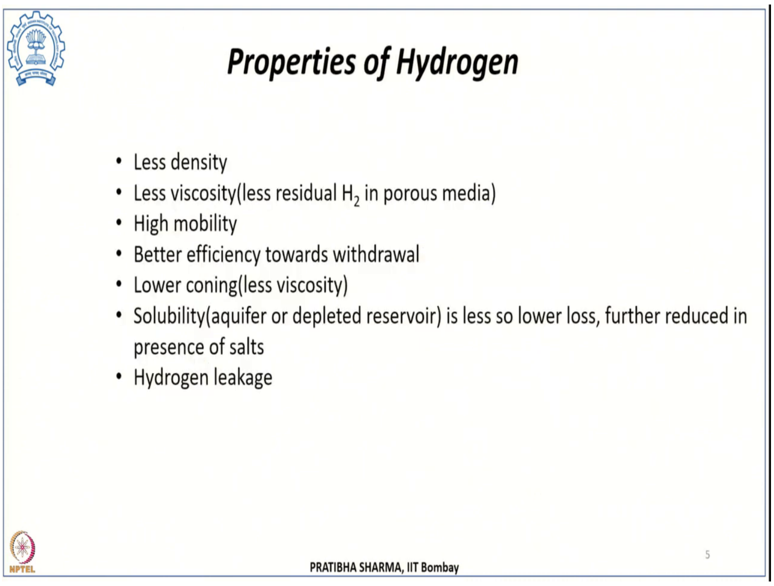
Besides other than that sometimes there are liquid gas interface reactions which can lead to certain hydrodynamic challenges. Hydrogen being a very small molecule, very low density, high mobility it can even lead to leakage. At the same time in certain processes the water which is being produced in the different processes that needs to be removed a large quantity of water has to be removed from that structure. There could be environmental issues with all these there can be efficiency reduction of the process.

So, when we look at the different methods of underground hydrogen storage, there are still much of research which is required and there should be certain up scaled pilot projects that are required to have a better understanding of this method of hydrogen storage. The starting should be with the proper site selection methods and that are needed not only to extend it to the less understood regions, but to understand the existing sites even more better.

After that site selection comes the monitoring procedures. So, improved monitoring procedures are also required so, that hydrogen can be stored safely and securely in these structures. For that realistic simulation models which could predict the performance of hydrogen storage, considering safety security of the surface as well as subsurface facilities which are used for storing and extracting hydrogen that needs to be carried out.

And further these models which are used needs to be further refined to understand the processes completely and integrate those processes within the models so, as to have a better understanding.

(Refer Slide Time: 16:12)



Now, before going into the details of such structures for hydrogen storage, we need to understand the properties of hydrogen. Actually, this most of the knowledge that we have about the underground hydrogen storage that comes from the experiences that we had from carbon dioxide storage or from natural gas storage. However, the properties of hydrogen, that differs from carbon dioxide as well as natural gas.

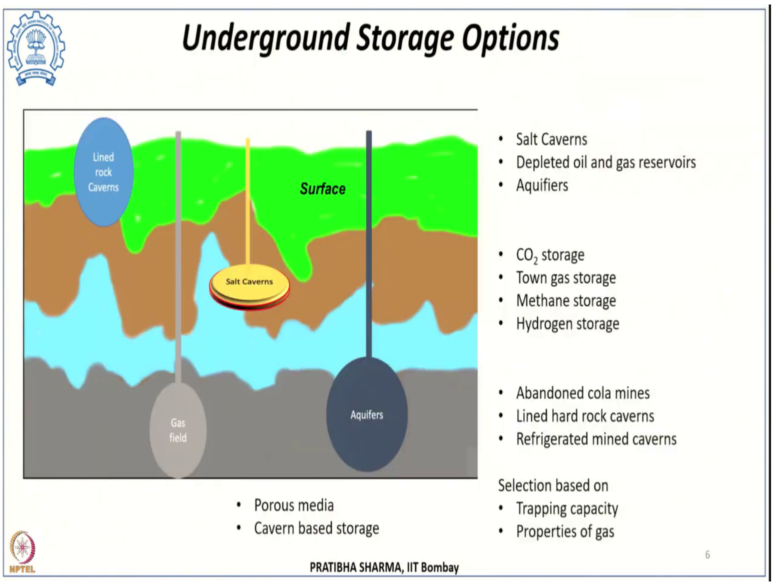
So, if we see the density of hydrogen since it is less than natural gas. So, the mass of hydrogen that will be stored in a given volume when it is hydrogen as against natural gas will be lower like it is one eighth of that which can be stored in compared to methane. Also the viscosity of hydrogen is lower so; that means, it will have a higher mobility. This is important when it is being considered in storing in porous media compared to if it is a blend of natural gas and hydrogen or a natural gas is used as a cushion gas in that case hydrogen has a higher mobility.

And this will we will be getting lesser of residual hydrogen in the porous media as compared to methane. So, this has an advantage when we consider the withdrawal of hydrogen in the withdrawal cycle of hydrogen. It has a higher mobility thus it has a better efficiency during the withdrawal process. Now since the viscosity is lower. So, as such the coning which is directly proportional to viscosity will be also lower in case of hydrogen and thus there will be less of loss of hydrogen is expected.

Besides that, the solubility of hydrogen is another important property that needs to be considered when we are considering the storage in aquifers or depleted oil and gas reservoirs. This is because if it is solubility would have been higher we would have a higher hydrogen loss, but interestingly the solubility of hydrogen is less in the different solvents or in the water or in the brine solution. So, the losses associated when we are storing hydrogen in aquifers or depleted oil and gas reservoirs is comparatively lower.

Further, when we are looking at the water, gas and salt solution or the brine then the solubility further reduces in the presence of salts. So, as such the losses associated when we are storing in these reservoirs is comparatively lower compared to the carbon dioxide or compared to the natural gas. But the molecule being the smallest one having a lower density high diffusivity, the problem of hydrogen leakage could be there which needs to be continuously monitored.

(Refer Slide Time: 19:15)



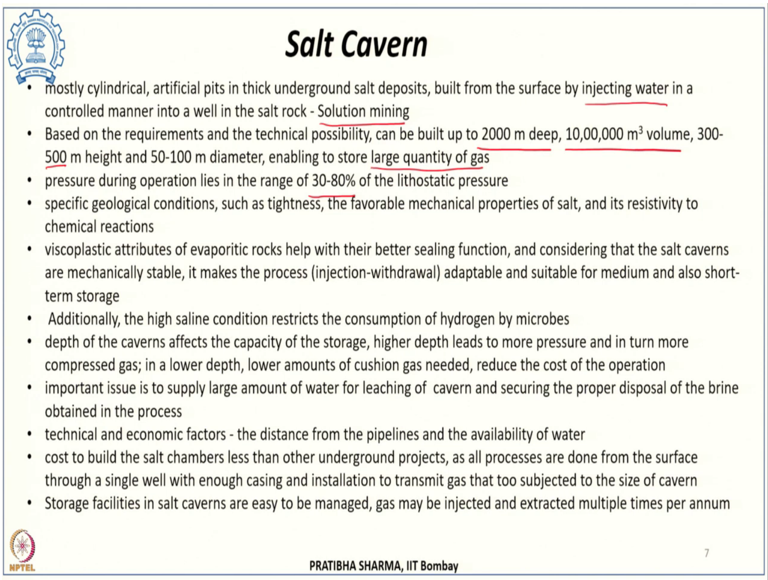
Now, among the different options which are available for underground hydrogen storage the important ones being the salt caverns, depleted oil and gas reservoirs and aquifers. Now these three options can be used for storing and it is being used for storing several different gases like it can be used for carbon dioxide storage, it can be used for town gas storage or methane storage and now also being considered for hydrogen storage. Now, other than these three options there are few more options which are being looked at for hydrogen storage.

However, with the increasing growing hydrogen demand, they may also get an increased interest like the abandoned cold coal mines or these could be lined hard rock caverns or refrigerated mine caverns. Now depending upon what is the geological structure we are using, we can categorize these structures roughly into two types either these can be porous media type of structures in which hydrogen can be stored, in porous media type of geological structures hydrogen is stored in the pores formed.

Like it could be carbonate formations or it could be sandstones or it could be cavern based storage, where the hydrogen is being stored in the salt caverns. And these salt caverns could be either those structures which are being excavated or it could be by produced by means of solution mining. So, every of each of these underground storage options they have their own characteristics.

However, which storage option will be selected that depends upon what is the trapping capacity of that particular structure, how much amount of hydrogen can be stored or kept inside that structure, at the same time what is the property of the gas. Like since these structures can be used for other gas storage as well either carbon dioxide, town gas, methane or hydrogen. So, which gas we are using, so which structure we are going to use that selection will depend upon also on the property of the gases.

(Refer Slide Time: 21:40)



Now, let us first look at the salt cavern based storage. Now these salt cavern based storage these are usually the cylindrical type of structures and these are artificial pits which are formed in the thick underground salt deposits. And these are built from the surface and these are made by means of either injecting water in a controlled manner inside a well in the salt rock this is also known as solution mining method.

Now, depending upon what is the capacity which is need to be stored what is the requirement what is the technical possibility of storing at that particular location that particular site of salt cavern these can be built to up to 2000-meter depth. These can store about 10 lakh meter cube volume and it can have 300 to 500 meters of height, 50 to 100 meters' diameter thus they can store large quantity of gas.

Now, the pressures that can be operated or the operational pressures that lies in the range of 30 to 80 percent of the lithostatic pressure. So, for these geological structures which are salt caverns specific geological locations are desired which has a certain tightness they have a favorable mechanical properties of the salt and also they have a resistivity towards chemical reactions. Now this resistivity towards chemical reactions is higher because of the presence of salt. So, there are less of microbial reactions which could lead to the losses of hydrogen. So, that is the advantage of storing in salt caverns.

Besides that, viscoplastic attributes of evaporitic rocks which can help in better sealing function that is also considering the salt caverns making them more mechanically stable. So, that makes the entire process which is considering the injection putting in hydrogen and taking out hydrogen the withdrawal that becomes more adaptable and suitable for both short as well as medium term storage of hydrogen.

At the same time the prevailing high saline condition, this restricts the consumption of hydrogen through various microbial processes by the microbes and leading to reduced loss of hydrogen. The depth of these salt caverns that is there at that particular site that will determine the capacity of storage like if the depth is higher we can attain more of pressure. Now if it is more of pressure; that means, we can have more compressed hydrogen in that particular geological site.

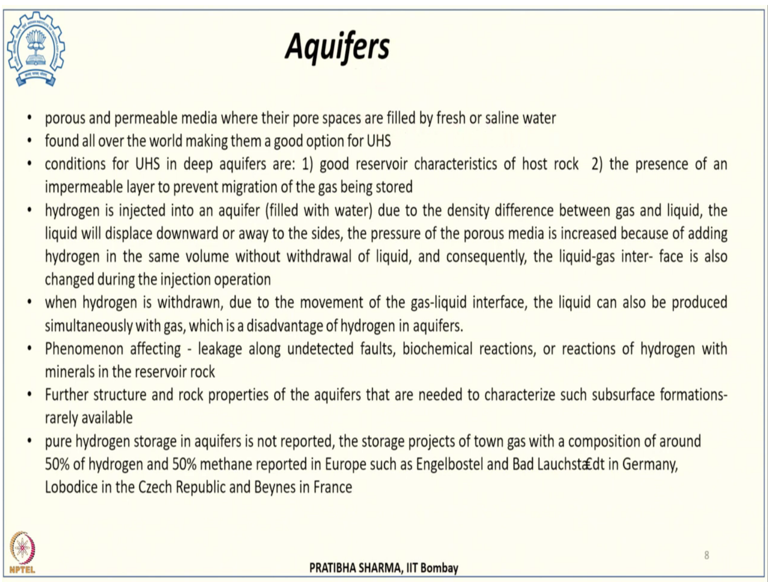
So; that means, if it is higher depth, higher pressure and more amount of hydrogen. However, if it is a lower depth one then lower amount of cushion gas will be required that again will has its own advantage that we will have reduced cost of operation in such caverns. The important issue that remains is that we need to supply a large amount of water and that is required for leaching of the caverns.

And again not only providing that large amount of water, but then removal and disposal of that brine solution which is obtained in the process is required and that remains a major issue in the salt cavern based storage. Other than these there are certain technical and economic factors that also require to be considered when it has to be stored in salt caverns.

Now these factors are like what is the distance from the pipelines or from the production site where it has to be stored at the same time at that location the availability of water that also has to be considered while this method of storage is being selected. If we look at the economic aspect the cost of building a salt cavern or salt chambers this is less than the other underground projects. This is because a single well is digged and that is also done from the surface through a with enough casing and installations to transmit the gas and that to subjected depending upon the size of the cavern.

So, if we look at the salt cavern based storage, this is the most economical and cost effective method of storage this is easy to manage as well. Because the gas when it is stored in salt caverns this can undergo several cycles of injection and extraction multiple times per annum. And as such this is the most cost effective method of storage and it is the only method currently on which there are different projects operating in the world. The second method for storing hydrogen in underground geological structures is in aquifers.

(Refer Slide Time: 27:14)



Now these aquifers are in fact, these are porous and permeable media where there are different pores, these pore spaces these are either filled with fresh water or with saline water.

Now, the advantage of these aquifers is they are not very much location dependent they are available all over the world. So, as such we can have a good option for underground hydrogen storage in the aquifers.

But the conditions that are required to be considered if we consider these for hydrogen storage are that it should have a good reservoir characteristic of host rock, it should not only house that hydrogen at the same time it should be impermeable. So, there should be a presence of an impermeable layer which will prevent migration of gas which is being stored. So, that is required for containing the gas which has been injected.

Now, when a hydrogen is injected into an aquifer which is already filled with water because of the density difference what will happen is, between the gas which is injected and the liquid which is water in these aquifers the liquid will displace down when gas is injected at a higher pressure in our case like it will be hydrogen. So, when it is injected at a pressure which is higher than the normal reservoir pressure in that case the liquid will be displaced either it will be displaced down or it will be displaced sideways.

And at the same time the pressure inside the porous media will be increased because now the same volume we are occupying gas as well as liquid which was already there without withdrawing the liquid. So, because we are adding hydrogen in the same volume as such the pressure will increase and as such the liquid gas interface will also change during the injection process.

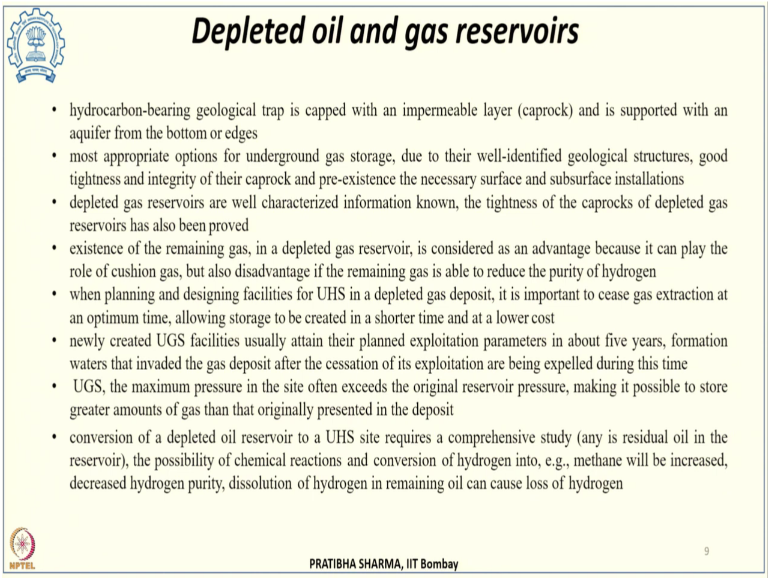
Now, when in from such aquifers hydrogen is withdrawn now there will be again a movement of gas liquid interface as it was during the time of injection and that liquid which can also come out along with the gas in this process. Now, this is the major disadvantage of aquifers. So, when during the withdrawal cycle along with the gas which is hydrogen in this case liquid can also come out.

The other phenomenon that can act is there can be leakages in the aquifers that could be because of certain faults which are which goes undetected. There can be biochemical reactions, there can be reaction of hydrogen with the minerals present in the reservoir rocks and that all can lead to loss of hydrogen. There could be structures present and the rock properties of the aquifers which we need to first understand before selecting any site for such aquifers for hydrogen storage.

So, at present like we need to first understand those structures which are formed, what are the properties of these aquifers these needs to be first characterized such that whatever are the subsurface formations they could be first understood well. Now, but the problem lies is at present such studies are not available. So, these are rarely available and there are no reports on such aquifers which store pure hydrogen.

However, there are certain projects ongoing projects of storing town gas, not pure hydrogen in a composition of 50 percent hydrogen and 50 percent methane which is reported in Europe such as Engelbostel and the other one in Germany, this one is in Lobodice is in Czech Republic, Bynes in France. So, these are some of the ongoing project, but these are for storing town gas and not for hydrogen.

(Refer Slide Time: 31:07)



Now, the third option that can be used for storing hydrogen is depleted oil and gas reservoirs. Now these are hydrocarbon reservoirs which has a hydrocarbon bearing geological trap. So, there should be a trap which will be used for storing hydrogen and this has to be capped with an impermeable layer and that is known as caprock. This is actually supported by an aquifer which can be either present at the bottom of it or onto the edges.

So, there is a trap which will host hydrogen, there is an impermeable layer which is caprock and then finally, it is being supported with an aquifer from the bottom side or from the edges. This is actually the most appropriate option for underground gas storage. The reason being these are already being well studied they are well identified geological structures we have already like during the explorations we have already studied the gas the gas tightness of these structures, their integrity of the caprock.

And these are the pre existing structures which we have already widely understood the necessary surface and subsurface installations are already there. So, these seems to be the most appropriate choice. Now, we already have a detailed information for these depleted gas reservoirs and these are already proven for gas storage applications. Now there could be certain remaining amount of gas which has not been recovered from these depleted oil and gas reservoirs and that has an advantage.

So, the remaining gas which is there in these depleted gas reservoirs that has an advantage that that gas can act as a cushion gas. So, there may not be requirement of additional cushion gas if we have certain remaining amount of gas. But at the same time this is a disadvantage as well. Because this remaining gas will contaminate the hydrogen which is injected inside and that will reduce the purity of hydrogen.

So, when we are planning for hydrogen storage or any gaseous storage in these depleted oil and gas reservoirs, it is essential that we have to plan that site in such a way that the gas extraction should be stopped at an optimum time. Now, if we do that at an optimum time the required time to create an infrastructure for storing gas or underground hydrogen storage system will require lesser amount of time and cost as well.

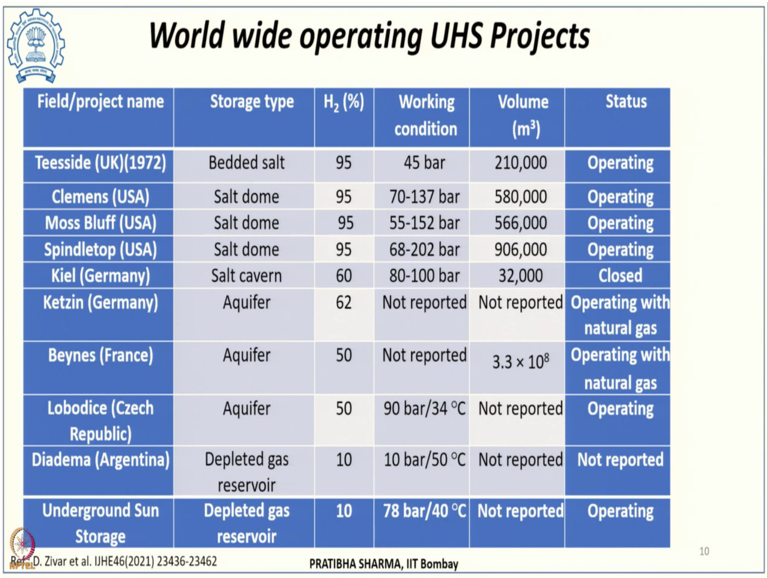
Now if we look at certain newly created underground gas storage facilities, then the planned exploration time it lies in a duration of about 5 years. And in that 5 years whatever is the water which gets invades into those gas deposits because we have stopped the exploitation of these reservoirs. So, the water which invades inside these formation geological formations needs to be taken out or expelled out during this duration of creating these facilities.

Now underground gas storage when it is done in these gas reservoirs depleted gas reservoirs usually it has a higher pressure than the original pressure at which it has stored the gases. So, the pressures attained could be higher than the original reservoir pressure as such it is made possible to store larger amount of gas, then it was originally present in these gas reservoirs.

Now, if we look at the depleted oil reservoirs, then when it is converted into underground hydrogen storage facility as such a very detailed study is required. The reason being if there is any residual oil present in the reservoir there are chances that there could be chemical reaction of that heavy oil with hydrogen and that can lead to even formation of methane.

So, rather than storing hydrogen we may end up getting more of methane that will be increased and that will result into reduced purity of hydrogen stored at the same time the hydrogen we are storing that gets dissolved into the oil and again lead to loss of hydrogen. So, in case of depleted oil reservoirs, there are more studies required before selection of a site.

(Refer Slide Time: 35:55)


World wide operating UHS Projects

Field/project name	Storage type	H_2 (%)	Working condition	Volume (m^3)	Status
Teesside (UK)(1972)	Bedded salt	95	45 bar	210,000	Operating
Clemens (USA)	Salt dome	95	70-137 bar	580,000	Operating
Moss Bluff (USA)	Salt dome	95	55-152 bar	566,000	Operating
Spindletop (USA)	Salt dome	95	68-202 bar	906,000	Operating
Kiel (Germany)	Salt cavern	60	80-100 bar	32,000	Closed
Ketzin (Germany)	Aquifer	62	Not reported	Not reported	Operating with natural gas
Beynes (France)	Aquifer	50	Not reported	3.3×10^8	Operating with natural gas
Lobodice (Czech Republic)	Aquifer	50	90 bar/34 °C	Not reported	Operating
Diadema (Argentina)	Depleted gas reservoir	10	10 bar/50 °C	Not reported	Not reported
Underground Sun Storage	Depleted gas reservoir	10	78 bar/40 °C	Not reported	Operating

Ref: D. Zivar et al. IJHE46(2021) 23436-23462

PRATIBHA SHARMA, IIT Bombay

10

If we look at the ongoing projects of underground gas storage in the pure form, there are only four such projects which are dedicated for pure hydrogen storage which can store 95 percent purity hydrogen and all these are salt cavern based storage. So, the oldest one the Teeside which is in UK, that has been operational for from 1972. So, that makes it very promising.

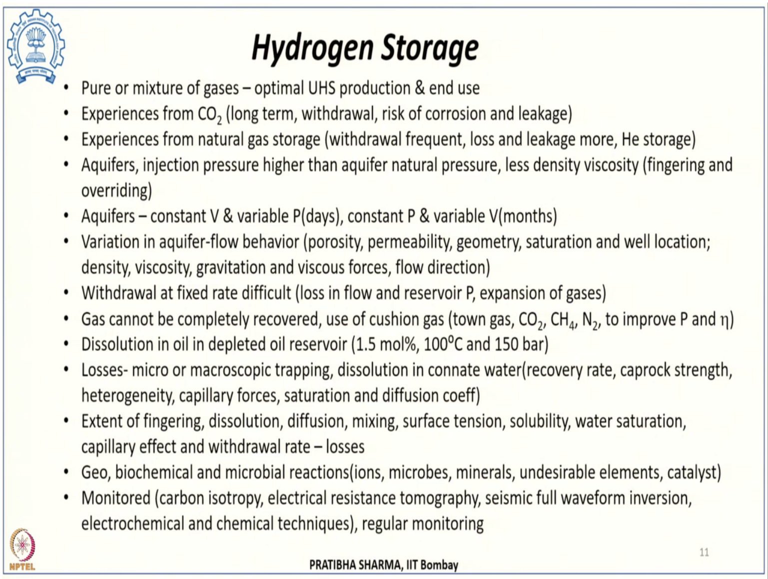
So, salt caverns are very promising geological structures where we can have long term storage and that has been operational from 1972 and has a volume of 2,10,000 meter cube and the working condition is that it can store 45 bar pressure hydrogen and this is operational. The few more which are under operation are at Clemens site in USA, Moss Bluff, Spindletop in US. So, these are the four sites which are operating all are salt dome based.

And the different pressures are like Clemens it is 70 to 137 bar, volume 5,80,000 meter cube, Moss Bluff 55 to 152 bar, 5,66,000 meter cube, Spindle top 68 to 202 bar, can store 9,06,000 meter cube. So, these are operational while the one Kiel at Germany this is being closed. Another one in Germany Ketzin this is an aquifer based storage this is operating with natural gas.

Another one in France the Lobodice this is an aquifer based and this is operational. In Argentina this is depleted gas reservoir and there is underground sun storage with depleted gas reservoir which can store hydrogen at 78 bar and 40 degree centigrade. So, these are some of the projects which are operating on underground hydrogen storage and there are many more which are being planned.

Now, when we have to store hydrogen in these geological structures we have to understand that the knowledge which we have gained is on the basis of storing natural gas or carbon dioxide. So, either we can store hydrogen in the pure hydrogen form or we can even store it in the form of mixture of gases. Now any optimal underground hydrogen storage production we will have to look at both which is the method of production and what is the end use wherein we are going to use that hydrogen which is being stored.

(Refer Slide Time: 38:29)



So, depending on that we can either have a pure hydrogen based storage or in the form of mixture of gases. So, whatever experiences which we are using in hydrogen storage in these structures that comes from either carbon dioxide storage where the carbon dioxide storage is basically meant for carbon dioxide sequestration which is long term phenomena which is a sort of permanent storage where we are only injecting and we are not withdrawing. So, that is the basic difference between carbon dioxide storage and hydrogen storage.

So, it only has one process which is a injection one withdrawal is absent. At the same time the if it is reacting and producing more carbon dioxide then that is not a problem when it is carbon dioxide storage. With carbon dioxide there are chances of risk of corrosion in the subsurface equipments which we are using there are chances of leakage because of the several reactions that can take place. So, that is the major difference that will be with carbon dioxide storage compared to that of hydrogen storage.

Also we have gained experiences from natural gas based storage, but again there are differences of hydrogen storage compared to the natural gas based storage with hydrogen the withdrawal frequency will be more. Now depending upon what is the market demand the amount of withdrawals will be more in case of hydrogen compared to the natural gas. And hydrogen being a smaller molecule there could be losses involved, there can be leak which will be more because of the high diffusivity because of the viscosity, because of the density of hydrogen.

And in that case the structures there which were used for helium storage can be understood well to have a better understanding for hydrogen storage. Now, there are different methods like aquifers we have seen could be used for hydrogen storage. In them the pressure at which we are injecting hydrogen definitely it has to be higher than the aquifer natural pressure so, that these displace the liquid and making a way for hydrogen storage.

And the densities of hydrogen since that is lower and the viscosity is also lower that can lead to certain challenges like there can be fingering or overriding or gas moving towards the top all these effects could be observed in aquifers. Now, if we look at the aquifers, if we look for days of storage then we can get constant volume and variable pressure. However, when it is for months of storage then it come months for injection then constant pressure and variable volume could be obtained.

Now these variations in aquifers these are basically because of the flow behavior and that flow behavior depends upon the geometrical parameters factors like the porosity, permeability, what is the geometry of that aquifer, what is the gas saturation, what is the well location. At the same time it also depends on certain active parameters like what is the density of the gas, density viscosity, what is the gravitation and viscous forces existing at that site location, what is the flow direction.

So, all that determine these variations whether it is constant volume-variable pressure or constant pressure-variable volume at the same time in these aquifers the withdrawal rate will not be constant. It will not be possible to have a fixed rate for a longer duration the reason being there will be expansion of gas when we are withdrawing then the there will be less of flow pressure which will be obtained and the reservoir pressure will also decrease with time.

Also since we are using a cushion gas since we cannot completely get the recover the hydrogen gas from these sites. So, about it is sort of considered as a loss like one third of the total volume of gas which is being stored cannot be recovered. Now in order to reduce that loss a cushion gas could be used which is of lower cost like a town gas, carbon dioxide or methane or nitrogen this will not only improve the pressure which reduces with the time, but it will improve that pressure at the same time will improve the efficiency.

If it is in depleted oil reservoirs, then dissolution of hydrogen takes place in the depleted oil reservoirs and it has been found that it is 1.5 mole percent at a condition of 100 degree centigrade and 150 bar. There can be different loss mechanisms that also operate like there could be microscopic or macroscopic trapping of hydrogen localized trapping that can occur in these structures, there could be diffusion of hydrogen that occurs in the various porous structures, there will be mixing up of hydrogen that will lead to losses, then dissolution will occur in the connate water.

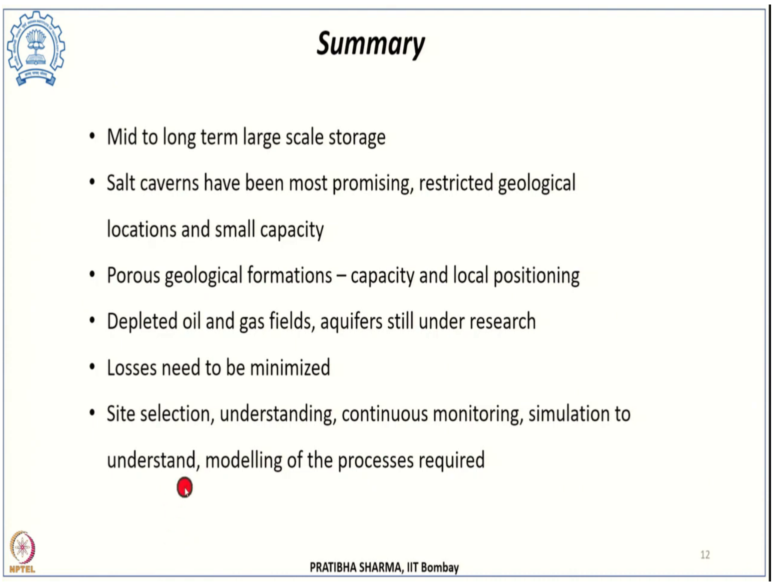
And that all will depend upon how fast we are recovering at what rate we are recovering or withdrawing the gas what is the caprock strength, what is the heterogeneity of the geological structure, what are the capillary forces, water saturation, diffusion coefficient. There will be different fingering, dissolution, diffusion, mixing surface tension solubility, water saturation, capillary effect and withdrawal rate all these will lead to losses at different extent.

Not only these will lead to losses there will be several reactions like geochemical, biochemical, microbial reactions because of the ions present, microbes present, minerals present there will be undesirable elements that may result into several reactions and leading to hydrogen loss there could be catalyst that could activate different processes and leading to hydrogen loss.

So, it is essential that not only the appropriate site selection, but monitoring throughout the process because this is a cyclic process and several injection and withdrawal processes are to be done. So, it has to be monitored throughout and that can be done through different processes like carbon isotropy for formation of methane we can check for it, electrical resistance tomography, seismic full wave inversion. There can be several electrochemical and chemical technique techniques that can be used for regular monitoring of such storage reservoirs.

So, to summarize the underground hydrogen storage in the various geological structures that we have seen these are options for mid to long term storage at the same time these are meant for large capacity hydrogen storage.

(Refer Slide Time: 45:17)



So, salt caverns these seems to be most promising, but the problem lies is their restricted geological locations and they can store in a smaller capacity. Now, there are other options like porous geological formations these could be aquifers or these could be oil and gas reservoirs we can achieve higher capacity and their local positioning is not a problem depleted oil and gas fields and aquifers these are still under research.

However, salt cavern based projects are already operational globally. What is required is we need to minimize the losses in these storage systems, we need to reduce the contamination levels through the various reactions. So, an appropriate site selection, understanding of the mechanisms, continuous monitoring various simulations to understand the processes, modeling the process is required so, as to have a technical and cost effective storage of hydrogen in these geological structures. Thank you !