Cryogenic Engineering
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Indian Institute of Technology, Bombay
Lecture No. # 04
Properties of Cryogenic Fluids

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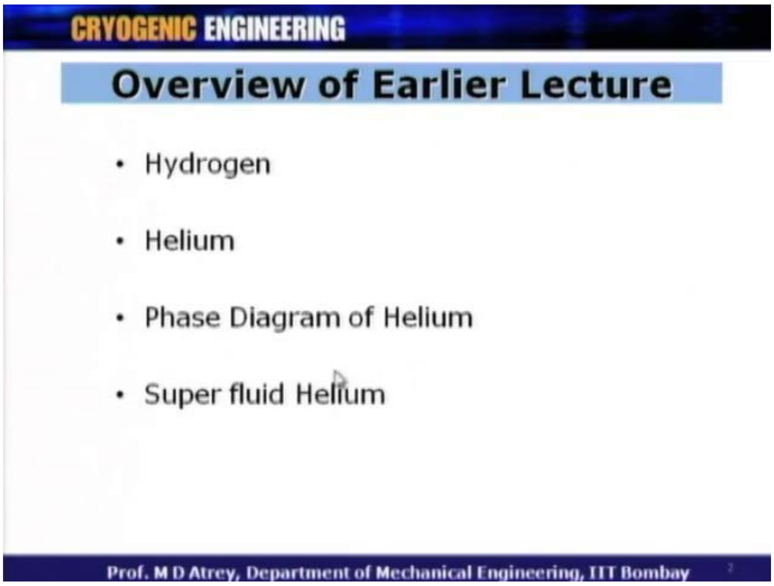

Before I present my this lecture, I just want to take an overview of my earlier lecture. In the earlier lecture, we talked about hydrogen, and we talked about ortho and para forms and its conversion of hydrogen. Then we talked about helium and I will cover a little bit of helium again in this lecture and it is usages etcetera. What we talked about last time was clearly what a phase diagram of helium and again I will briefly touch this. So that today's lecture you understand in a better way. And then we talked about super fluidity; property of super fluidity for helium or super fluid helium.

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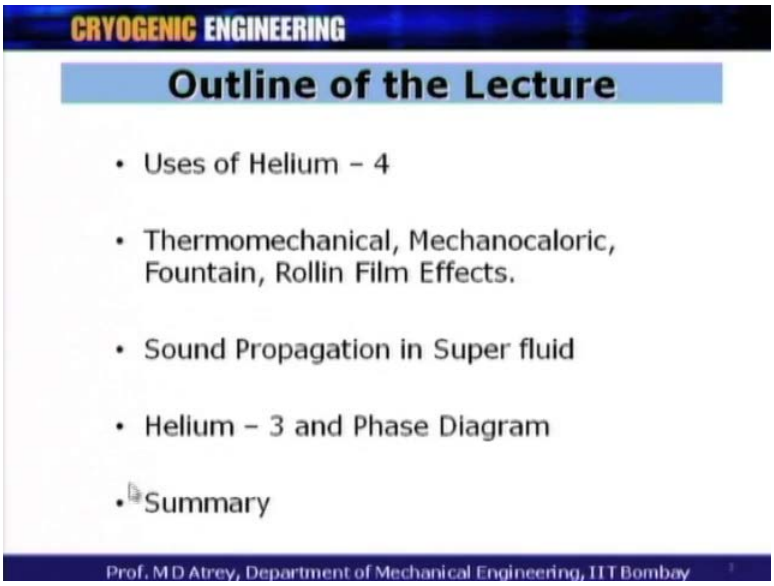

In this lecture, I will talk about uses of helium - 4, then I will talk about various effect that helium shows helium gas shows which is thermomechanical, mechanocaloric, fountain and rolling film effects. There are various effects and I will touch in a brief what these effects are. Then sound propagation in super fluid helium is a very interesting phenomena and we touch what exactly it is just to understand, how sound propagates in super fluid helium. Then helium - 3 which is one of the isotopes of helium, we will talk about helium - 3 and its phase diagram which also is a very useful gas as far as helium is concerned. And at the end of this I will touch up one briefly summarize what we talked about all the cryogen still there.

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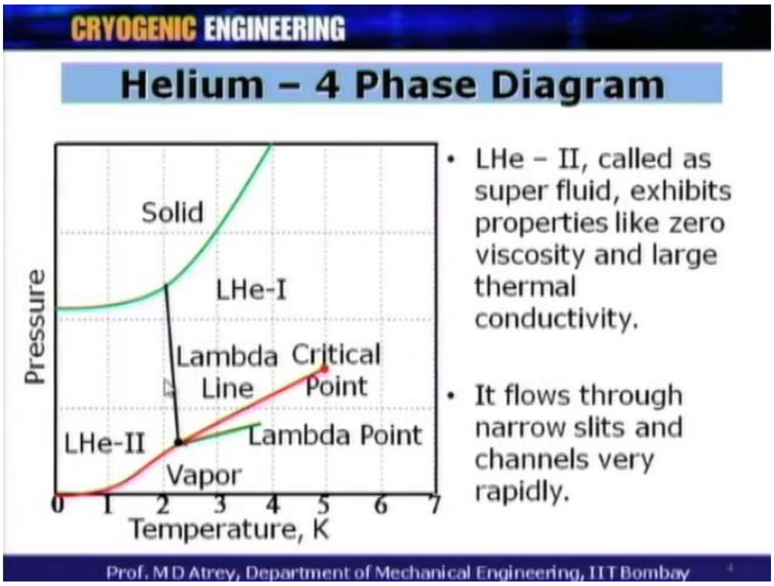

Now, we talked about helium - 4 phase diagram in detail last time, and we found that we got a vapor, liquid and solid phases, they do not meet at any point meaning which they do not have a triple point, they do not coexist together. At the same time, we talked about the helium - I and helium - II; how the helium - II separates or how the transition happens, when helium - I is cooled down the lambda line. So, this is existence of lambda point at 2.17 kelvin, below which as soon as liquid helium - I comes below this point is a phase transition of second order, and we talked about what that phase transition was all about.

So, liquid helium - II phase emerges which has got very typical characteristics of very high thermal conductivity and very low viscosity. So, liquid helium - II called as super fluid, it exhibits properties like zero viscosity and large thermal conductivity. It flows through narrow slits and channels very rapidly. That means, it does not obey the normal laws, it has got very specialized laws for itself. And as we understood that - as we go down from 2.17 kelvin below, the percentage of super fluid will start increasing; at 0 kelvin it will be all 100 percent super fluid, that is 100 percent liquid helium - II.

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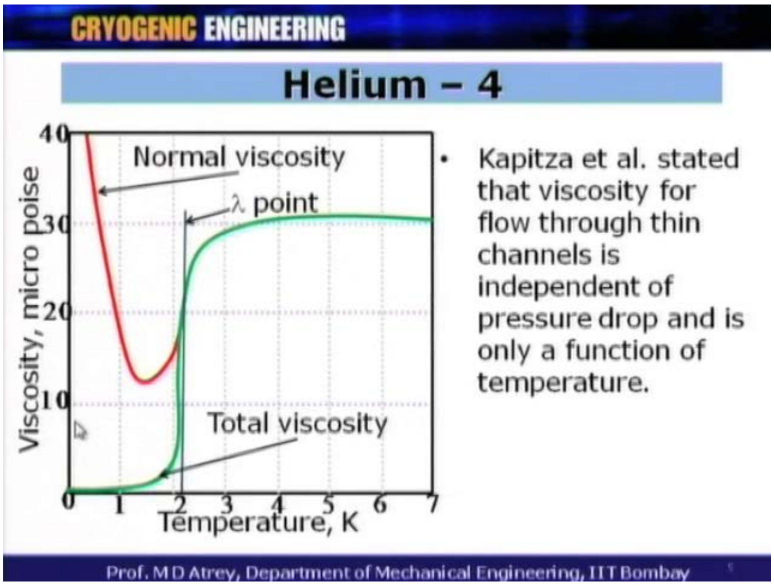

That could explain by this particular curve, where you see that the viscosity is almost 0 at 0 kelvin. At lambda point, what you have is a normal viscosity, therefore what you have is a liquid helium – I. And as soon as one comes below lambda point, the total viscosity starts coming down, because the percentage of liquid helium - II or super fluid starts increasing. Kapitza et al stated that viscosity for flow through thin channels is independent of pressure drop and is only a function of temperature. So, here you can you can see that as you reduce the temperature the viscosity starts changing it decreases. Although the normal viscosity is showing an increase, but the normal component that is helium - I is lays and lays as you go down the temperature towards 0 kelvin. And in we found that the two fluid module can explain this behavior, we talked about at last time, I will not touch that this time.

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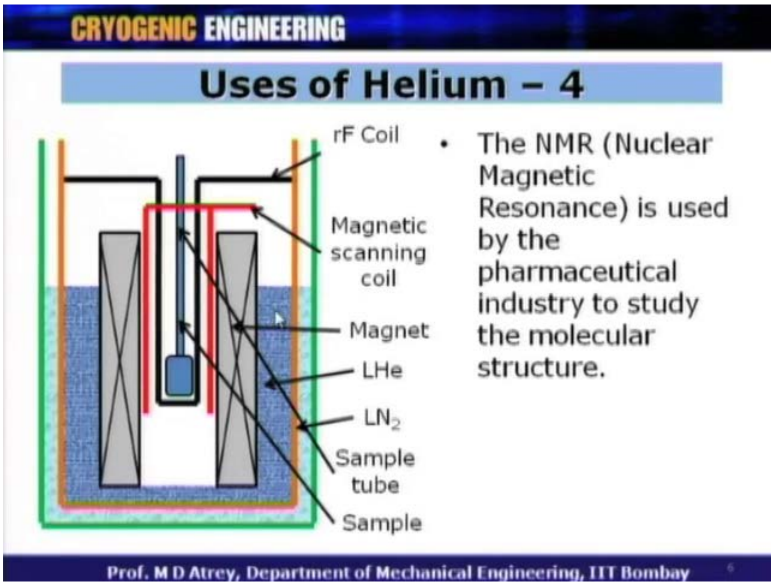

Based on this super fluid helium and helium – 1, there are lots of utility value to helium – 4, and we will just briefly touch upon those utilities or the uses of helium – 4. And this is the picture I had shown you in the first lecture when I talked about various applications of cryogens. This is for NMR applications which is a Nuclear Magnetic Resonance, and what we use here is a super conducting magnet, and what you can see this super conducting magnet is dipped in liquid helium. In fact, it should be completely dipped in liquid helium then only it will become super conducting.

The sample of which the NMR has to be done for pharmaceutical company it is very important to know the molecular structure of this particular chemical or the sample which is kept for NMR. This sample comes at the center of the magnetic field which is created by the super conducting magnets. So, this liquid helium bath which is that 4.2 kelvin is then surrounded by liquid nitrogen bath which is 77 kelvin. And as you can imagine, this helium will continuously evaporate over a period of time, and this nitrogen also will evaporate over a period of time, and you have to continuously replenish this liquid helium and liquid nitrogen as the levels get dropped down. If by mistake the level of this helium comes down below then this magnet will sees to be a super conducting magnet. And this is a very important aspect of super conducting magnet that it should always be kept dipped in liquid helium.

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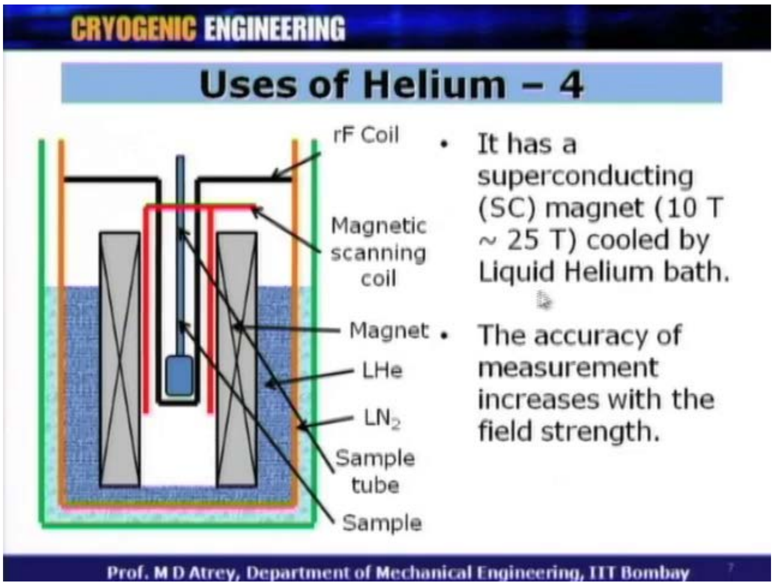

Now, in order to have a good NMR, what we need is a very high magnetic field. That is why we go for a super conducting magnet which allows a large current to flow through in, and therefore you get a very high magnetic field. The super conducting magnet, now will give you 10 tesla to 25 tesla, because it becomes super conducting. Otherwise in order if you want to have a 10 tesla to 25 tesla electro magnet it is not possible. And that is the greatest usage of super conducting magnet which basically exists because of the cryogenics or liquid helium associated with it. This is a very important usage, almost every technical lab, every chemical lab, every pharmaceutical lab, will have to have NMR, apparatus with them. The accuracy of measurement increases with the field strength and that is why higher the magnetic field better is the accuracy; better is a picture, better is understanding and the chemical structure can very, very clearly visible in this cases.

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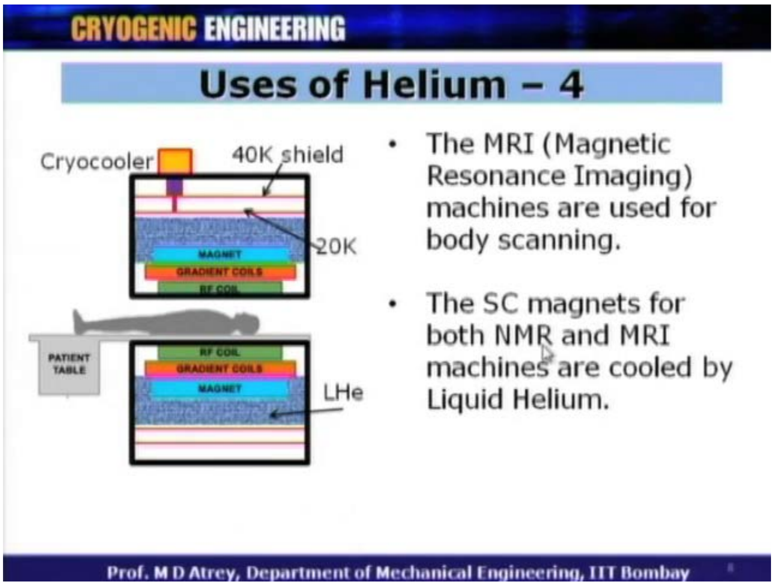

The next use of helium - 4 is for a similar purpose, but now it is made for human beings. Instead of sample being in NMR what we have is a human being, undergoing MRI which is Magnetic Resonance Imaging. Now, you can see here, in a horizontal direction a patient is being kept and he is surrounded by a magnet. So, you can see a magnet then you got a gradient coils and RF coil, which is associated electronics with this MRI. What is important is to see that this magnet again here is completely dipped in liquid helium. And in many cases, this liquid helium could be surrounded by either liquid nitrogen or now a days we can use even cryocoolers to cool the outside shields.

We possibly briefly touched in the initial lectures, that the cry coolers are nothing but close cycle coolers, and they also use helium gas for getting low temperature in a close cycle manner. Now, this cryocoolers which generate 40 kelvin temperature or 20 kelvin temperature continuously, and would do the something what otherwise liquid nitrogen would do alright. So, this is a very important application, in fact the importance of liquid helium or the need of liquid helium and a cryocoolers grew, because of MRI systems all over the world. The super conducting magnet for both NMR and MRI machines are cooled by liquid helium.

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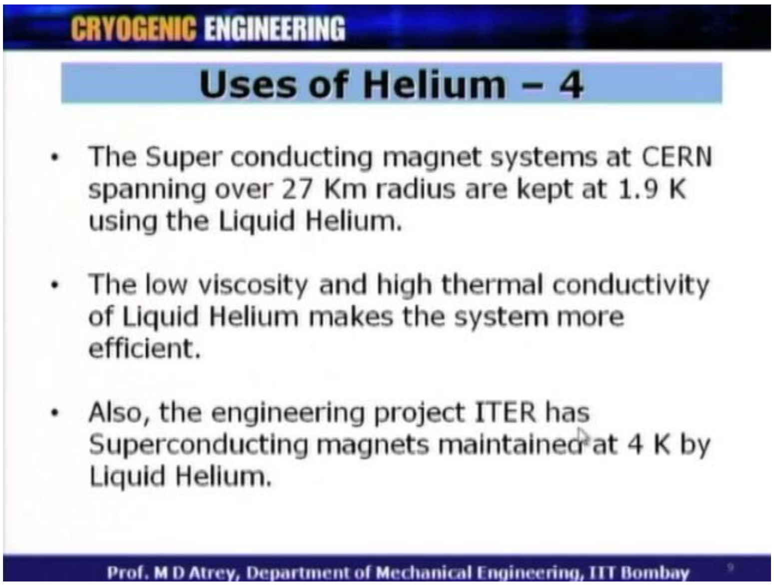

There are many other usages; the super conducting magnet systems at CERN which is a big bang experiment which is still going on, which spans over 27 kilometer radius are kept at 1.9 kelvin using liquid helium. Now, you can imagine 1.9 kelvin is a super fluid helium. And because of its high conductivity, it gives best heat transfer and those places; it cools the magnet most effectively. The low viscosity and high thermal conductivity of liquid helium makes the system more efficient. Also the engineering projects ITER which is the tokomak project, which is a nuclear fusion project has super conducting magnet which is maintained at 4 kelvin using liquid helium. These are two experiments which uses maximum liquid helium as of now; that the big uses of cryogenics.

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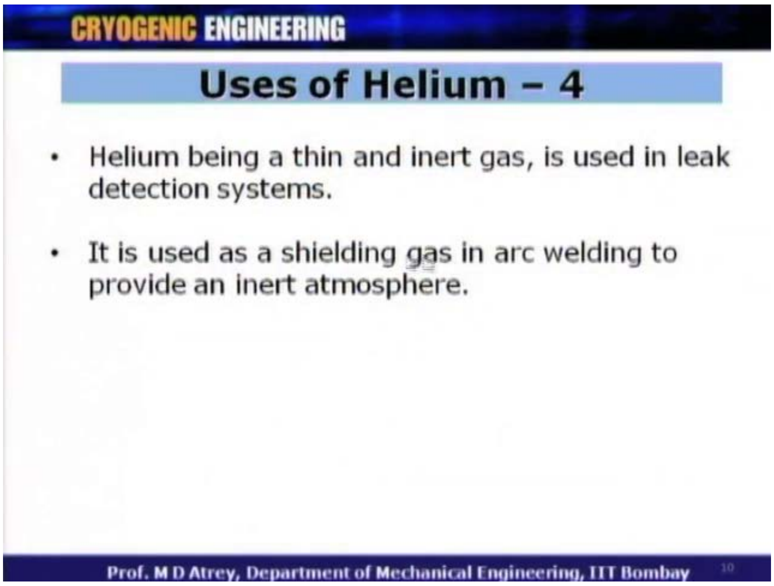

Now, helium being a very thin gas - very thin and inert gas, it is used in leak detection system. This is a very simple application and you can find helium leak detectors are very, very common in usage, wherever the leak tightness is of importance. The helium gas is also used as shielding gas in arc welding to provide an inert atmosphere. Having done this, now I will focus more on liquid helium - II that is the super fluid. This is one of the most important and very characteristic phase transform liquid. It has got typical special properties and we will see what exactly it is.

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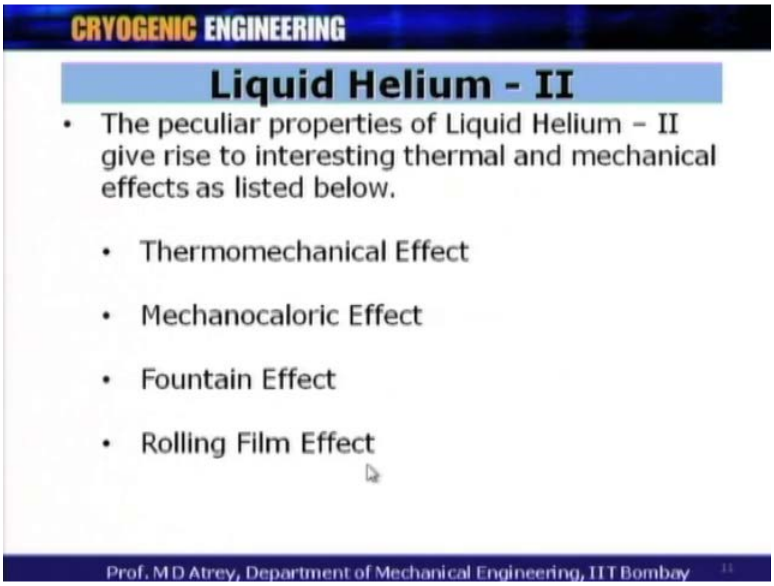

We talked about the properties of low viscosity and very high thermal conductivity. These are very, very typical peculiar properties of liquid helium - II which will not find normally other liquids. Now, this peculiar property give rise to very interesting thermal and mechanical effects. And what are these effects; they are thermomechanical effect that means thermal plus mechanical effect; they are mechanocaloric effect which is mechanical plus thermal kind of effect, the orders are reversed over here. Third effect is the fountain effect and the fourth effect is rolling film effect. Now, I would like to understand what these effects are and how liquid helium - II play a very important role in showing these effects.

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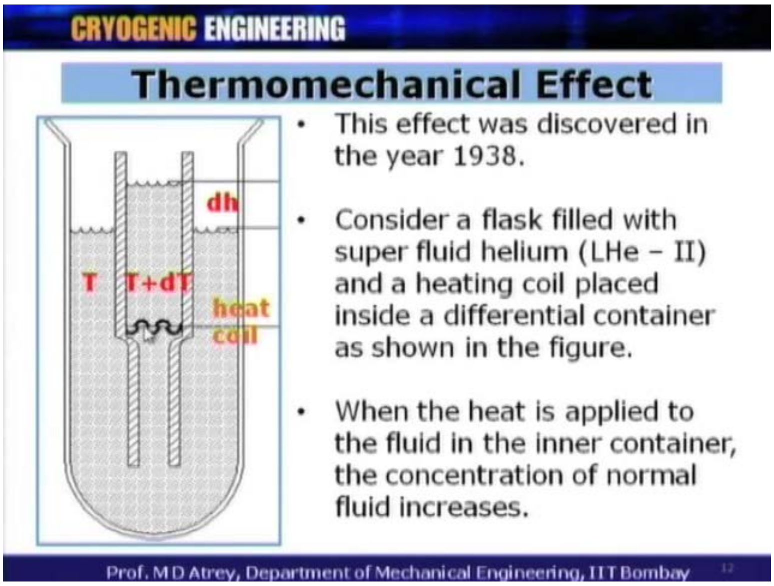

Let us come to thermomechanical effect. This effect was discovered in the year 1938. And you can see a flask over here, this is a flask and this flask is completely filled with liquid helium – II. In this flask, what you see again is a different container at this point, and there is a heating coil placed in this. So, you got a flask which is filled with super fluid helium and heating coil plays inside a differential container as shown in the figure. The whole thing is filled with liquid helium - II that is super fluid.

Now, what we do is we apply some heat at this point. As soon as we apply some heat at this point, the temperature here will rise, and as soon as the temperature rises whatever super fluid was there, it will go into normal condition. It will get transformed into normal condition, because the temperatures have increased over there. So, when the heat is applied to the fluid in the inner container, the concentration of the normal fluid will increase here, because you will have a face transformation again, and super fluid concentration will decrease and the normal fluid will concentration would increase.

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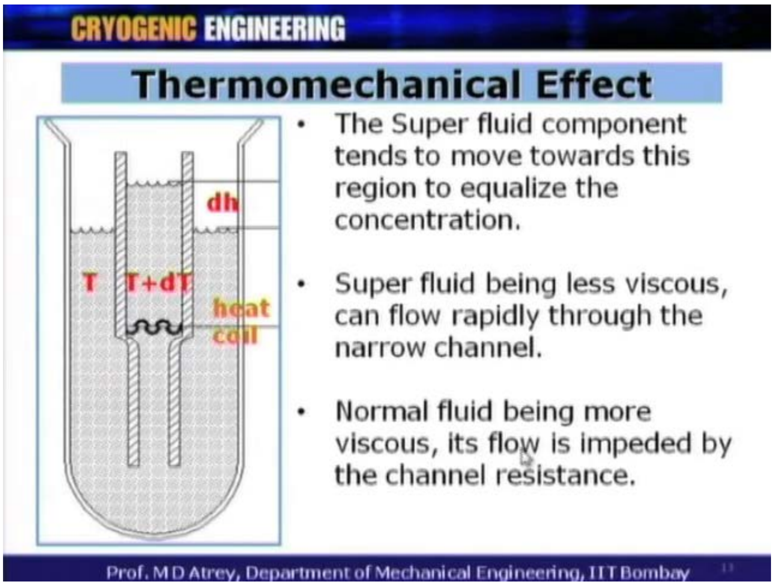

The super fluid component tends to move towards this region. Now, you can see all this is surrounded by super fluid, and is this is got liquid helium – II. As soon as there is a decrease of concentration of super fluid - II here, the liquid will start flowing from region of high concentration to the region of low concentration. So, liquid helium - II which is region of high concentration outside would start to come and try to equalize the concentration inside and outside. The thin opening here, kind of a neck over here which will not allow normal liquid helium to pass through it alright, this is the important part of it.

The super fluid component tend to move toward the region equalize the concentration. The super fluid being less viscous can flow rapidly through this narrow channel. So, this channel which are the very small dimension, this will not allow the normal fluid fib to pass through it, because it is viscous; what will it allow? It will allow liquid helium – II pass through it, because it has got less viscosity. So, as soon as you start heating over here, there is the rush of liquid helium - II to go through this thin narrow channel; so, as to equalize the concentration of liquid helium - II all over. Normal fluid being more viscous, it is flow is impeded by the channel resistance as a result, because heating over here will induce a kind of flow and as soon as the flow starts it will induce a pressure difference.

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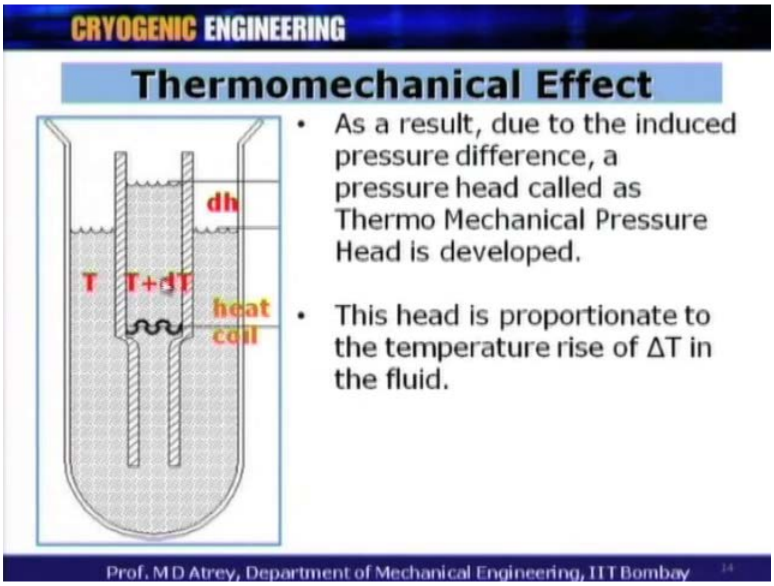

So, as a result due to induced pressure difference, a pressure head which now we can call as thermo mechanical pressure head, because it is induced because of this temperature difference over here. Because of rushing of liquid helium – II, you can find a pressure head of dh height getting generated at this point. So, you can see because of thermal action, one mechanical head is getting generated or the flow of fluid is happening from outside container to inside container through a thin little channel, and this is what we call as thermomechanical effect. This head is proportional to the temperature rise delta T in the fluid. So, dh value will ultimately depend on what your delta T is alright and this is what we call as thermomechanical effect.

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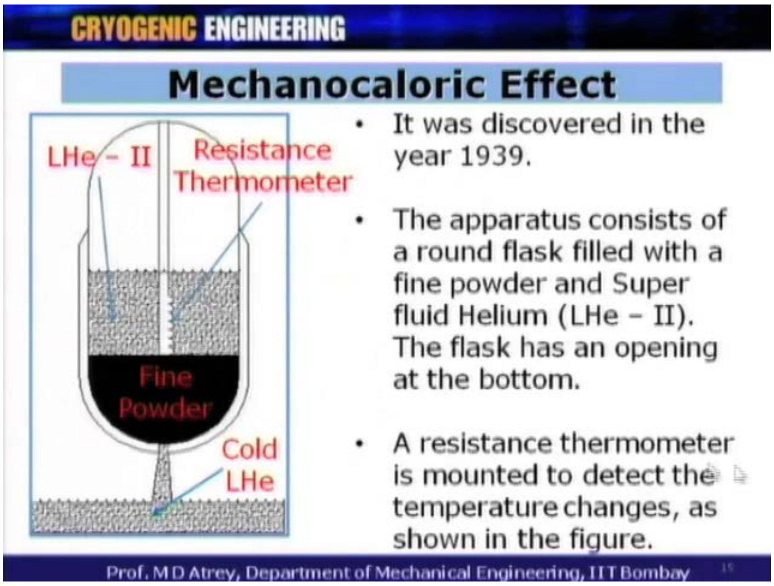

The next effect we talk about is Mechanocaloric effect. Now, here a mechanical action would give to some caloric effect or thermal effect. What it is? This was discovered in the year 1939. Again you have got apparatus over here which is filled with some fine powder at the bottom and in liquid helium - II is kept in this container. So, the apparatus consists of a round flask filled with fine powder and super fluid helium that is liquid helium - II which is very, very less viscous. The flask has an opening at the bottom. So, this is a small opening at the bottom. Also one resistance thermometer is kept over at this point, in order to get temperature over time at this particular point. So, a resistance thermometer is mounted to detect the temperature changes as shown in this figure. Now, let us see what happens.

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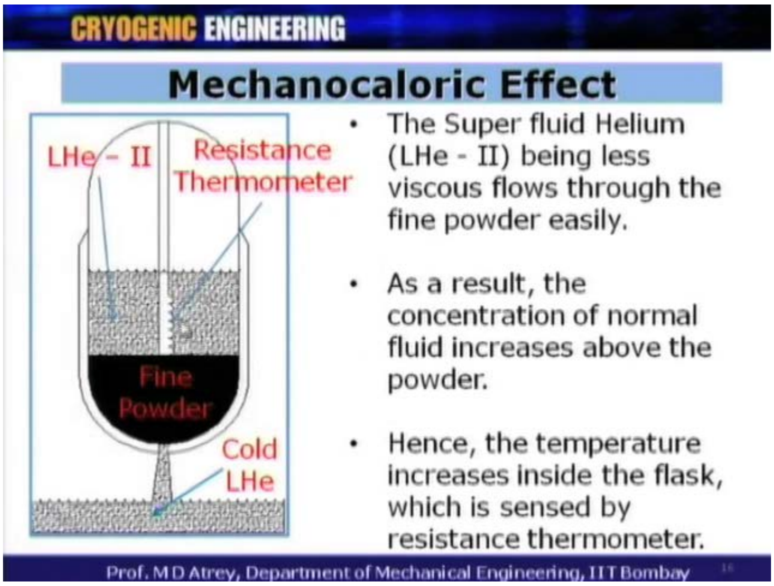

Now, this is super fluid over here, and this super fluid being non viscous, being less viscous, being 0 viscous we can say; it will travel through this fine powder. And it will go through this fine powder, because the resistance of fine powder is not enough to stop it alright. This liquid helium - II slowly go down here and will come out from this orifice at other end, this node opening at other end, and this liquid helium - II will start coming through this fine powder travel through it and go down.

So, what will happen, over a period of time, the liquid helium - II part here would start coming down and what will remain at the top is normal helium - liquid helium- I. And most of the all the liquid helium - II would come down. As a result of which the liquid helium - II will have less temperature; liquid helium - I normal will have lambda point temperature or higher temperature. One would have created here higher temperature at this point and lower temperature below this flask and this is what we call as mechanocaloric effect. Because some mechanical action of travel of fluid through this fine powder has created one thermal effect or a temperature difference across this fine powder alright.

So, here just to read that as a result the concentration of normal fluid increases above the powder, because liquid helium being less viscous flows through the fine powder easily. And what you get at the end, the temperature increases inside the flask which is at this point, and we can see the temperature, because of resistance thermometer here.

Suddenly, we can see how the temperature changes over a period of time because the thermometer. And you can see that a mechanocaloric effect has been achieved. Having seen this two effect a similar effect could be seen as what is called as fountain effect alright.

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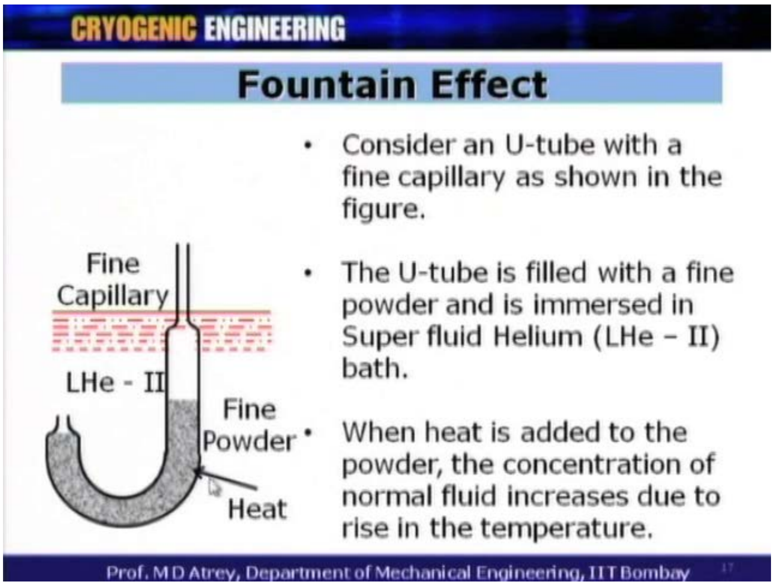

So, again you can see a U-tube here with a fine capillary as shown in this figure. And it is dipped in a container having liquid helium - II. So, this is U-tube which is got fine powder in this. And the U-tube is filled with a fine powder and is immersed in super fluid helium bath alright. As soon as you put this U-tube in the liquid helium - II bath, the liquid helium - II will go inside and occupy the place alright. So, U-tube is filled with a fine powder and is immersed in super fluid helium - II bath. Now, what we do is we apply some heat at this point. As soon as we apply heat at this point, the liquid helium - II at this point suddenly it will get converted to normal helium and this normal helium… So, when heat is applied to at this point, whatever liquid helium - II was here at this point will become normal helium that is liquid helium – I, and again the concentration of liquid helium - II at this point will decrease.

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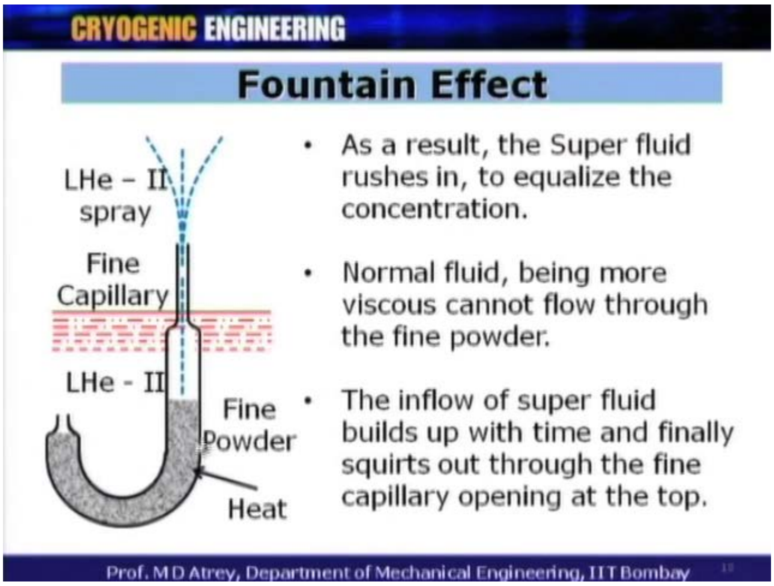

Again what happened as in the earlier case, the super fluid helium from outside will try to rush in; it will try to equalize this concentration. So, slowly as you go on applying heat, the super fluid helium - II will travel through and will get will occupy the place inside though inside this, and over a period of time, the normal fluid being viscous will not be able to pass through it, only helium - II will pass through it. And over a period of time, what you see is some kind of a fountain effect, because only liquid helium - II is passing through it, it will occupy place, it will pressurize, it will build up a pressure and slowly what you see is what is called as fountain effect.

So, fountain effect is nothing but liquid helium - II spray in this case. The inflow of this super fluid builds up with time, and finally squirts out through this fine capillary opening at a top, because only liquid helium - II can pass through this and fountain effect has been established here. And this is basically with the same application of same reasoning of less viscosity of helium – II, we can see these effects.

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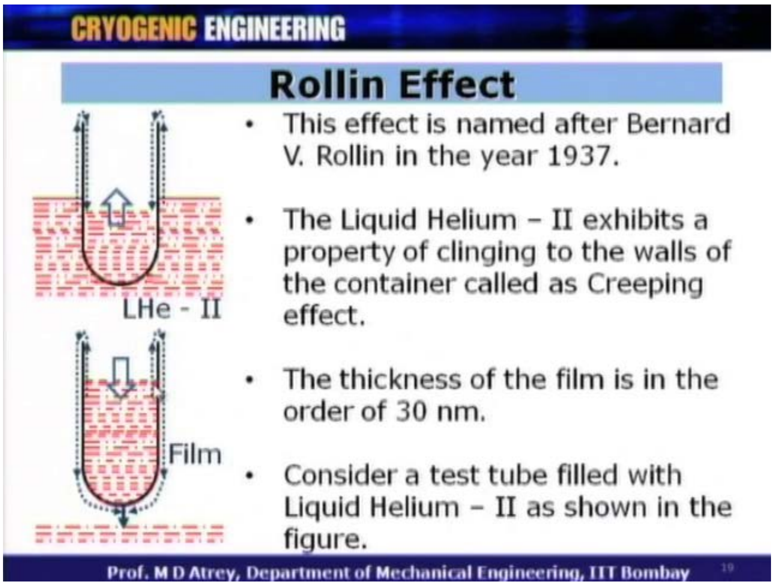

Now, what you see is a next effect which is called as Rollin effect. Now, here this effect is basically named after Bernard V. Rollin in the year 1937. The liquid helium - II exhibits a property of clinging to the walls of the container called as creeping effect. What you see in this picture is the same thing; you see this wall of this tube liquid helium - II is clinging to the wall and what we call as a creeping effect. The thickness of this film is in the order of 30 nanometer. Now, what happens exactly in this effect? Consider a test tube filled with liquid helium - II as seen in the figure.

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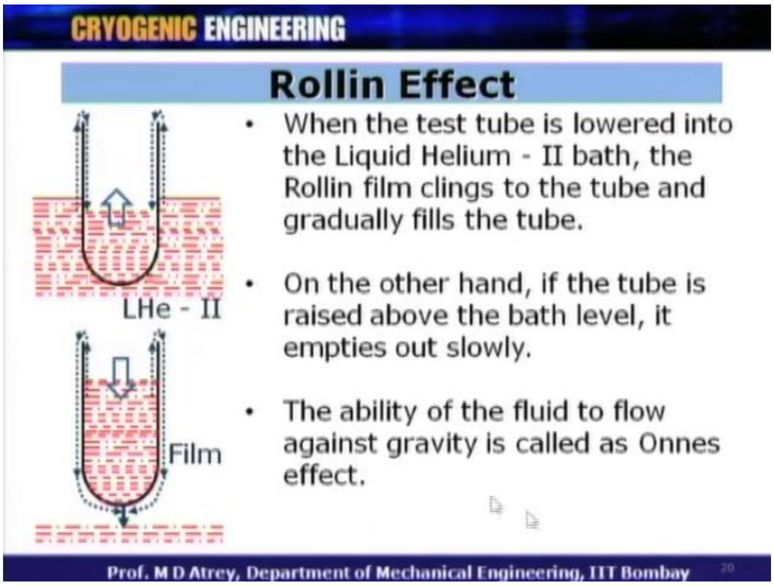

When the test tube is lowered in the liquid helium - II bath, which is over here. Now, we can see when the test tube is lowered in this liquid helium - II bath, the Rollin film clings to the wall and gradually fills the tube. So, as soon as you dip in this tube, this liquid helium - II will cling to the wall of this tube and it will start going again the gravity, it climb up and it will start going down. So, what is happening is because of this creeping effect, it forms a film on this surface and slowly the height of this level will start increasing. So, this liquid helium - II which was over here, it will enter the tube, because of this creeping and this is what we call as Rollin effect alright. And it will gradually fill this tube.

Now, on the other hand, if I lift this tube up as you see in this case, if I leave this tube up it will slowly get emptied, because of this Rollin effect again, the helium - II from this particular tube starts clinging to the walls of this tube and liquid helium - II will start coming down. You can see slowly the level of this liquid helium - II in this tube will start going down. And this is essentially what happens, because of the Rollin effect, you can see this clearly over here. And the ability of this fluid to flow against the gravity, in all these cases this fluid flow is happening across the gravity. This is going up opposite direction to the gravity. This is called as Onnes effect alright and all this constitutes what is called as Rollin effect. Why this happen?

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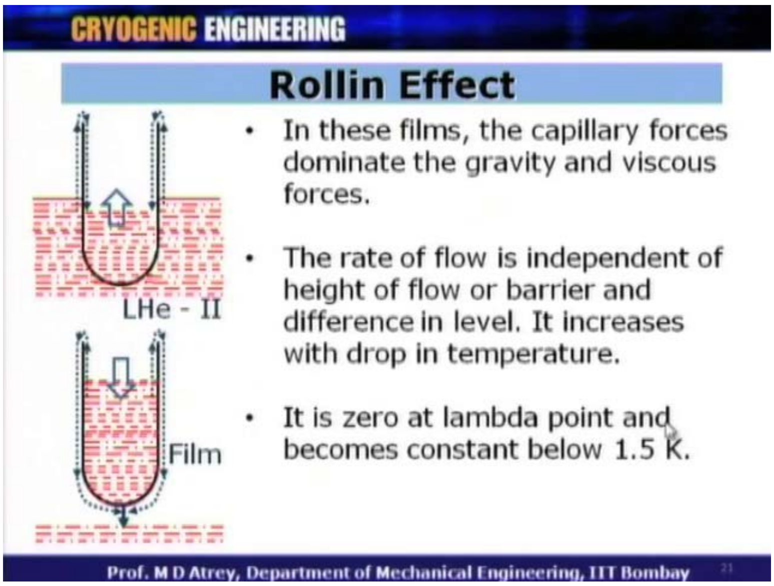

In these films, the capillary forces dominate the gravity and viscous forces. It is against gravity, it overcome the viscous forces and that is why one can see the Rollin effect. The rate of flow is independent of height of flow or barrier and difference in level. Normally, it would have been a function of all this parameters, but in this case it is not, it increases with the drop in temperature. So, as you go down the lambda temperature, as you go towards 0 kelvin this effect will show. It is 0 at lambda point. So, this effect is not shown when the temperature is at lambda point that is 2.17 kelvin and below 1.5 kelvin, it shows a constant effect. It becomes constant the rate of flow becomes constant below 1.5 kelvin.

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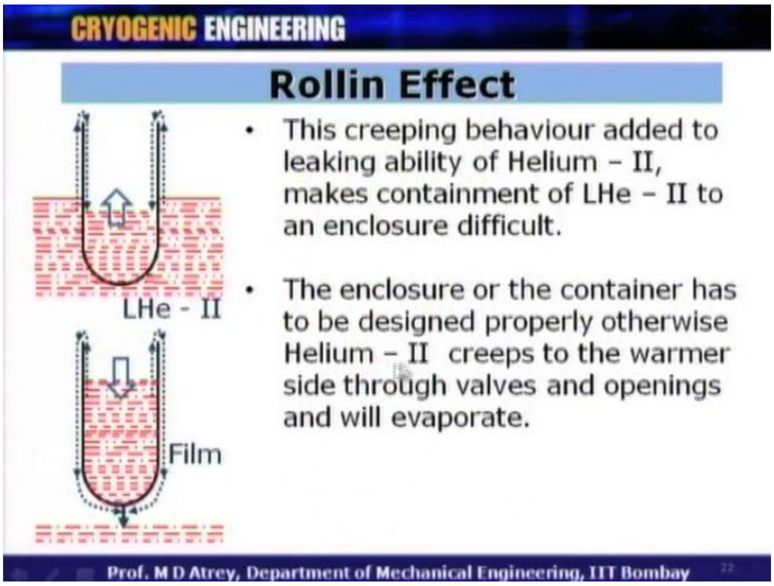

Now, this creeping behavior added to the leaking ability of helium - II. So, two effects are combined; that it clings to any surface any wall. In addition to that it has got leakage ability; that means, because of thinness of helium gas or helium liquid or low viscosity of helium. It makes it very difficult to contain liquid helium – II to an enclosure. These are very important aspects alright. If you want to store liquid helium – II, one has to be very, very careful; you should not have valves, you should have proper containers, you should not have cracks anything like that. The enclosure or the container has to be designed properly, otherwise liquid helium - II creeps to the warmer side through walls and openings will evaporate. This is the very important aspect of it.

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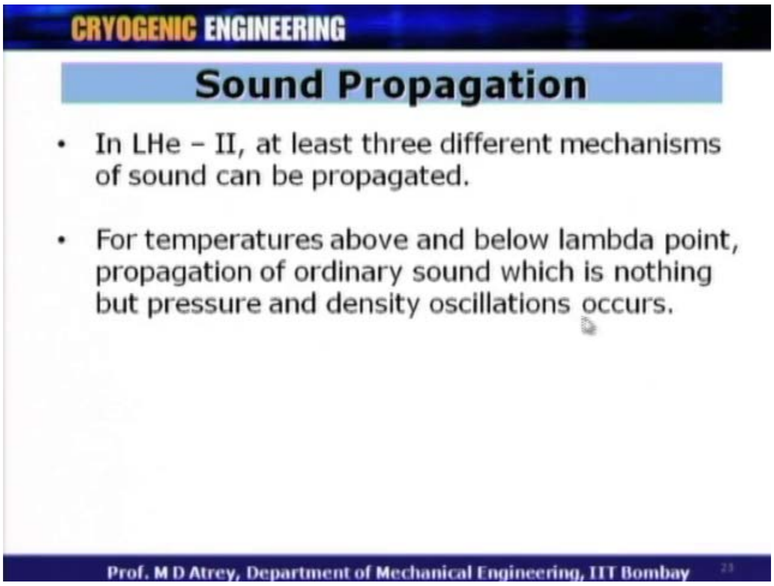

The third important property is sound propagation. Sound propagation in liquid helium - II or liquid helium - I is not normal, there is something addition to that alright. So, in liquid helium - II at least three different mechanisms of sound can be propagated. For temperatures above and below lambda point it is 2.17 kelvin that is in liquid helium - I and liquid helium – II, propagation of ordinary sound which is nothing but pressure and density oscillation occurs. So, this is normal sound, sound requires medium and liquid helium - I offers and liquid helium - II offer one medium, and therefore, what you have is ordinary sound which is nothing but pressure and density oscillation. So, that is sound number one what we call us. This is called as first sound.

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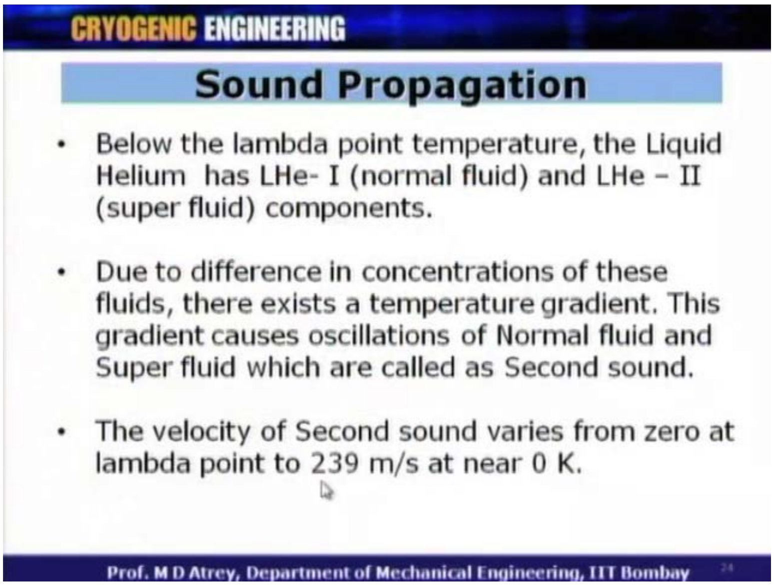

Now, below lambda – II, what we have is now liquid helium - I and liquid helium – II; what we have is a normal fluid; what we have is a super fluid. As soon as two different medium come. Due to difference in concentration of this two fluids, as you know that the liquid helium - I normal and super fluid, what exist is a temperature gradient. If you have got a 100 percent normal fluid what you have got is 2.17 kelvin temperature. It is about 100 percent super fluid what you got - got is a 0 kelvin temperature. And in between what you have got is a different temperature or you got a temperature gradient now.

This gradient causes oscillations of normal fluid and super fluid. And this will give to what is called as second sound. This is the very important thing that below lambda point what you got is a LHe - I and LHe – II - normal fluid and super fluid, and this oscillation in LHe - I or Normal fluid and super fluid in combination what is give as second sound. So, first sound is the normal sound second sound is coming because of temperature gradient coming in a mixture of liquid helium - I and liquid helium - II that is below lambda point. The velocity of sound varies from zero at lambda point, for the second sound varies at zero at lambda point and around 239 meter per second near 0 kelvin. So, this is very important. At 0 kelvin, the the temperature gradients will be tremendous. Therefore, you got a very high velocity of second sound at 0 kelvin.

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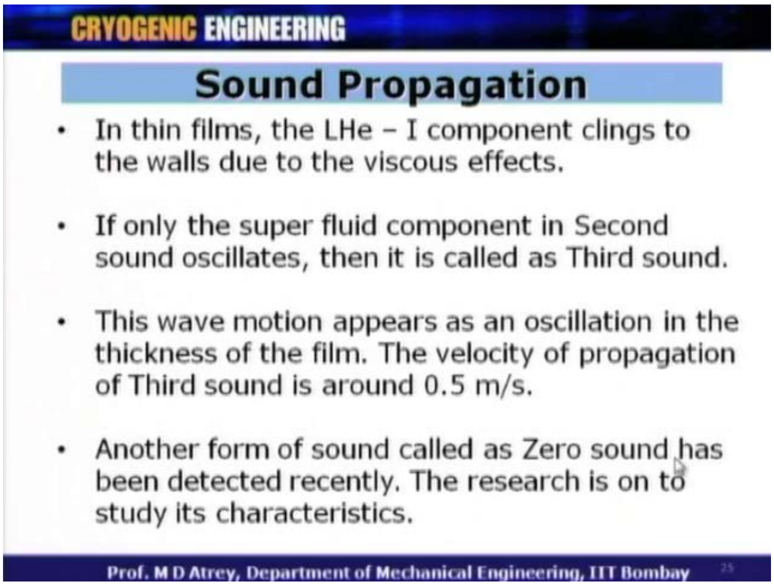

Now, there is third sound also. In thin films which we just saw a thin film when the the fluid gets cling to the walls of a surface. So, in thin films, liquid helium - I component clings to the walls due to viscous effect, liquid helium - I has got finite viscosity while liquid helium - II we say as what absolute 0 viscosity alright. So, when in a film what does liquid helium - I do it clings to the wall, and therefore it is occupied all the time. If only the super fluid component in second sound oscillates now. There is no oscillation in the liquid helium - I, because liquid helium - I has cling to the wall; while the super fluid component in the second sound oscillates only liquid helium - II. This is what we called as third sound.

In second sound, we had the combination of oscillations in liquid helium - I as well as liquid helium - II and that is what we call as second sound. In the third sound however, the component in liquid helium - I or oscillations in liquid helium - I are not at all there; why, because liquid helium - I has completely occupied the place on the wall. While the oscillations are happening only in the super fluid now which is LHe - II and this is what we call it third sound in this case. This way motion appears as an oscillation in the thickness of the film. The velocity of propagation of third sound is around 0.5 meter per second. This is what we talk about first sound, second sound and third sound. The one more sound called zero sound. It has been detected very recently and lot of research is been carried out on this also.

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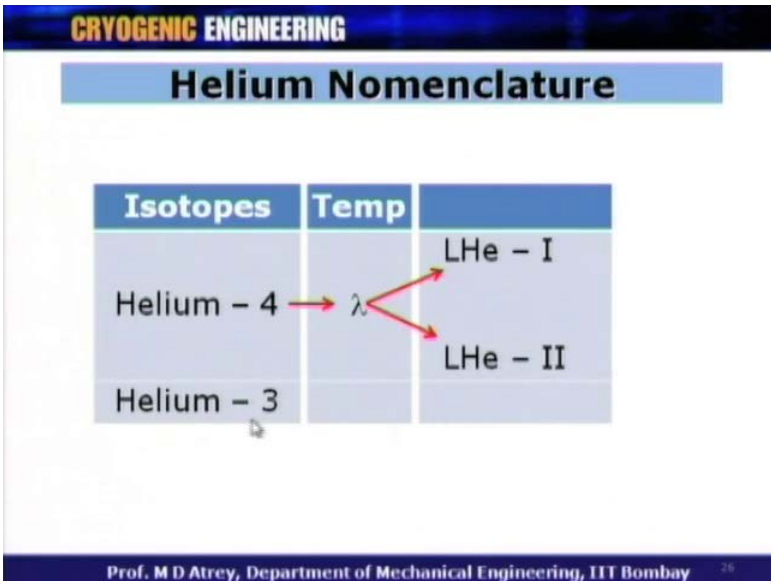

Just to summarize what we have been talking about, because what we here in helium nomenclature is helium - 3, helium - 4, helium - I and helium - II. I just wanted to tell you more about these that helium - 3 and helium - 4 are nothing but isotopes alright. Helium - 4 is what we discussed till now. Helium - 3 is an isotope of helium. And under helium - I what you got is a lambda point temperature, and in this lambda point temperature what you have is a liquid helium - I and liquid helium - II. So, I just want you to understand different helium - I, helium - II as well as helium - 3 and helium - 4. Helium - I and helium - II are nothing but coming from helium 4 below lambda point in the liquid form, but helium - 3 is nothing but isotope of helium. And now I will talk about helium - 3.

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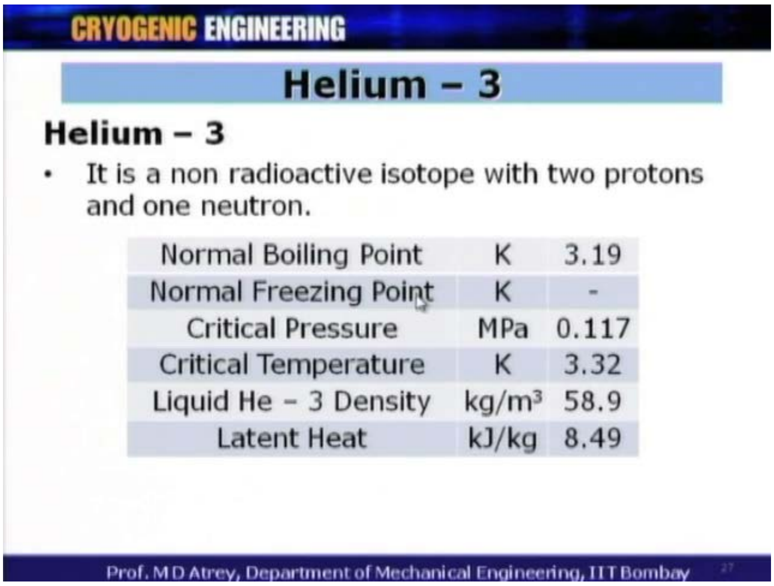

So, we will see now the isotope of helium which is helium - 3. Helium - 3 is a non radioactive isotope with two protons and one neutron. You remember the third isotope which was tritium which was radioactive, but what we use in cryogenics is helium - 3. Now, they are the general properties of helium - 3 which has got a boiling point of 3.19 kelvin, which is a normal boiling point at one atmosphere. Again it does not have a freezing point like helium - 4. The critical pressure is 0.117 M Pa. Now, this is very important, this is only 1.17 bar just above atmosphere.

When the critical pressure is very less, naturally critical temperature also is very less; which is 3.32 kelvin. So, you can see the boiling point is 3.19 and the critical temperature is 3.32 alright. The liquid helium - 3 density is 58.9. The latent heat is very, very small 8.49 kilo joule per kg; it means that smallest latent heat coming liquid helium - 3 will get evaporated or it will get vaporized. So, once has to be very sure about the heat in leaks in this case. Whenever we are using heat liquid helium - 3 the heat leaks have to be really really taken care of. This should no heat leaks to the system, otherwise liquid helium - 3 will get immediately evaporated.

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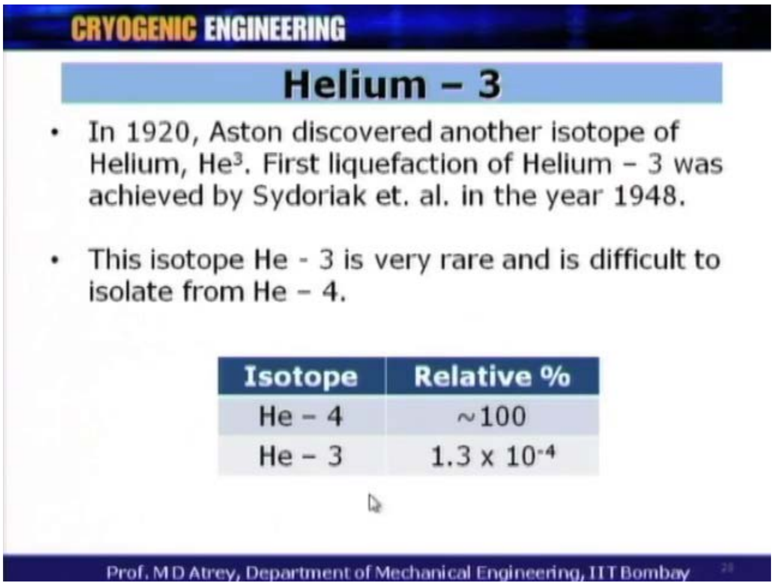

In 1920, Aston discovered another isotope of helium which is helium - 3. So, it was discovered as old as 1920. And the first liquefaction of helium - 3 was achieved by Sydoriak et al in the year 1948. So, 1920 was discovery of helium - 3, while 1948 was liquefaction of helium - 3. This isotope which is helium - 3 is very, very rare very rare and is difficult to isolate from helium - 4.

Now, what is the relative percentage of existence of helium - 3 as compared to that of helium 4, we can see from this table. So, helium - 4 is very, very close to 100 percent, and helium - 3 is 1.3 into 10 to the power minus 4 percent that is 0.0001. So, we can imagine how rare this gas is. It is very rare gas and because it is very rare, you can understand the value of or the cost associated with use of helium - 3. One has to be really careful in using helium - 3 that is one and one has one has to really justify the usage of helium - 3 as compared to that of helium - 4.

The cost effect are tremendous, the cost of helium - 3 could be almost 100 times more than that of helium 4. Helium is also a rare gas itself and helium - 3 is much much rare, and therefore, this relative percentage tells how difficult it is to get helium – 3. And if you want to use liquid helium - 3 then how costly it could be. It just listen an idea that you have to not only come down to 3.13 to liquefy helium - 3, and then store it and prevent the heat in liquid system. These are real important aspects associated with studies related to or experiments related to liquid helium - 3.

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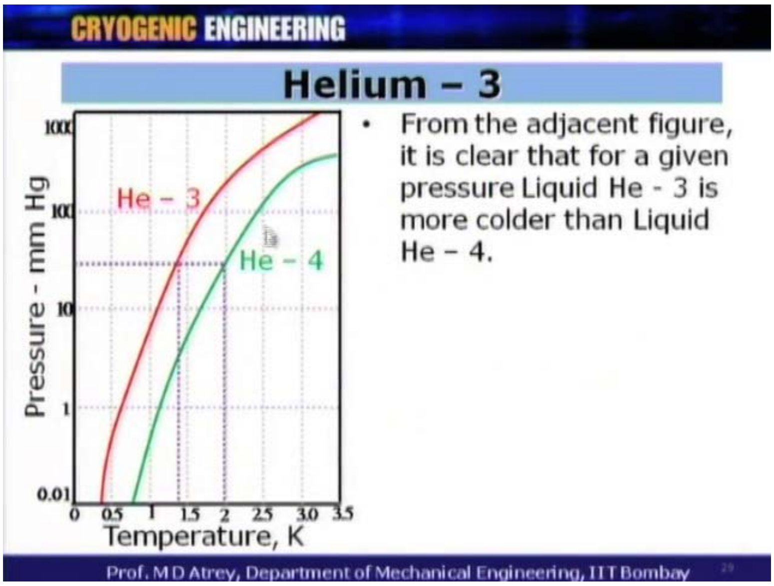

Now, what you see from this is a pressure versus temperature diagram for helium - 3 and helium 4. Just for comparison, you can see the vapor pressure curve for helium - 3 and the same curve for helium - 3 at this point. And from here you can understand that for any pressure if I plot a horizontal line what I get is a for a given pressure helium - 3 has got less temperature has come to that of helium - 4. So, if I could achieve a lower and lower pressure, using helium – 3 I will get lesser and less temperature

So, from the adjacent figure it is clear that for a given pressure, liquid helium - 3 is more colder than liquid helium 4. See if I really want to reach lower and lower temperature, I can reach really less than 1 kelvin or even less than 0.5 kelvin using helium - 3. I cannot do that using helium - 4 and these are the important aspects. So, you can see for a constant pressure at this line, if I draw two verticals I get two kelvin and less than 1.5 kelvin for the same pressure, and this is an important aspect. If I want to create lower and lower temperature, if I want to generate lower and lower temperature, I can replace use of helium - 4 by use of helium - 3. But then as I earlier said one has to really justify the cost associated with use of liquid helium - 3 or use of helium - 3 gas also. That is the most important aspect.

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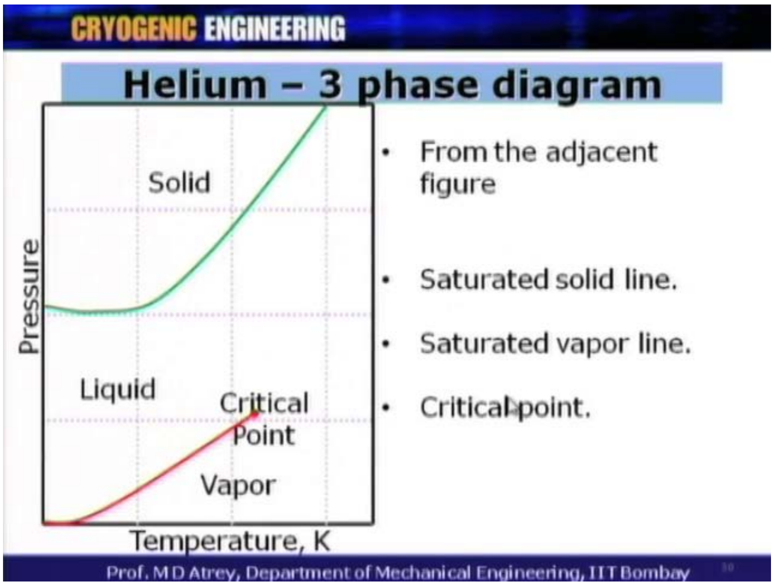

Have been done this the next important part associated with helium - 3 is the phase diagram; this is very interesting. What we can see form here is the phase diagram for helium - 3. So, you can see a saturated vapor curve for helium - 3 and what you see here is a vapor, what you see here is a liquid, what you see here is a solid. The diagram looks as similar to what it was at helium - 4 as for as these three lines are considered. And we can again see that vapor, liquid and solid in case of helium - 3 cannot co-exist; it does mean that it does not have a triple point alright.

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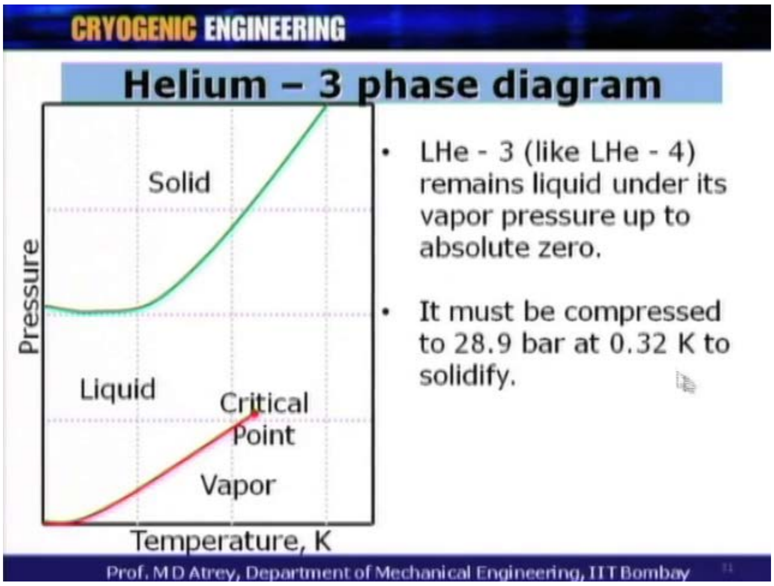

Liquid helium - 3 like liquid helium - 4 remains liquid under its own vapor pressure up to absolute zero. It does not get solidified alright, increments liquid till this point. And if I want to make it solid, I must compress it to 28.9 bar at this point at 0.32 kelvin. Unless I do that I will not get solid helium - 3.

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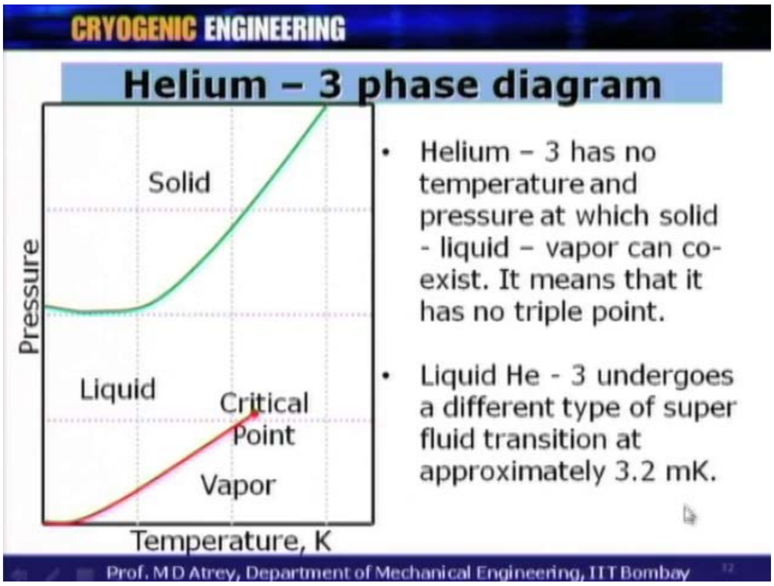

So, meaning the same thing that helium - 3 has no temperature and pressure at which solid - liquid - vapor can co-exist meaning that no triple point, and as given earlier, it has to be compressed to around 28 bar, if you want to get solid helium – 3. This phase diagram looks very similar to that of helium - 4 in terms of having no liquid, but in helium - 4 what we had was liquid helium - I and liquid helium - II; the phase transformation which is not there in helium - II. These are these are transformation of other kind at very, very low temperature near 0 kelvin. L iquid helium - 3 undergoes a different type of super fluid transition at approximately 3.2 millikelvin. That means, very, very close to 0 kelvin, it has got a different type of super fluid transition alright.

I am not going to deal with this, because really a very physics oriented discussion have to go into this. As far as cryogenic engineers are concerned what we should know is the helium phase diagram, and we should really know the vapor pressure curve for helium - 3 and helium 4 respectively.

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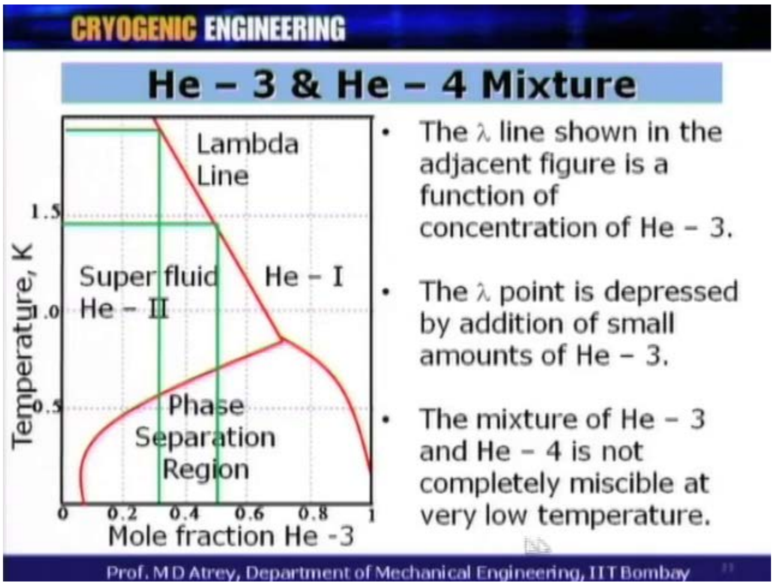

Now, there is a very important aspect associated with helium - 3 and helium - 4 mixture, and this is this curve. Now, see carefully and read carefully in this curve; what you are got as the temperature and what you are got as a mole fraction. What you see at this point is the lambda line. So, lambda line which is shown in adjacent figure is a function of concentration of helium – 3. Now what we are dealing with is a helium - 3 and helium 4 mixture. As soon as helium - 3 is added to helium 4 or let us start with if we have helium - 4 only, you got a lambda point of 2.17 kelvin. And as we add helium - 3 to 8 and we make a mixture, the helium - 3 is completely miscible to helium - 4 here, but as the fraction of helium - 3 increases the lambda point decreases.

So, you can see for this particular fraction, you got a lambda point here and for other fraction you get a lambda point over here. So, depending on the percentage or mole fraction of helium - 3, you will have different lambda points. So, this is lambda point, this is lambda point for corresponding mole fraction of helium - 3. So, this basically shows that as you go on adding helium – 3, your lambda point decreases. So, that is why I say here, the lambda line shown in the adjacent figure is a function of concentration of helium – 3. The lambda point is depressed by addition of small amount of helium - 3. So, as you go on adding helium - 3 your lambda point temperature started coming down here, here, here.

Now, what we have is a mixture of helium - 3 and helium – 4, and it is not completely miscible at very low temperature, this is what understand over here. See if I come down lower and lower, I get a different phase diagram, I get a phase separation over here. Meaning which above this particular temperature what I had was miscibility of helium - 3 and helium - 4, but when I come down when I come down below 1 kelvin what you find is a completed different diagram or the phase diagram changes over here. It has got two fraction, but two vapor pressure curves alright, and this is what we deal with.

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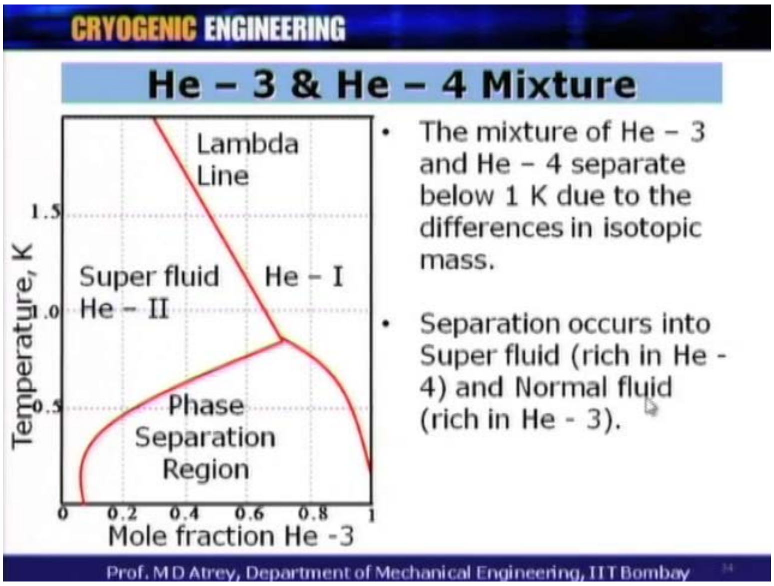

The mixture of helium - 3 and helium – 4, they separate below 1 kelvin due to differences in isotopic mass alright. The masses are different and because of typical behavior of this particular mixture, as I come down below 1 kelvin and typically around 0.87 or 0.8 kelvin; suddenly, you find that I got distribution or separation of helium - 3 and helium - 4. So, one region has got practically 0 percentage of helium - 3 or very, very less amount of very, very low fraction of helium - 3; while other fraction has got almost 100 percent helium - 3.

So, we can see, when I have got come down around 0.8 kelvin, I got two fractions separated out; one fraction is having no percentage of helium - 3, and therefore it is helium - 4. For a mixture of helium - 4 and helium - 3, I get helium - 4 and at this particular temperature what I will have is a super fluid helium - II. So, what I will have is a super fluid helium - II, but that is of helium - 4. The other end will be completely helium - 3. So, here you can see that the phase separation happening; one is super fluid helium - II and other one is helium - 3. So, separation is occurring into super fluid which is rich in helium - 4 or practically all is helium - 4, and normal fluid rich in helium - 3. So, this is normal helium - 3 right now, and almost 100 percent rich in helium - 3. These are the very important aspects.

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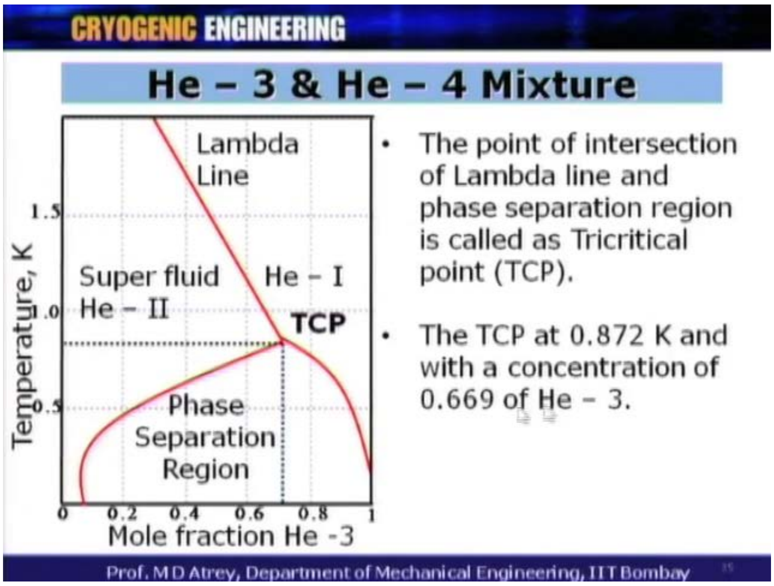

Now, this point of intersection of lambda line - this is lambda line and it intersect this phase separation region at a point which is called as Tricritical point, which is called as TCP point; Tricritical point or a TCP is at this point which basically is occurring at a particular temperature, is occurring also at a particular molecule fraction of helium - 3 alright, and this is denoted by TCP. The TCP is at 0.872 kelvin with a concentration of helium - 3 of 0.669 mole fraction. So, these are the very important aspects of helium - 3 and helium – 4, and these are exploited dilution the refrigerator. This factors are basically exploited and dilution refrigerator.

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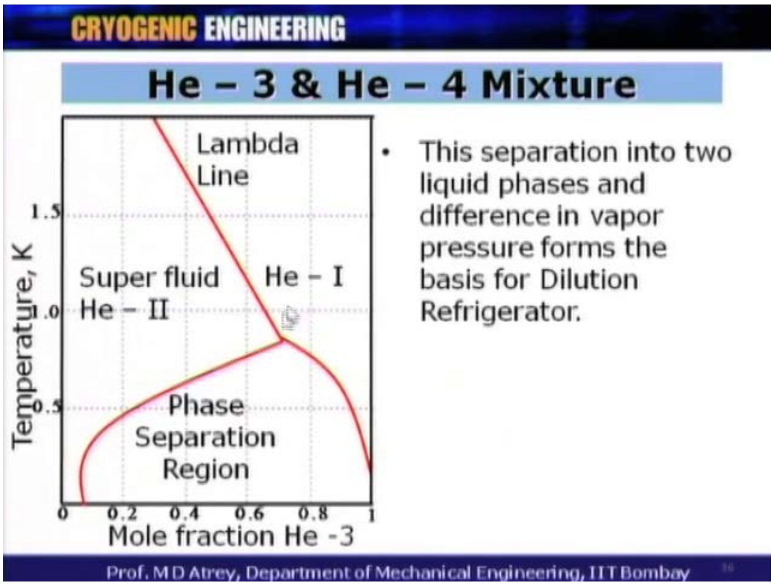

This separation into two liquid phases and differences in vapor pressure forms the basis of dilution refrigerator. So, you got a vapor pressure at this point and you got a vapor pressure curve at this point, and this phase separation of helium - 3 and helium - 4. Now, this two helium - 3 and helium - 4 are not miscible, you will clearly find helium - 3 above helium – 4, because of the immiscibility of this two fluids and this is what we exploit in dilution refrigerator in order to reach lower and lower temperature below or close to 1 kelvin or below; this is what basically is exploited; this principle is of this cps being exploited in this case.

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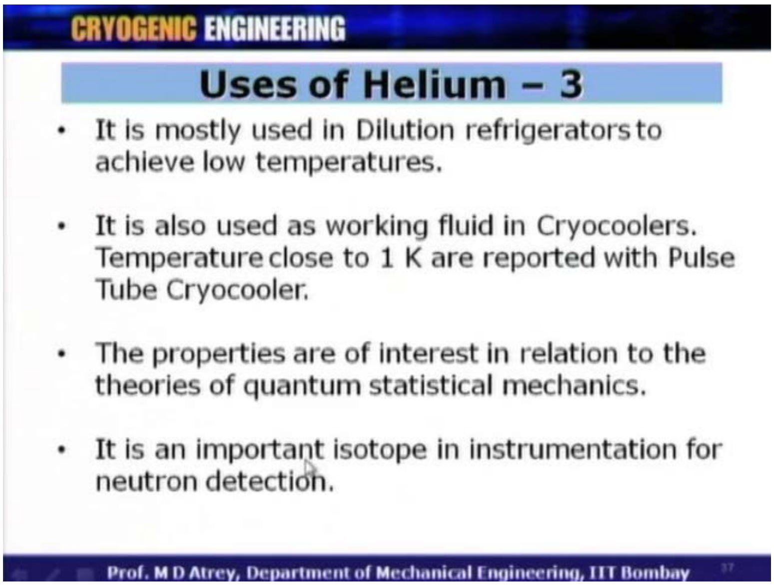

I will come to the uses of helium – 3, I just briefly talked about helium - 3 vapor pressure curve then I talked about the phase diagram of helium – 3. Now helium - 3 is a very costly gas, and therefore, it is usage has to be really justified. All the equipment's which use helium - 3 are very, very costly. In fact, one would not prefer to use helium - 3 unless justified. As we just talked about it is mostly used in dilution refrigerators to achieve low temperatures. It is also used as working fluid in cryocoolers and temperatures close to 1 kelvin or reported with pulse tube cryocooler. I know at least 2 or 3 papers which have used helium - 3 in place of helium 4. And suddenly at a temperatures they could reach are very close to 1 kelvin around 1.27 kelvin have been reached using two stage pulse to refrigerator, while some one has used three stage pulse to be refrigerator that the first attempt we had and they reach around 1.7 kelvin using helium 3.

But again they also had to justify the usage of helium - 3 in those devices, because just the usage made the devices very, very costly and commercially speaking we do not have any refrigerators of now or the cryocoolers as of now which uses helium - 3 as a workings substance. However, most of the helium - 3 requirement is in dilution refrigerator, and this is very, very widely used dilution refrigerators in order to carry experiments below 1 kelvin temperature levels. The properties of helium - 3 or of real interest in relation to the theories of quantum statistical mechanics; why all this separation happening; what happens at 3.2 milli kelvin are very interesting aspects of liquid helium - 3 studies and related to theories of quantum statistical mechanics. It is an important isotope in instrumentation for neutron detection alright. So, wherever neutron detection experimentation is going on helium - 3 is a inhabitable choice. And this is what I would like to touch upon helium - 3 as (( )).

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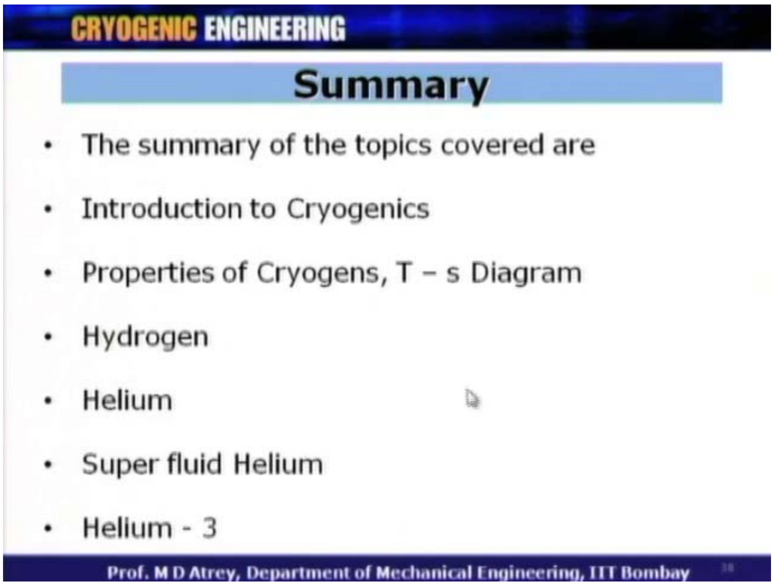

Now, coming to the summary of the entire lectures related to cryogens, what I talked about was first introduction of cryogenics; we discussed in details in sufficient details about various cryogens, we also talked about temperature entropy diagram, its importance. And most of the times I have represented the properties of the cryogens on the temperature entropy diagram. I except all of you basically to understand the T - s diagram very, very clearly, and to get maximum information from T - s diagrams, because that is what we will use to solve various problems when we come to liquefier and refrigeration and gas separation problems.

We talked about hydrogen and we talked about the importance of ortho to para forms or different forms of hydrogen, we talked about conversion of ortho to para as we go on reducing hydrogen. We talked about the liquefaction of hydrogen and what is the necessary condition that complete ortho to para transformation should take place during liquefaction, otherwise all the liquid which is generated will get evaporated, because ortho to para conversion is basically a exothermic process.

Then of course we talked about helium; what is important helium is its phase diagram understand LHe – I, LHe – II, understand lambda point, lambda line, understand the properties of super fluid, understand the concept of super fluidity, also understand about various effects which we talked about in today's lecture, we have got thermomechanical, mechanocaloric, fountain effect, Rollin film, etcetera. Why do they occur is the most important thing; what is the property that governs this effect. Also we talked about the super fluid helium and its effect, we talked about sound propagation through super fluid also, we have got a first sound, second sound, third sound and now zero sound is being studied or being researched as far as super fluid helium is concerned. Lastly, we talked about helium – 3, we talked about the phase diagram of helium – 3, we talked about the separation of helium - 3 below 0.8 kelvin, we talked about TCP temperature over there alright and we talked about the usage of helium - 3 in this.

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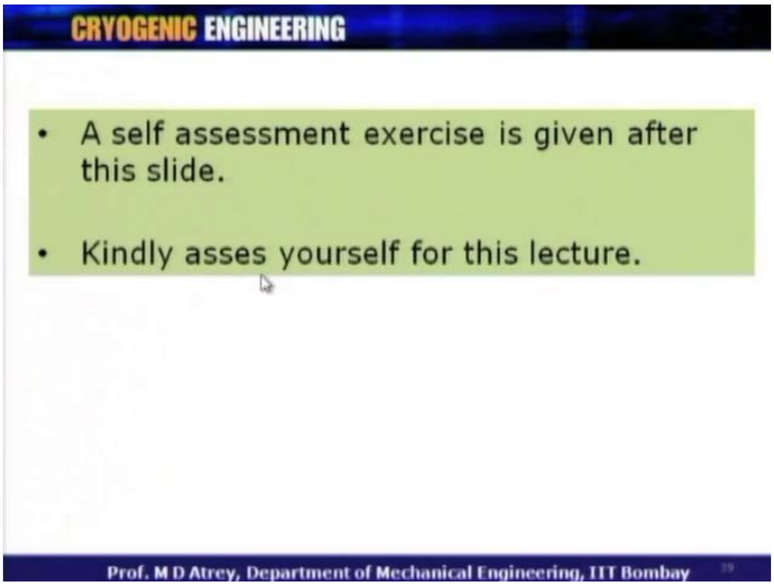

Finally, here I would again like to emphasize that there is a self assessment exercise given after this slide. I would like you to asses yourself based on the understanding of all the three lectures and this lecture also. Please asses yourself and try to solve all the problems given over here.

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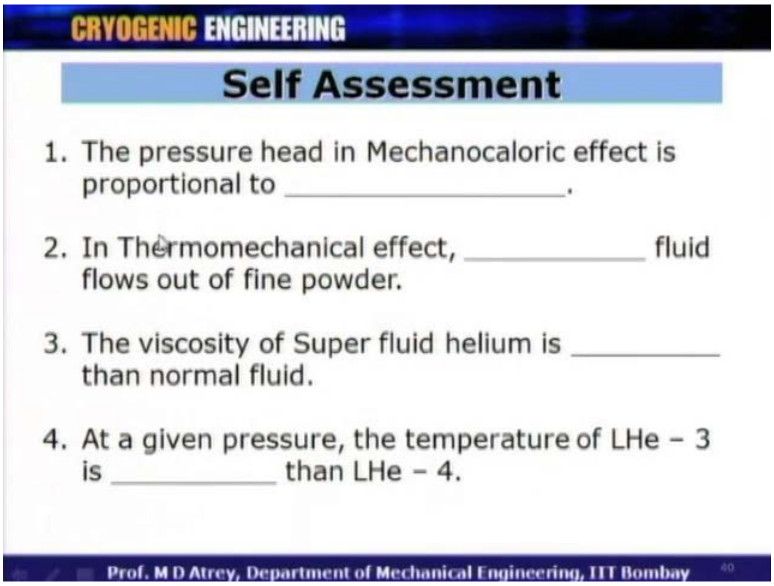

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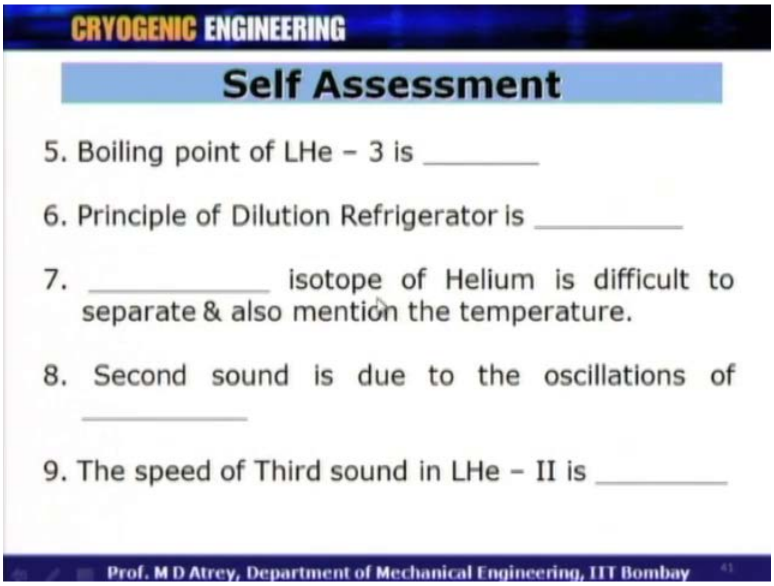

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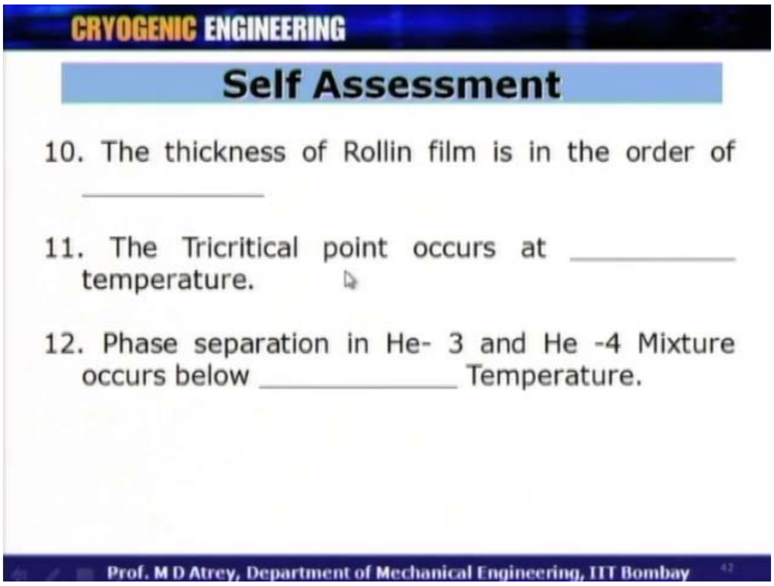

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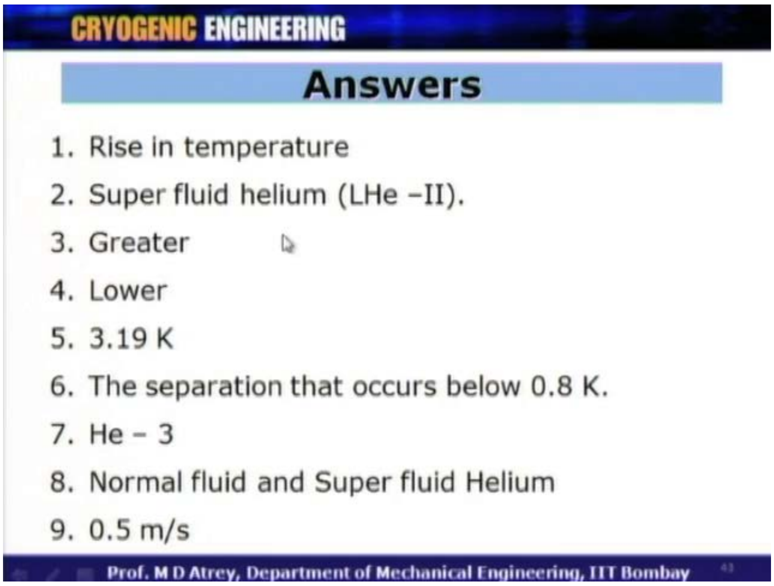

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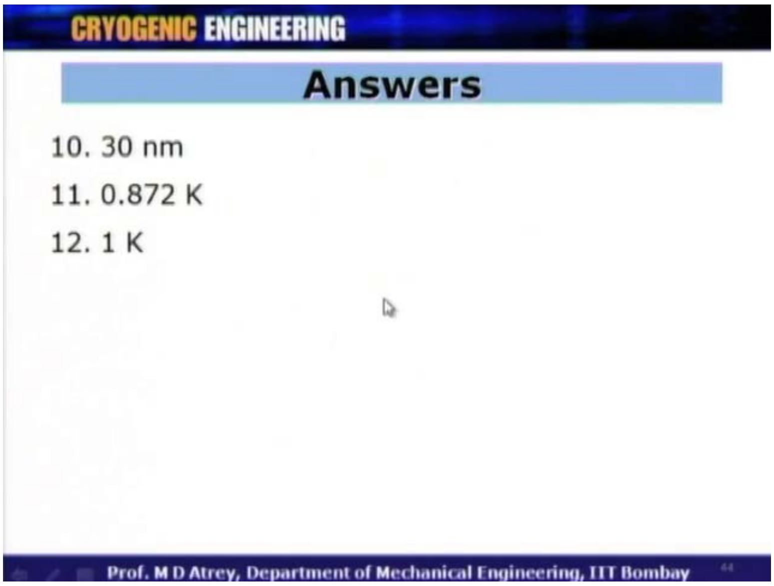

So, we have given 1, 2, 3, 4 and lot of problems over here what you can is the do the self assessment for yourself and the answers are given at the end.