Cryogenic Engineering
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Lecture No. # 35
Cryogenic Insulation

So, welcome to the thirty fifth lecture of cryogenic engineering under the NPTEL program. In the earlier lecture, I had covered the part regarding insulation and we are continuing the earlier lecture only regarding insulation in cryogenic engineering.

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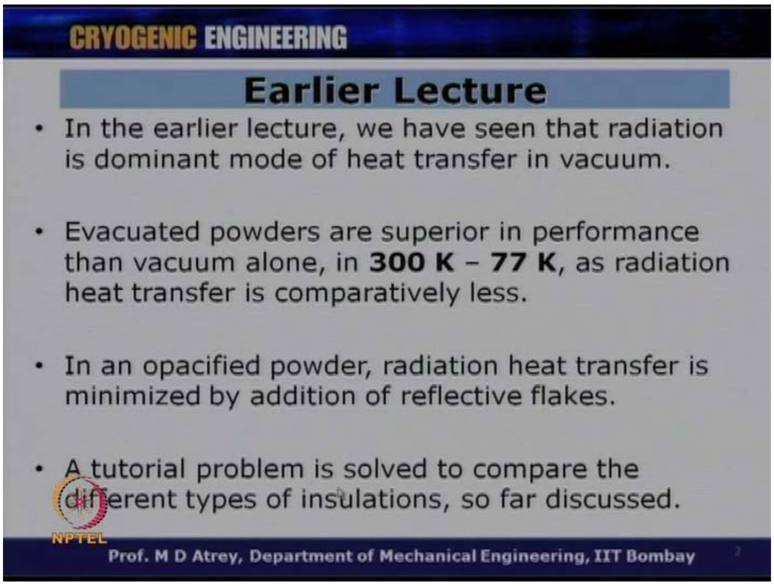

So, in the earlier lecture, we have seen that radiation is dominant mode of heat transfer in vacuum. We found that evacuated powders are superior in performance than vacuum alone in the range of temperature which is 300 kelvin to 77 kelvin. That means still liquid nitrogen temperature. And later, we found that radiation dominants. So, in this range as radiation heat transfer is comparatively less alright. But below 77 will it be found that the radiation takes over and therefore, we will have to look for other ways of insulation in those cases. Also we found that in an opacified powder, radiation heat transfer is minimized by addition of reflective flakes. Because of the presence of this reflective flakes, the radiation heat transfer is minimized and therefore, this we found was beneficial as compare to the evacuated powder. However, we talked about various disadvantages of having flakes also.

And then we had taken a tutorial problem, in order to understand the effect of various insulations we had understood till then. So, a tutorial problem is solved to compare different types of insulation, so far discussed. And what I want to do now is basically continue with this problem, and then you know take away from that problem and basically bring about the importance for new insulation that could be use for lower and lower temperatures.

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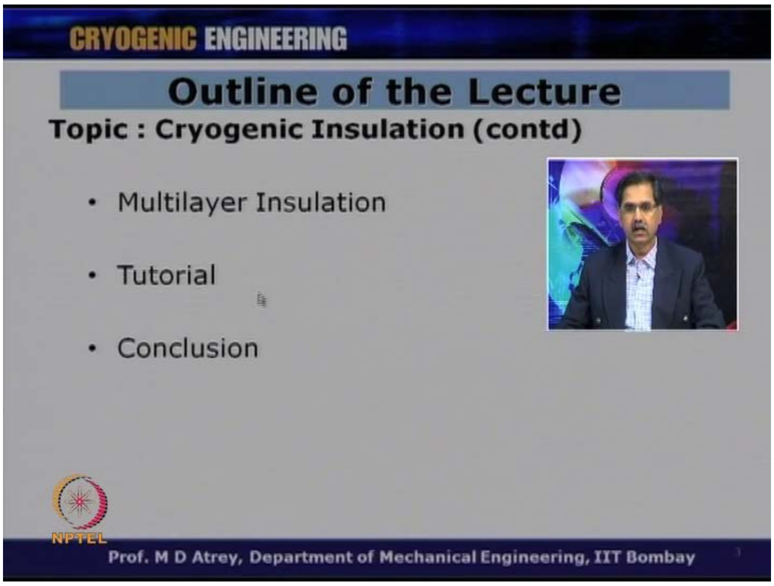

So, in this particular lecture, we will talk about multilayer insulation which is a very important insulation in cryogenic engineering. And then I will take a tutorial to cover or understand what this multilayer insulations, calculations are all about and we can take a some cases or some studies regarding those. And finally, will conclude the this particular topic of cryogenic insulation alright.

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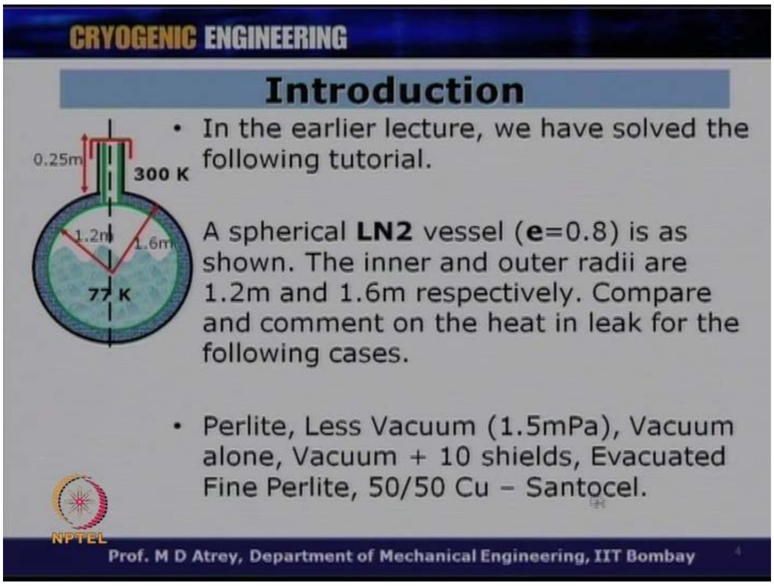

So, in the earlier lecture, we have solved the fallowing tutorial and I will now go through that tutorial will find what results we had got, and then I would extend that particular tutorial to understand the need of multilayer insulation alright. So, let us look at this problem. So, this was the problem basically, where we had a 77 kelvin or liquid nitrogen bath or liquid nitrogen cryogen inside, and this is 300 K outside, and we had a small cryostats spherical in nature, and we had this dimension 1.6 meter outside diameter, 1.2 inside diameter. And this is just for a academic purpose basically, and we are not bothering to calculate the neck conduction. We just want to calculate the heat in leak that is happening, because of the insulation material.

So, a spherical LN2 vessel, emissivity given as 0.8 is as shown over here. The inner and outer radii are 1.2 meter and 1.6 meter respectively. Compare and comment on the heat in leak for the following cases. And the following cases were basically the insulation cases, when we had perlite as insulation between this outside 1.6 meter and 1.2 meter radii. We had a less vacuum case; we had only 1.5 mpa vacuum case. Then we had a good vacuum or vacuum alone, perfect vacuum we can say. Then we had a vacuum plus 10 shields, we had evacuated fine perlite, we had a 50 by 50 copper - santocel as a pacified powder. And then we had computed the heat in leak for all this possible insulations and result was as given over here.

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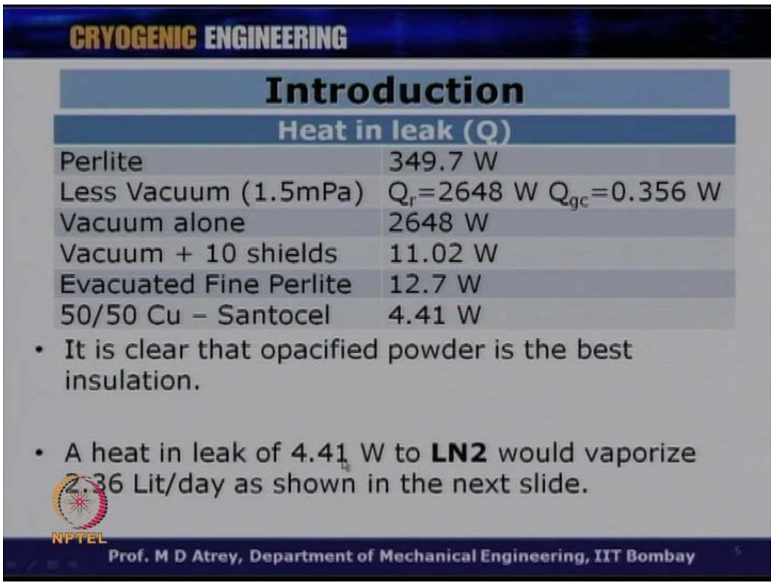

So, we had a perlite powder, we had 349.7 watt as heat in leak. We had less vacuum then we had lot of radiation heat transfer happening, because there was no medium inside, they was basically only vacuum. So, 2648 watts where the loss due to radiation and we had a free molecular conduction also which is just 0.356 watts which is actually can be neglected, because it is very small amount as compare to the value of Q r. When we had vacuum alone was 2648 watts, then we had vacuum plus 10 shield we had only a 11.02 watts as heat in leak. But then we talked about that it is not very simple to have 10 shields in a cryostat, because it will increase the weights and thing like that. Then we had evacuated fine perlite which is giving you only 12 watts as heat in leak. And when we had a opacified powder with copper flux or what is we call as a trade name of santocel we had only 4.41 watts as heat in leak in this cases.

So, it is clear that opacifeid powder is the best insulation to this. So, we say that now, we could minimize the heat in leak for 77 kelvin or liquid nitrogen kelvin case. And we found that opacified powder was the best candidate followed by fine perlite, assuming that vacuum plus 10 shield is not a very practical solution. So, we can go for one of this two cases as insulation for a liquid nitrogen cryostat or a container.

So, a heat in leak of 4.41 watts to LN2 to liquid nitrogen would vaporize around 2.36 liters per day as shown in the next slide. So, it is not go in to evaporate lot of liquid nitrogen alright; 2.36 liter per day is a reasonably conservative estimate. If 4.41 watts of heat in leak is incident, it is coming on the liquid nitrogen cryostat. How did we calculate this? We can do some algebraic computation to arrive at this rate of evaporation of liquid nitrogen and a very important to see how we calculated this. Because this will be useful tool for various calculations further, and therefore, I will show this simple calculation.

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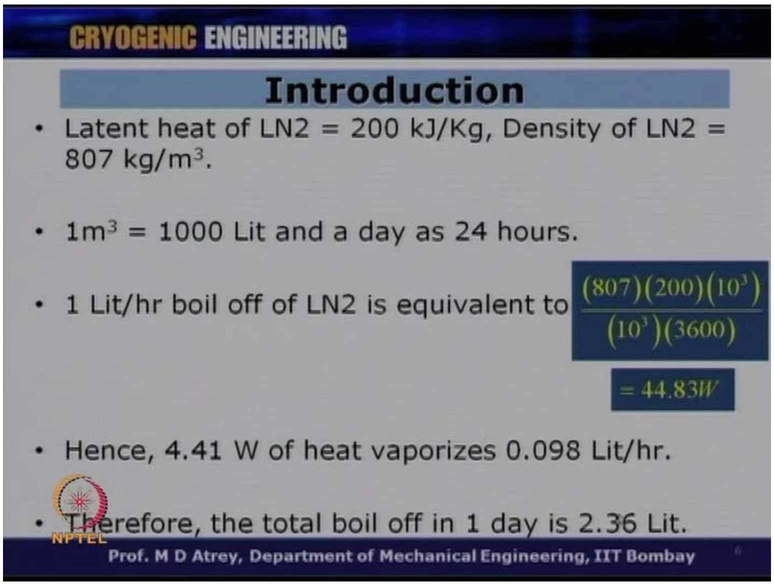

So, if you want to calculate the amount of heat, it is a evaporated, because of the incident heat in leak. We know the latent heat of liquid nitrogen is around 200 kilo joule per kg, while density of liquid nitrogen is 807 kg per meter cube. We know that 1 meter cube is equal to 1000 liter and 1 day has 24 hours. So, if I want to calculate the boil of required for 1 liter per hour; if I have got a boil off of 1 liter per hour of liquid nitrogen, let us calculate how much watts of heat in leak should be there, how many watts should be coming on the liquid nitrogen path. So, that the resultant boil off is around 1 liter per hour.

So, if I got a 1 liter per hour boil off of liquid nitrogen, it is equivalent to, let us convert is 1 liter per hour to 1 kg per hour alright. So, that we can rope in the density of liquid nitrogen also and this amounts to this. So, I have got a 1 liter per hour that means 1 by 10000 liter meter cube here. If I want to 1 meter cube is equal to 1000 liter cube that means 1 liter equal to 1 upon 10000 meter cube which is this 10 to the power 3 multiplied by its density which is 807 kg per meter cube alright. That means you will get so many kg now in 1 liter multiplied by so much of kilo joule per kg is the latent heat.

So, in order to evaporate the 1 liter will have to have 200 kg kilo joule per kg as a latent heat part alright and then we got a per hour. So, we want to basically convert this per hour 3600. So, we get now per second, because we want to gets watts. And this is kilo joule and that is why we have got 10 to the power 3 here.

So, this will amount to so many of watts which are responsible to cause a boil off of 1 liter per hour alright and these amounts to 44.83 watts. So, what is what is it mean? If you got a heat in leak of 44.83 watts it will amount to 1 liter per hour boil off of liquid nitrogen. So, if you have a boil of 4.41 watt which is what we calculated earlier, it would result in a boil off of 0.098 liters per hour which is very small and which is very very much acceptable. So, in 1 hour will have 0.098 or 98 cc per hour as boil off of liquid nitrogen. Therefore, the total boil off in 1 day if you multiplied by 24 hours will be 2.36 liters per day which is again acceptable solution.

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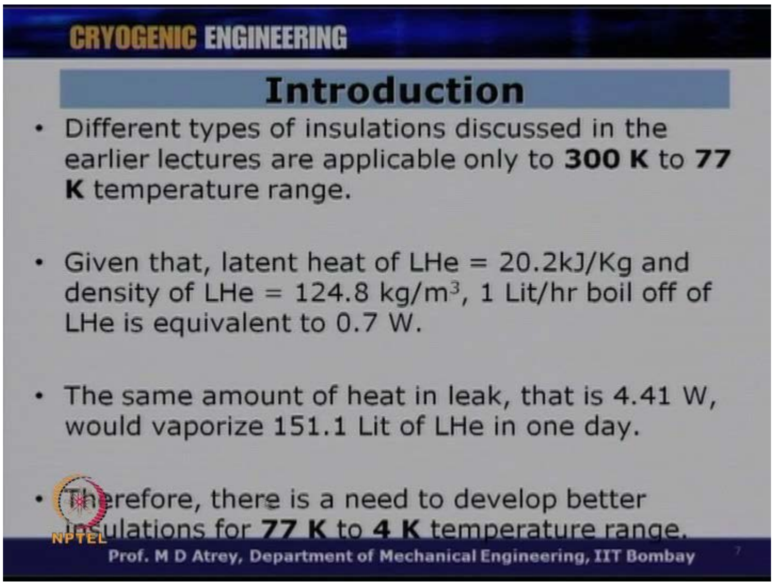

Taking it ahead; different types of insulation discussed in the earlier lectures are applicable only to 300 K to 77 kelvin. We found that all this insulations calculation what we had done where up to 300 K to 77 kelvin. However, if I want to now understand what is my insulation for liquid helium; let us see the gravity, if I got a same amount of heat in leak coming for liquid helium how much boil off will occur for liquid helium now. So, given that latent heat of helium is only 20.2 kilo joule as against 200 for liquid nitrogen. So, you can understand the latent heat is very, very small and therefore, smallest amount of heat in leak will cause lot of helium to boil off. And its density is 124.8 kg per meter cube. So, if I want to do the same calculations now, I can repeat those calculations for liquid helium, and 1 liter per hour boil off now for liquid helium will be equivalent to only 0.7 watt.

So, understand this figure, for nitrogen it was 44.7 watts would result in a boil off of 1 liter per hour. While for helium 0.7 watts of heat in leak would result in boil off of 1 liter per hour and that is because we are talking about the latent heat is almost 10 Times less as compare to that of liquid nitrogen. At the same Time we have got a density which is much smaller for liquid helium as compare to that of nitrogen. And because of this will have only 0.7 watts required or 700 milli watts requirement to cause a boil off of 1 liter per hour of liquid helium. That means what I want to show basically here is the smallest heat in leak will cause liquid helium boil off.

Now, if we take the same amount of heat in leak as that was present for liquid nitrogen case. The same amount of heat in leak that is 4.41 watt. If that is incident now for liquid helium, it would vaporize 151 of liters of liquid helium in 1 day alright. So, what was 2 liters only per day, now suddenly become 151.1 liter of liquid helium in 1 day which is not at all acceptable. Looking at the cost of liquid helium, looking at the cost associated with the liquefaction of liquid helium, having a boil off of around 151.1 liter per day is not acceptable at all. And therefore, what is understandable from this that opacified powder, perlite powder may not be good insulations for liquid helium.

And therefore, will have to go for something else for liquid helium. What was good for liquid nitrogen is not good enough for liquid helium. That is what we want to basically learn from this. If I have got a heat in leak of 4.41 watt at 4.2 kelvin it would cause such a big boil off which is acceptable at all in cryogenic engineering. Therefore, there is a need to develop better insulations for now a case, let us say 77 kelvin to 4 kelvin or at 4 kelvin temperature levels. That is why we are going to now multilayer insulation.

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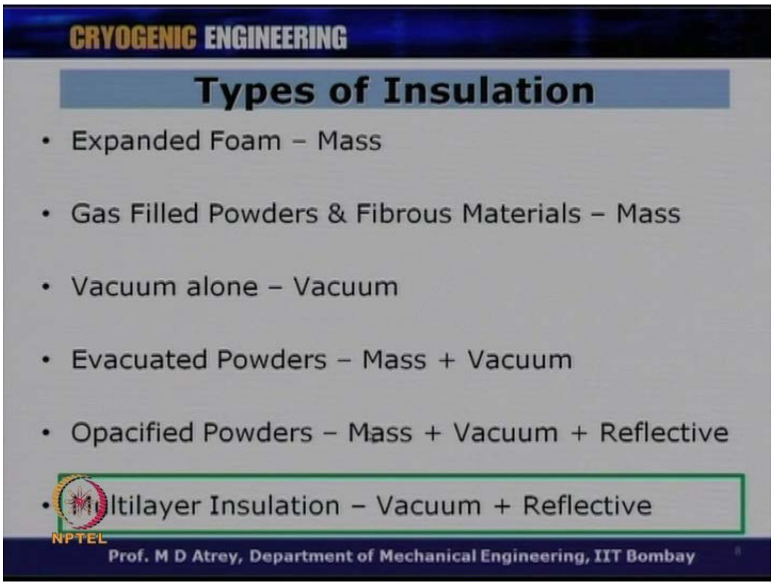

So, these where the insulation which we had talked about of which we had studied all this first 5 cases; what we are going to learn now is about multilayer insulation; which basically have vacuum, which works in vacuum and also which has got a reflective medium also. So, right. So, here we will talk about multilayer insulation now in this particular lecture. So, let us see what is this multilayer insulation is all about.

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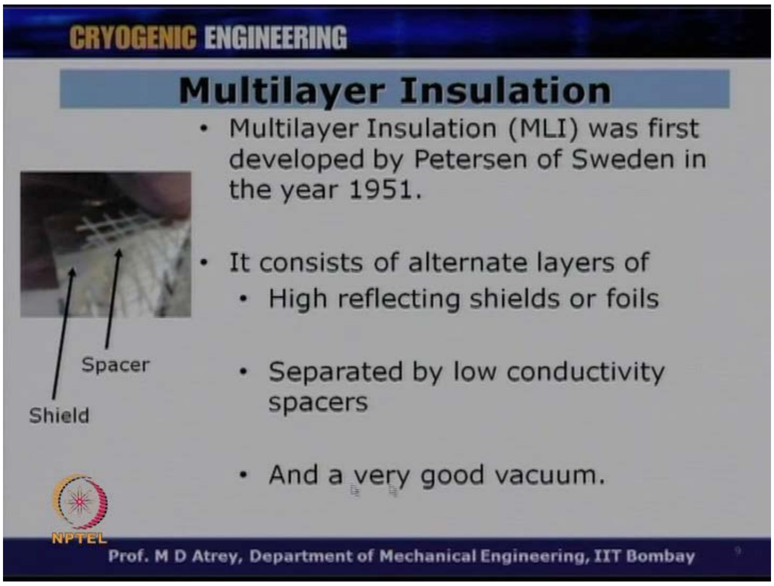

So, multilayer insulation was first developed by Petersen of Sweden in year 1951, and as I have shown the figure over here. It consists of alternate layers of high reflective shields of foil here. We can see here that the high reflective shield or foils. And we have got a spacer material it is separated by low conductivity spacer. So, multilayer insulations are different layers put together and each layer would consist of high reflective shield or foil which will take care of radiation. While the next layer, in between the 2 layers what we have is a kind of spacer which is separated by low conductivity spacer. So, I just would like to show you, I got a sample to show you here. So, this is what a multilayer insulation would look like. You got a highly reflective multilayer insulation or a shield over here. And if I open this, you can see that it is separated by some kind of a nylon net which is followed by again multilayer. So, you can see so many layers separated by a spacer and this spacer is basically a non conductive spacer alright.

So, you got a various layer separated by spacer and they are stacked the entire thing will be stacked around the cryostat or liquid helium container or liquid nitrogen container. So, you can see several layers coming together, each of them is separated by a spacer fallowed by reflective material alright and this is what constitute a multilayer insulation alright.

So, as I just show you, it has it consist of a alternate layers of highly reflecting shields or foils separated by low conductivity spacer and a very good vacuum now. This is applicable, multilayer insulation can work only when you got a very good vacuum. That means we do not have any gaseous presence - any gas presence over there. No molecular conduction, no free molecular conduction, no convection, if we are insure that no conduction and convection then only multilayer insulation will be effective otherwise they will not be .

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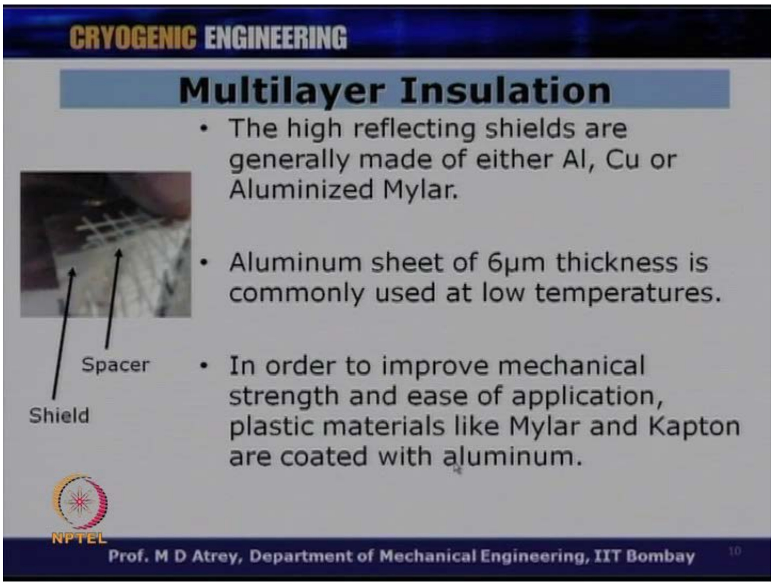

The high reflecting shields are generally made up of Aluminum, Copper or Aluminized Mylar. The aluminum sheet of 6 micrometer thickness is commonly used at low temperatures. So, we can see the thickness is very, very small. In order to improve mechanical strength and ease of application, plastic materials like Mylar and Kapton are coated with aluminum. So, aluminum is coated with some kind of a Mylar material in order to get strength. So, that they are put vertically down in the cryostat or containers.

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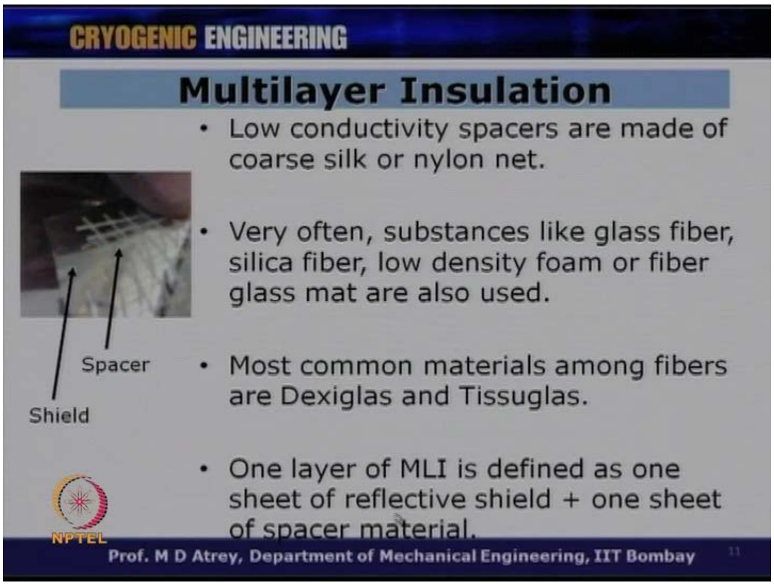

Low conductivity spacers are made of coarse silk or nylon net. I just showed you this spacer material. Very often, substances like glass fiber, silica fiber, low density foam or fiber glass mat are also used. This spacer could be of any types alright. Most common material among fibers are Dexiglas and Tissuglas. These are basically the trade names for the spacer, normally Dexiglas could be used for such multilayer insulation or nylon net could be use for such multilayer insulations. One layer of multilayer insulation normally short form as MLI is defined as one sheet of reflective shield plus one sheet of spacer material and this is what I just shown to you.

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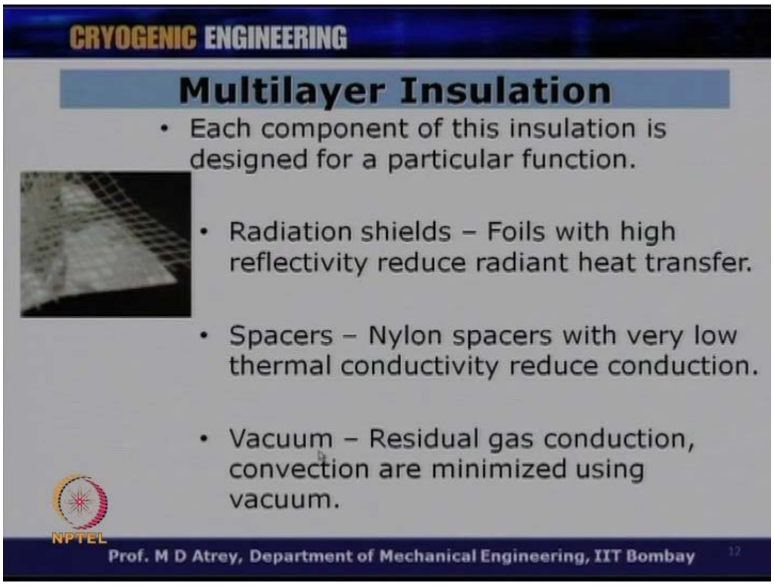

Each component of this insulation is designed for a particular function alright. What are different functions? We got a radiation shields - radiation shield or foils with high reflectivity it will reduce the radiation heat transfer. So, the highly reflective material, we found that highly polished material is basically take care of radiation heat transfer. The spacer which would be nylon spacer with very low thermal conductivity it reduces conduction. So, whatever solid conduction may have, because we have got this layers put in the form of layers and these layers do not the radiation shield do not touch each other each other, basically they are you know spaced across a spacer and this spacer is of low thermal conductivity, and this will take care of the solid conduction. And therefore, these are very important component of multilayer insulation.

And we have got a vacuum, because I have said that multilayer insulation works only in the presence of vacuum and good vacuum, and this vacuum is take care of residual gas conduction, convection, is going to be minimize, because of this vacuum. These are very important three aspects of multilayer insulation.

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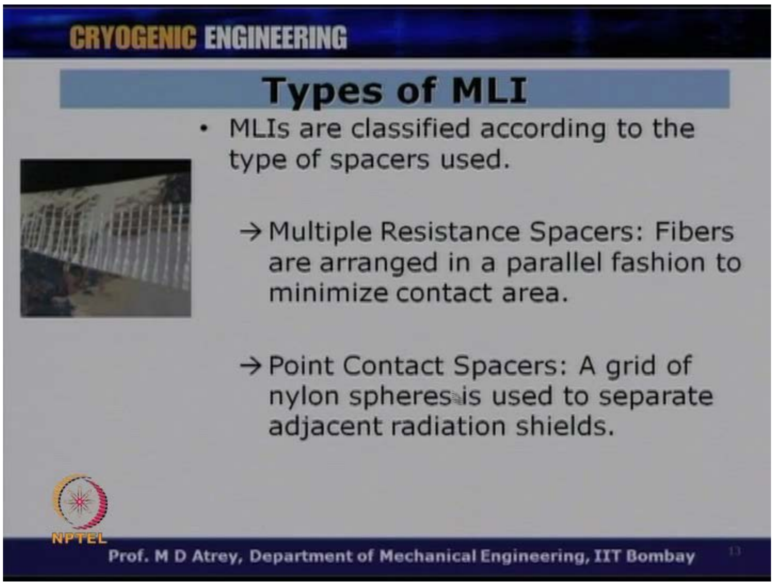

So, what are different types of multilayer insulation? Let us have a look at this point. So, multilayer insulation are classified according to the type of spacers used; one can have different classification, but I am going to show is basically the classification made depending on the spacer that are used in the multilayer insulation insulation. So, you can see the multilayer insulation is first type is multiple resistance spacers. So, you have got a different types of spacers and they got a multiple resistance aspect associated with. What is it? It is the fibers are arranged in a parallel fashion to minimize contact area as shown in this figure. I can show the same thing to you. So, you can see the same thing over here.

So, you can have a spacer basically which is having. The spacers are arrange in a kind of the parallel and then you got a reflective surface. And then again fallowed by the spacer and again fallowed by the things. So, this is what the first type. So, multiple resistance spacers I just showed you; fibers are arranged in a parallel fashion to minimize contact area. Then we have got a point contact spacer, I do not have that sample. A grid of nylon spheres is used to separate adjacent radiation shields. So, this is different type of spacer.

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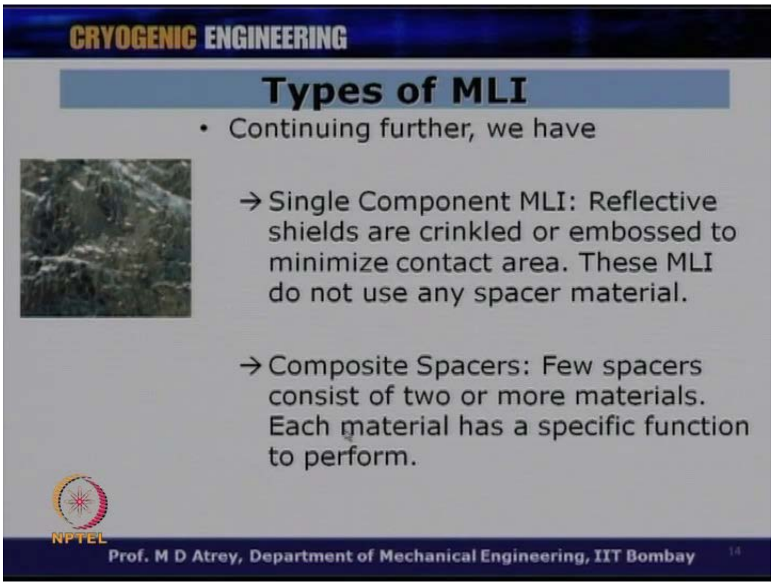

Continuing further, what we have is a single component MLI. The reflective shields are crinkled or embossed to minimize contact area. Instead of having the plane reflective surface, you got a crinkled that means point touches, in order to basically minimize the solid conduction we have got a crinkled surface of material insulation. And in this case we do not use any spacer material. So, I just want to show it here also. So, this is (( )). You got a crinkling done at various point and the multilayer insulation touches each other at only those points. This will basically minimize the solid conduction part and you can see that we do not have any spacer in this. So, basically they avoid crinkle surface alright. There is no spacer used in this case. The multilayer insulation will touch each other only at those spots which is where it crinkled. It will not have a continuous contact, it will not have a area contact, it will have only point contact which is what is responsible for minimizing the solid conduction, which otherwise was taken care in the earlier case was by the net or by the spacer. So, this is called crinkled material insulation or single component multilayer insulation. This is also shown in the figure over here.

And then we have got a composite spacers. In this case, we can have different materials. So, composites spacers few spacers consist of two or more materials, each material has specific function to perform. So, we can have different spacer material also which will have its requirement as per in the applications alright. But I am not come across this spacers being use normally. It is the very special case where some basic expectations are there in terms of it must be conductivity or some other function we can use different material as spacer at different points. So, these are different types of material insulations.

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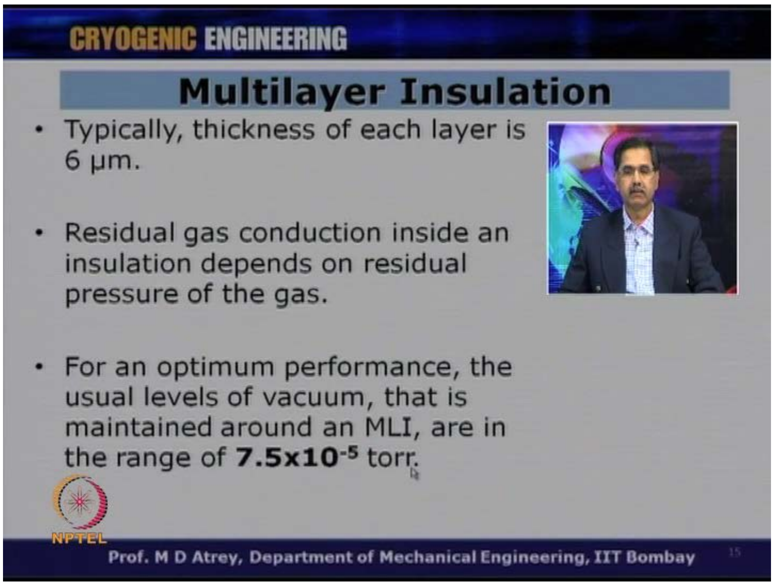

Typically, thickness of each layer is around 6 micrometer. So, this is what we earlier also talked about. Then the residual gas conduction inside an insulation depends on residual pressure of the gas. So, we are saying that we are in a much better vacuum now. And therefore, the residual gas conduction is absolutely minimum as which could be which could be consider 0 in this cases. So, multilayer insulation works only we got a when we got a perfect vacuum alright. For an optimum performance, the usual level of vacuum that is maintained around an MLI, are in the range of 7.5 into 10 to the power minus 5 torr. So, this is the vacuum level which is acceptable for multilayer insulation. You should not have minus 3 or minus 2 torr vacuum level; you should have minus 5 and below as acceptable vacuum for multilayer insulation to be effective.

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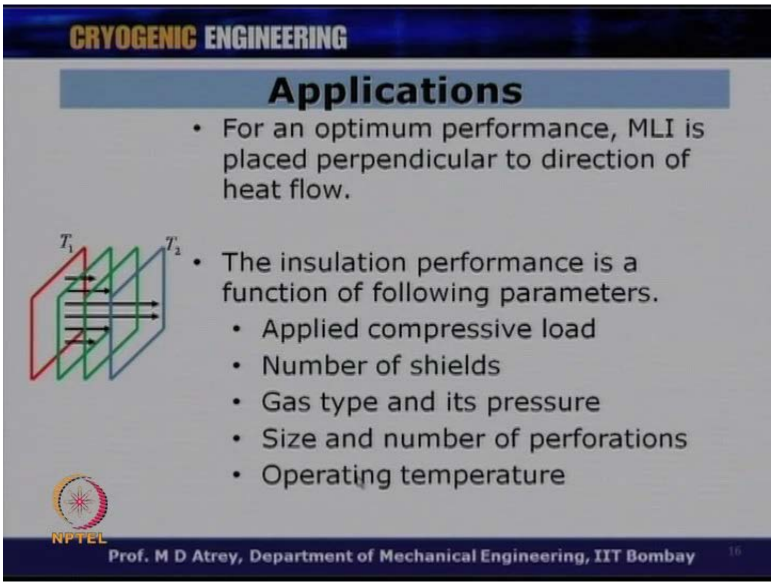

So, if I want to apply multilayer insulation now, for an optimum performance, multilayer insulation is placed perpendicular to direction of heat flow. So, you got a direction of heat flow like this multilayer's will be kept across, it perpendicular to the direction of the flow in this fashion, T 1 and T 2, T 1 is the high temperature, T 2 is the lower temperature. It would rush from T 1 to T 2, and there will several multilayer insulation which would take care of this, which will not laid this Q go inside. So, this place perpendicular to the direction of heat flow.

The insulation performance is a function of following parameters. The insulation will vary the performer could be dependent on various parameters and what are this parameters. Applied compressive load, if the multilayer insulations are compress too much then the conductance parameter will change and more compressive load would result in heat loss. So, you will have more Q going inside if you have got a more compressive load. So, we should keep minimum compressive load just just to make sure that this multilayer insulations stack, you know stands for vertical. And therefore, for that we will have to have some compressive load, but that should be kept as minimum as possible.

Number of shields: Now, it is a very important component and I will touch upon this component later; just to tell you the point that number of Shield is a very important parameter and will be optimum number of shields; for a particular application, for a particular size, will have an optimum number of shields that has to be taken into account and only so many shields have to be use. Normally it could be 20, 30 or fourties 40 layers per inch or in centimeter that could be given else; 40 layers per centimeter, 50 layer per centimeter that is what could be optimum number of insulations shields for a given application.

Then gas type of and its pressure; we just talked about what kind of gas could be there and what kind of pressures we talking about, we should have a perfect vacuum, and therefore, we should have any gas. If at all gas is there, its conductivity should be as minimum as possible. We have said that depending on the gas type it should be have no free molecular conduction and therefore, we should have perfect vacuum maintained in multilayer insulation.

The size and number of perforations; if at all number of perforations are maintained on the in the insulation it should ensure that a good vacuum is present between 2 layers of insulations also. So, having insulation, but what will be the vacuum between the 2 layers in order to have a good vacuum between the 2 layers of insulation, we should have some perforations on the insulation. Because of which the gas there could be sucked out by to maintain a good vacuum. And therefore, number perforations also will make a difference. And of course operating temperature, because operating temperature will determine how much gives incident due to radiation and how much Q will be there, because of which the solid conduction also would take place. So, less delta T that is what could be preferred earlier.

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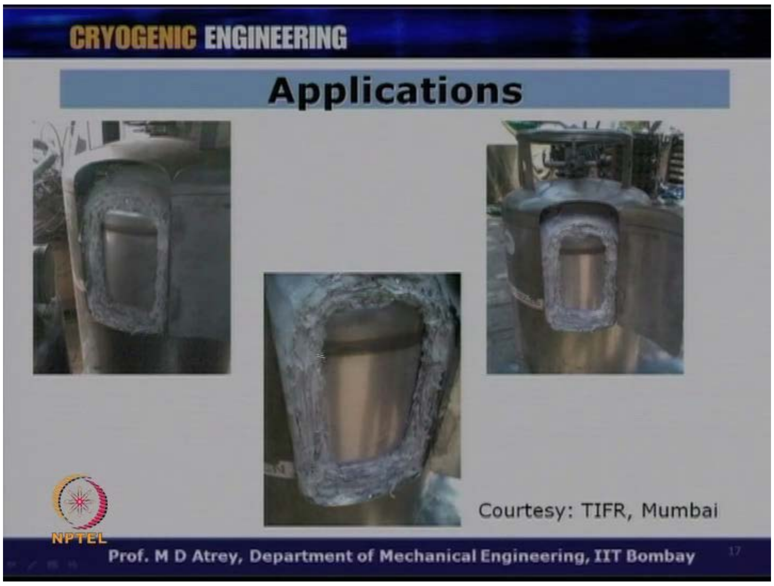

So, just to show how it is applied, I have got photographs, courtesy TIFR, Mumbai. We can see liquid helium or liquid nitrogen whatever devour we are talking about. This is inner vessel and this is outer vessel, and we can see the gap in between is filled with with the multilayer insulation put from top to bottom on the top as well as on the bottom side. So, you can see various number of, so many layers of multilayer insulations are kept in the gap from outer vessel to the inner vessel from 300 kelvin to 77 kelvin or 4.2 kelvin whatever this content is made for.

So, you can see very nicely how they are stacked. Now, stacking of multilayer insulation also is an art, how do you keep, how do you put them over the inner vessel alright. So, it is a very important thing to arrange this multilayer decision nicely over the inner vessel. This is very important to understand how the multilayers are applied on the inner vessel.

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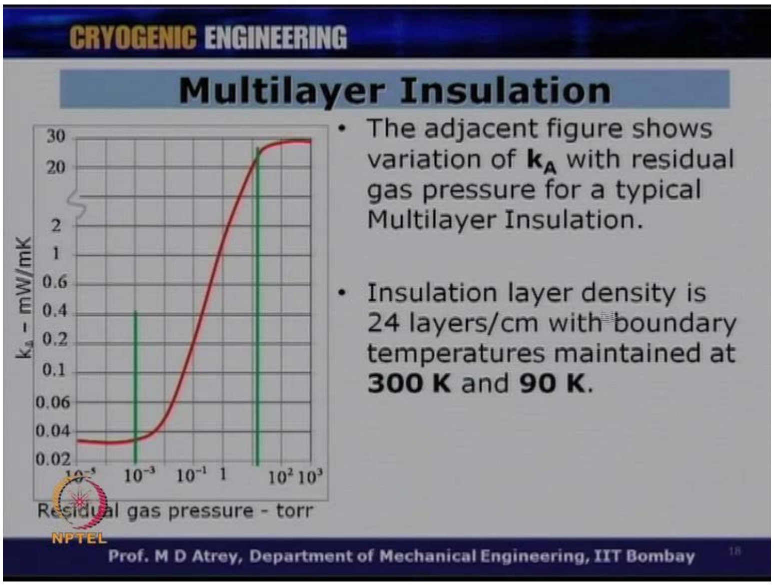

So, multilayer insulation now, the adjacent figure shows the variation of apparent thermal conductivity for multilayer insulation with residual gas pressure. So, basically this will tell you what is the effect of vacuum on the apparent thermal conductivity for a typical multilayer insulation. So, you can see that insulation layer density is 24 layers per centimeter in this case and a temperatures are 300 K and 90 K for which the values are given over here.

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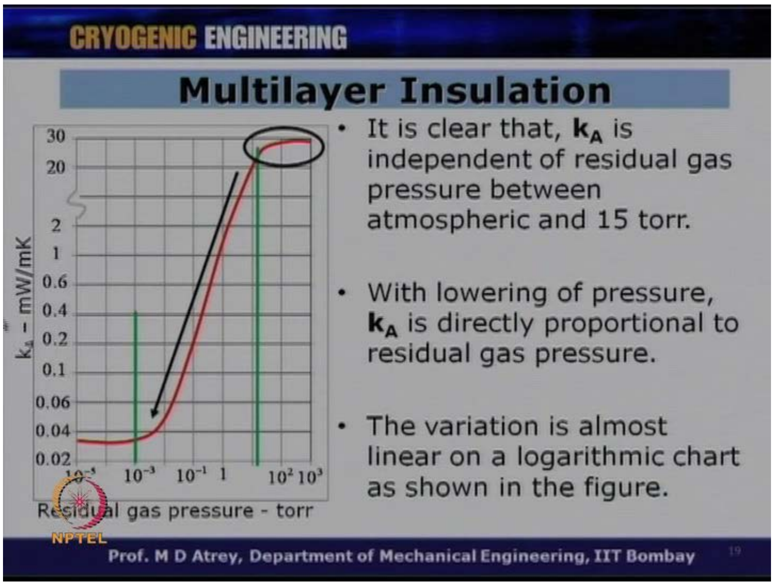

It is clear that K A is independent of residual gas pressure between atmospheric and 15 torr. You can see for this atmospheric condition, 215 torr K A is very high and therefore, multilayer insulation cannot be use in this in this pressure range. Because K A we want to basically minimize alright. So, in this case we cannot use multilayer insulation at all or if you use the apparent thermal conductivity is going to be very, very high. With the lowering of pressure now, if we reduce the pressure from let us say from 15 torr to 10 to the power minus 3 torr, K A linearly decreases. That is what we had seen earlier also in we can see it right now also. With lowering of pressure, K A is directly proportional to residual gas pressure. So, if become to 10 to the power minus 3 from 10 to the power 15 torr, K A will linearly get reduce from very high value upper on 20 or 30 to around 0.03 to 0.04. That is what we can see from here.

The variation is almost linear on a logarithmic chart as shown here. Now suddenly, as you reduce the pressure from 15 torr to 10 to the power minus 3 torr, value of K A will come down from 30 milli watt per meter kelvin to around 0.4 mill watt per meter kelvin. So, such a drastic reduction will happen as soon as you have a good vacuum now, and that shows that will basically make us realize the importance of vacuum to be maintain for multilayer insulation.

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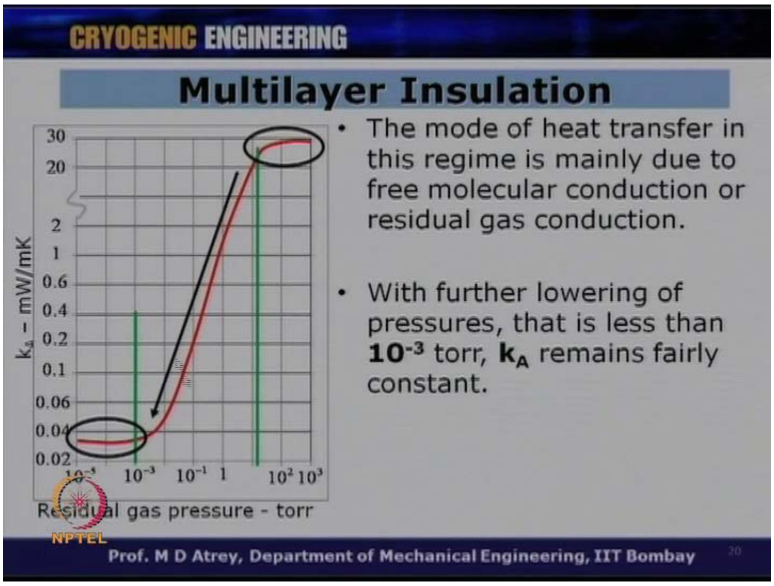

If you go further down from now; the mode of heat transfer in this region will be made mainly due to free molecular conduction or residual gas conduction alright. Radiation will be taken care of, because of multilayer insulation. But will have a gas conduction now which is very, very important to be minimize by lowering this vacuum.

With the further lowering of pressures now, if you come below 10 to the power minus 3 now, the K A value gets minimize which is around 0.03 milli watt per meter kelvin; K A remains fairly constant. That means will have to have multilayer insulation vacuum to be maintained below 10 to the power minus 3. So, we say normally minus 5 is the mostly acceptable vacuum pressure for application of multilayer insulation alright. So, this shows that if we are below minus 3 the multilayer insulation are best suited over here, while not in this range and not in this range definitely not in this range.

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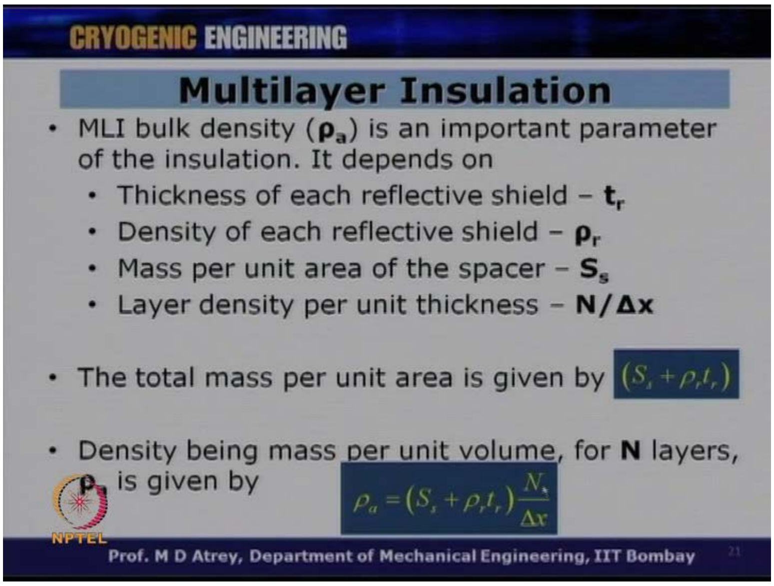

Now, multilayer insulation bulk density rho a is an important parameter of the insulation. And basically, now we have calculate how many multilayer insulation should be kept, what is this optimum multilayer insulation is this. So, the bulk density rho a is an important parameter and it will depend on various parameters like what is the thickness of each reflective shield. Suppose it is t r, the density of each reflective shield is going to be rho r that is the material of multilayer insulation coming into picture. Then mass per unit area that means kg per meter square of the spacer material which is S s alright. This is spacer material and this two are the reflective material, and the layer density which is a very important concept. So, layer density per unit thickness that means so many layers per centimeter per inch that is what normally this is refer to which is equal N upon delta x; delta x is the distance from outer to inner multilayer insulation.

So, how many number of layers will be there per centimeter or per inch which is what we call as layer density and this is very important concept as I just told you. So, total mass per unit area therefore, will be given as S s plus rho r t r. So, total mass per unit area be S s plus rho r t r. That will be total mass per unit area. Density being mass per unit volume, for N layers rho a will be given as rho a is equal to S s plus rho r t r into N upon delta x. For n layers, it will be N Time this divided by delta x. So, (( )) so many kg per meter cube will be what we call as bulk density or MLI bulk density. So, basically we will talk about N delta x N by delta x which is layer density and corresponding components are coming, because of the spacer material as well as in the reflective materials.

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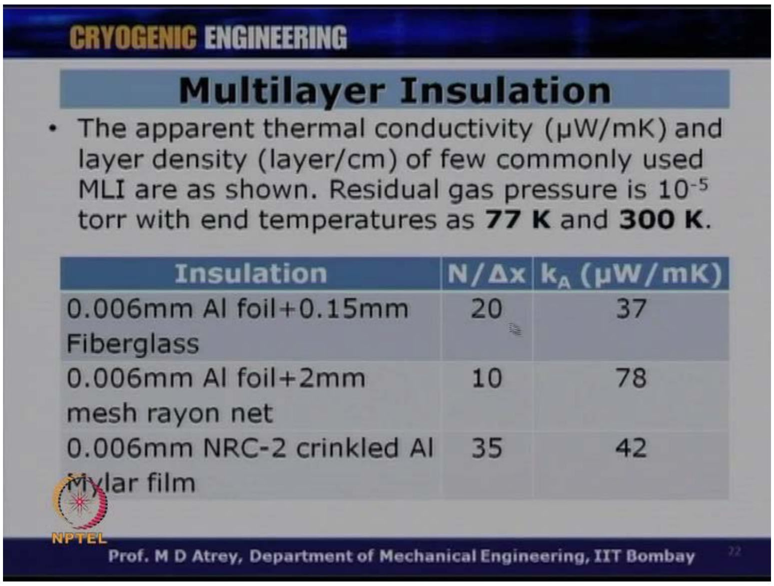

Now, the apparent thermal conductivity which could be in micro watts per meter kelvin for multilayer insulation and the layer density refer to as layers per centimeter of few commonly used MLI are as shown over here. The residual gas for this is 10 to the power minus 5 torr and the end temperatures are 300 to 77 kelvin as just shown over here. So, you can see now if I have got a 0.006 millimeter of aluminum foil and the pressure of 0.15 millimeter fiberglass pressure and a layer density of 20 layers per centimeter will have K A apparent thermal conductivity as 37 micro watts, 37 to 10 to the power minus

6 watt per meter Kelvin, such a low value, here as compare to any other earlier value if you see.

Similarly, if you got a pressure of rayon net will have different layer density for this material now. And we can have a K A value of 78 micro watts. Similarly, we can have NRC-2 crinkled Aluminize Mylar Film, we can have around 42 micro watts meter kelvin. So, you can see that we are talking about in micro watts 2 digit; that is my apparent thermal conductivity for a multilayer insulation.

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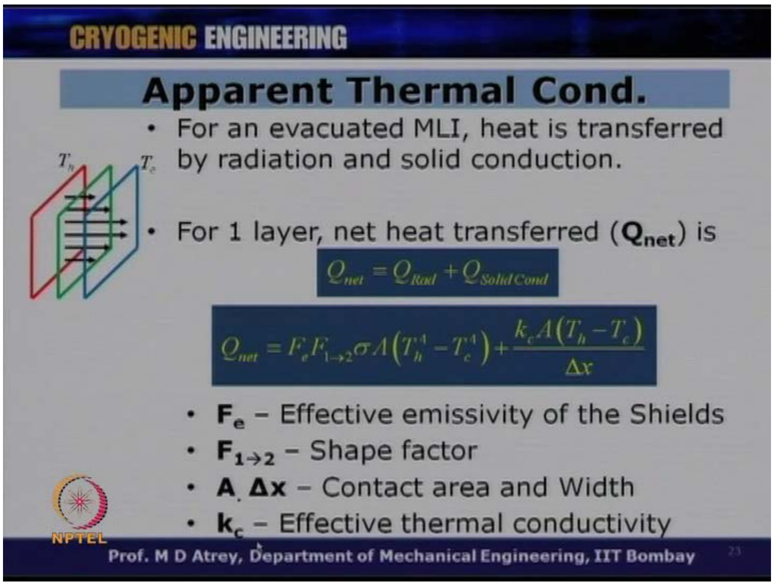

So, apparent thermal conductivity if I want to calculate for multilayer insulation now. For an evacuated MLI, heat is transferred by radiation and by solid conduction. Assuming that conduction, convection are taken care off; the gas convection and gas conduction has been taken care off. The only modes of heat transfer that could be present here is a radiation and solid conduction. The solid conduction will be more and more, if more and more multilayer insulation are put together in a given space of delta x.

So, for one layer, let us calculate net heat transferred as Q net as given as Q net is equal to Q radiation plus Q solid conduction. This is what one way we are talking about. So, we can put formula for it. So, Q net is going to be the formula for radiation now, similarly the formula for solid conduction alright. So, K c into a T h minus T x T c upon delta c; please refer that K c will depend on the number of layers also. This is going to be now effective thermal conductivity of the spacer material.

So, F e is a effective emissivity of the shield over here which is a radiation parameter. F 1 2 is a shape factor which normally we take as 1. While A and delta x are the contact area and the width here. And K c is a effective thermal conductivity of the spacer material or with the what is coming as thermal conductivity of the MLI basically. So, what we call refer to as solid conduction also here. But that will be function of how many layers are there. And therefore, K c is a parameter which will vary with number of shields, number of spacers materials also.

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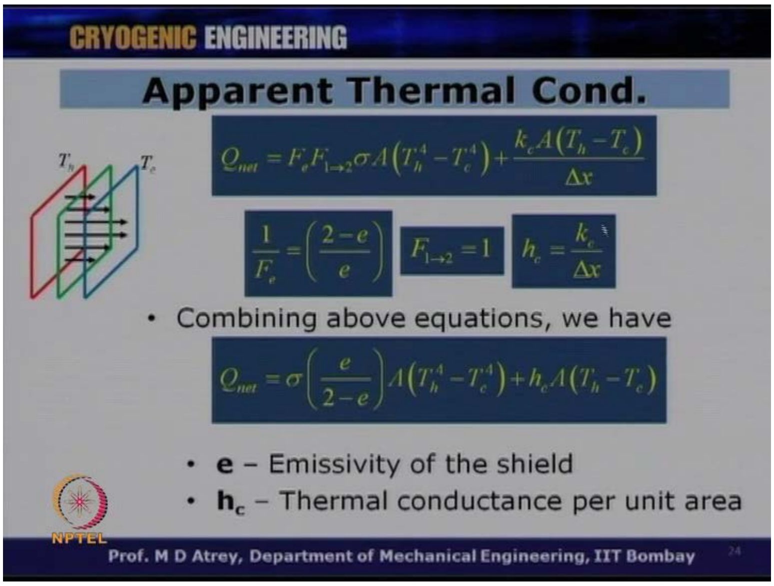

Extending this further, we can put the value of 1 upon F e as 2 minus e upon e, F 1 2 as 1 and as so. Referring h c taking k c upon delta x and h c which what we call as solid conductors. So, putting this values over here we get combining this equations I can put this. My Q net is equal to this parameter, h c into A into T h minus T c where e is the emissivity of the shield and h c - thermal conductance per unit area. So, I am just replacing h c as k c upon delta x, we found that k c also would vary with the number of layers or layer density. So, h c is thermal conductance per unit area.

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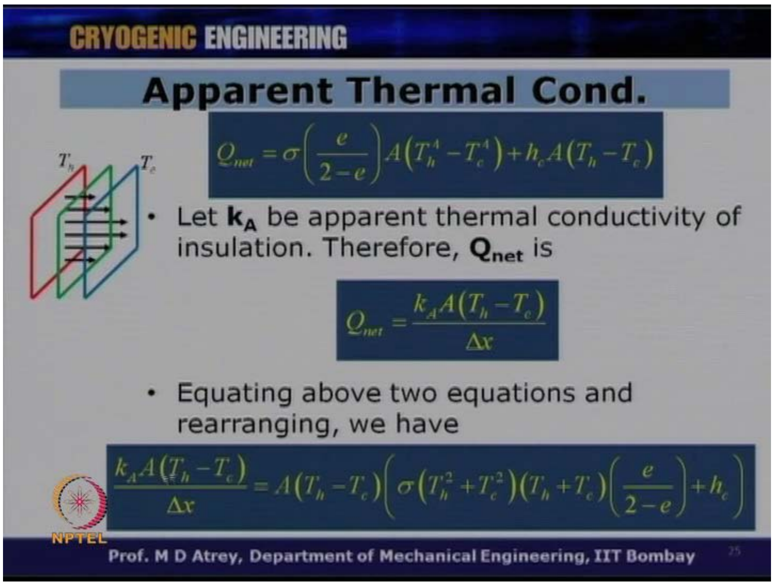

Let us now find out what is apparent thermal conductivity for multilayer insulation. Let k A be the apparent thermal conductivity of the multilayer insulation and therefore, Q net in this case is equal to k A into A into T h minus T c upon delta x. Equating this two parts I will say k A into A into T h minus T c upon delta x is equal to what Q net we got over here alright.

So, here we have got calculate now what is my apparent thermal conductivity for multilayer insulations. I would now like to calculate here multilayer insulation, and if we can see that we can get rid of this A into T h minus T c A into T h minus T c in both the sites. So, getting rid of A into T h minus T c and getting the value of k A now delta x would come on this side.

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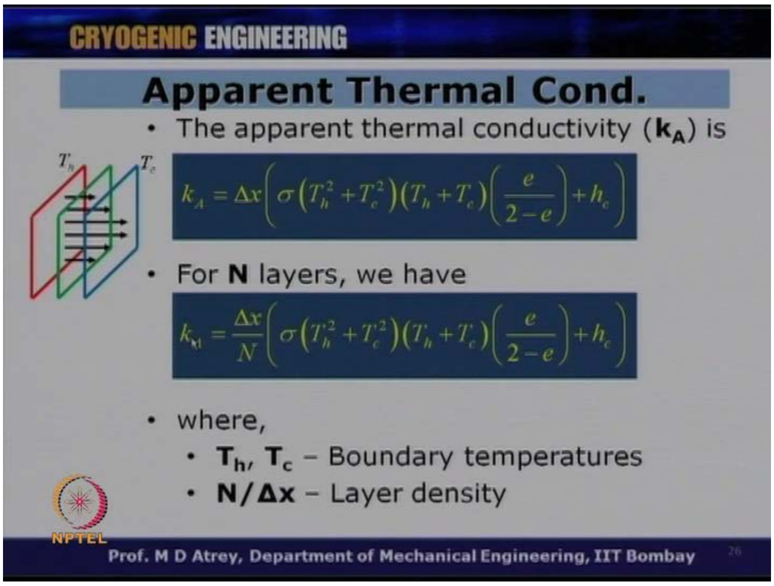

So, apparent thermal conductivity now is equal to k A is equal to delta x into the bracket and this bracket has the component due to radiation and due to solid conductors h c. So, for N layers now, will have k A is equal to delta x upon N sigma radiation component plus h c is going to be solid conductors. So, you can see now entire thing divided by layer density, we can say N by delta x which is my layer density, which will determine now the value of k A, where T h and T c as the boundary temperature, N by delta x N by delta x is the layer density. Now, let us see what happens to apparent thermal conductivity as a parameter of N by delta x and we can see that this curve is 0.

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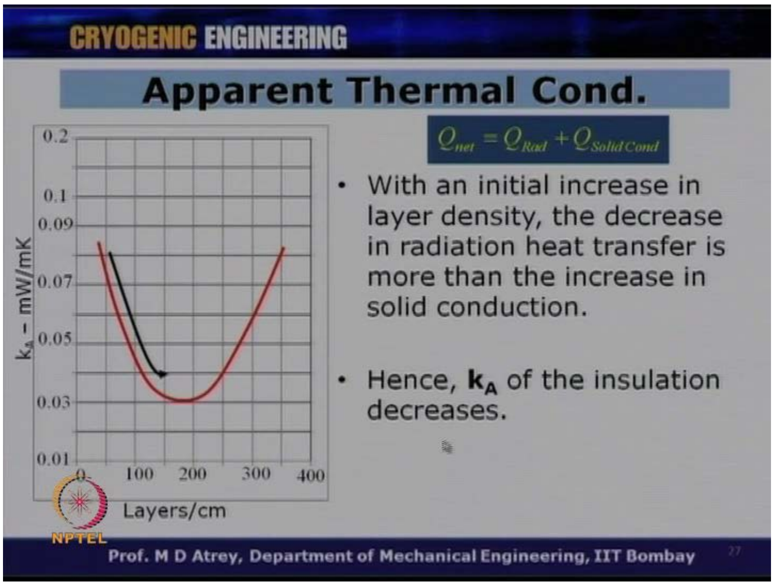

So, layers per centimeters given here which is nothing but N by delta x. Against which we found a apparent thermal conductivity and you can see that this kind of variation is shown. And we can see that at a particular number of layers per centimeter, we can have minimum k A value in milli watts per meter Kelvin. Why does it happen?

So, we know that Q net is equal to Q radiation plus Q solid conduction for multilayer insulation. If I go on increasing the number of layers if I go on increasing the number of layers here with the initial increase in the layer density, the decrease in radiation heat transfer is more than the increase in solid conduction. We know that if we go on increasing number of layers in a given centimeter in 1 centimeter we have 100 layers per centimeter for example. Will have so many layers that they will start touching each other and therefore, the solid conduction would start increasing.

So, as you go on increasing the number of layers, the radiation losses will reduce. But at the same Time, the solid conduction will start increasing alright. So, if we go on increasing N by delta x, initially your Q r will come down, but Q solid conduction would start increasing. But the decreasing Q r is going to be much more pronounce than the increase in Q solid conduction and therefore, initially we will have a decrease in the value of k A as we go on increase in the layer density. So, hence k A of the insulation decreases in this range.

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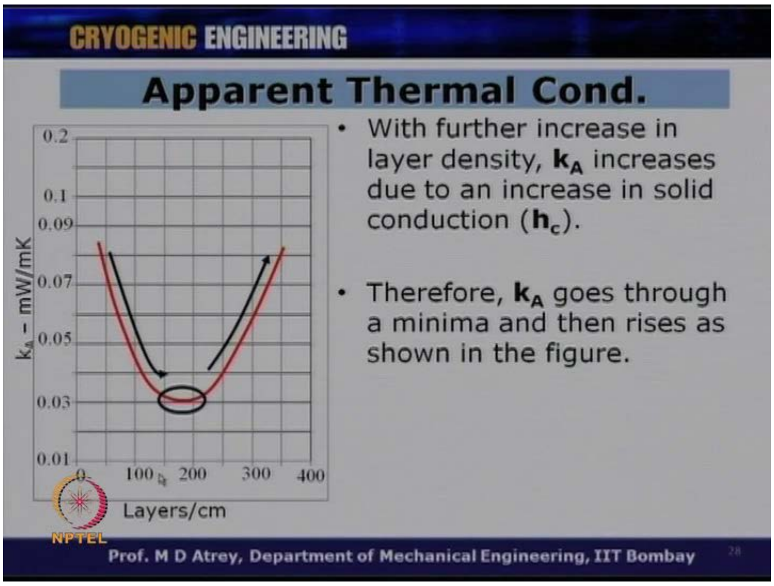

But if the layer density goes beyond a particular value with the further increase in layer density, K A increases due to increase in solid conduction. Because after sometimes there will be so many layers which will be touching each other now. That the solid conduction h c which depends on N by delta x will start increasing alright. So, in this case after some Time, after some number of some optimum number of layers per centimeter, this will start increasing, which means that initially it was decreasing, later are it is increasing. That means it will go through a minimum at some point in Time, at some layer density.

So therefore, k A goes through a minimum at and then it rises as shown in this figure. So, hour layer density should be kept as this minimum layer density. So, whatever is layer density, we should have minimum value of k A associated with that and that should be use for application. So, it is very important to understand that there is the concept of optimum layer density for multilayer insulation. In the initial case radiation get reduced, but solid conduction starts increasing. However, the radiation decrease is more than the increase due to solid conduction. But beyond this optimum point, the solid conduction increases much more than the decrease in radiation heat transfer. And therefore, it goes run optimum value of or the minimum value of k A corresponding to which you have got a optimum layer density. And for every application, we should find out what is this optimum layer density and that is what we should use of for calculation purpose. That is what we should we should use for application also.

So, with this concept of optimum number of layers to minimize the thermal the apparent thermal conductivity of multilayer insulation; we have now understood what is multilayer insulation, how does it work, how do we calculate the conductivity - apparent thermal conductivity of multilayer insulation, why does it have this optimum concept of number of layer density and also we found that what are different types of multilayer insulation and I just showed you different types of multilayer insulation also

In addition to that I got two numbers of multilayer insulation which I would like to show again before I will go and take a problem. So, you have got a… You can use only aluminum sheet also. So, some foils could be use alright. This is a thicker one and that also can be use as multilayer insulation which could be some Time separated by some kind of a glass fiber or but this is thicker one. This is also a different type and also I got a different type which is normally plain and you have got a different kind of spacer which you can see a very special spacer with thin dexiglas kind of a spacer also has been used over here. So, I showed you various multilayer insulation and we have got a different spacers also that could be possible. Because there are lot of manufactures of this multilayer insulation and depending on availability and the cost. We can have different combinations of spacers as well as reflective surfaces alright.

So, we have seen various combinations of reflective material as well as for spacer. And you can have different manufacturers of this multilayer insulation. However, what is most important is how do you put or how do you apply this multilayer insulation on a cryostat or a cryocontainer. It is an art and therefore, normally in experienced person will would put this multilayer insulation and this basically depends on how you cut, it how you put it, minimum number of minimum layers, minimum compressive, low, etcetera the parameters which effect the performers of multilayer insulation. So, with this background now, I will take you to a tutorial where you can understand the effect of multilayer insulation and how do we calculate the boil off that occurs because of multilayer insulation. So, let us take a tutorial now and then I will end this particular topic later.

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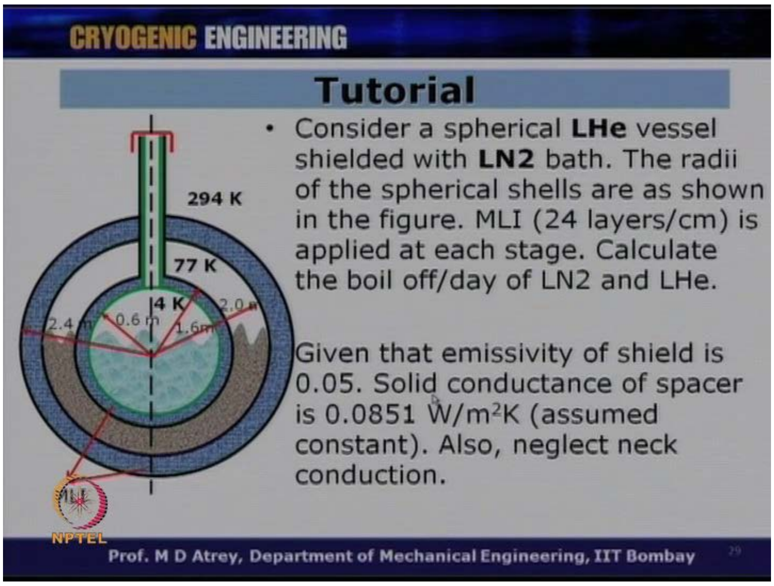

So, I will go back to the tutorial which I had taken last Time. But now here I am now having a typical application of material insulation. We got a outside temperature let us say at 294 kelvin, then we have got a multilayer insulation put from outside, till we have got a bath of liquid nitrogen put over here. Then again we have got a vacuum and we have got a multilayer insulation put around here, and we are storing liquid nitrogen liquid helium at 4.2 kelvin; have written 4 kelvin, because that is a just way of designation of temperature, but this is liquid helium here, this is liquid nitrogen here. Why do we have liquid nitrogen here? So that, the radiation from 294 straight away do not go to 4 kelvin or liquid helium which will cause a huge boil off. So, instead of that we have got a buffer temperature of 77 kelvin and the radiation now go only from 77 kelvin to 4.2 kelvin to liquid helium.

So, will have two boil off; one is the boil off of liquid nitrogen from here and one is a boil off of liquid helium from here. I have not sure in this case, but does there should be way of taking out this boil off that because continuous boil off would happen and therefore, liquid nitrogen will come out continuously, liquid helium will come out continuously. The boil off should not be kept inside otherwise the pressure inside will increase. Also we can neglect the conduction occurring across the neck, because we just want to study here, the calculations due to insulations or heat leak that is going to happen due to this insulation.

So, let us read the problem; consider a spherical liquid helium vessel shielded with liquid nitrogen bath. The radii of spherical shells are as shown in the figure. The MLI are around 24 layers per centimeter is applied at each stage. We got (( )) we got a vacuum at this blue whatever color has been shown over here. It is a basically volume plus multilayer insulation and also you have got a vacuum plus multilayer insulation. In both the cases, we have got a 24 layers per centimeter as the layer density and this is applied at each stage that means between 294 to 77 kelvin, we have got a multilayer insulation of 24 layers per centimeter. And from 77 kelvin to 4.3 kelvin we have got a multilayer insulation of 24 layers per centimeter. In both the cases, we have kept perfect vacuum of the order of 24 minus 5 torr.

Now, what we have to do is to calculate the boil off per day for liquid nitrogen as well as for liquid helium. What is given now; given that the emissivity of shield is 0.05, the solid conductance of spacer is 0.0851 and we have going to neglect the neck conduction. Neck conduction is also is very important way of having heat in leak. But at this point, we just consider the losses due to insulation and corresponding to those heat in leaks will calculate the what is the boil off for nitrogen and what is the boil off for helium right. This is my problem.

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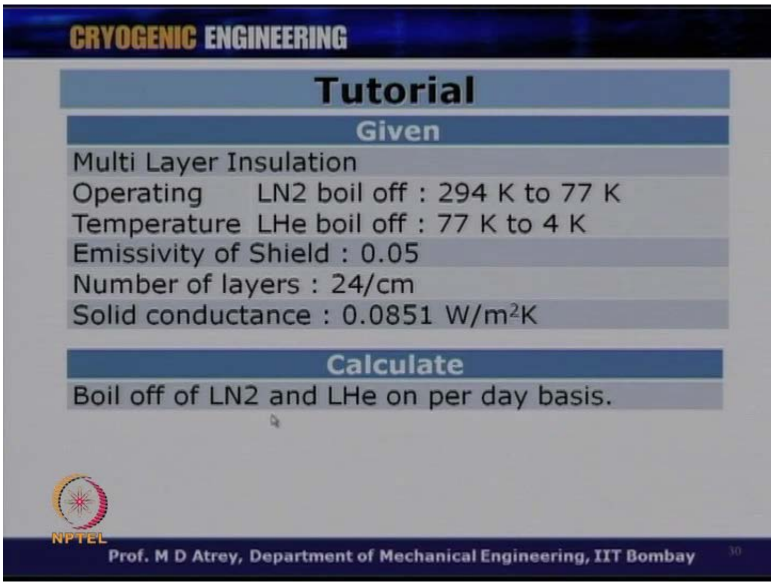

So, what is the data which is given to us is multilayer insulation, operating LN2 boil off, what is the temperature for this, operating temperatures 294 kelvin to 77 kelvin and operating temperature for liquid helium boil off will be from 77 kelvin to 4 kelvin. So, operating temperature for liquid nitrogen and liquid helium are, the heat in leak is going to happen from 294 to 77 kelvin for liquid nitrogen case, and for a boil of calculation for liquid helium we got a temperatures of 77 kelvin to 4.24 kelvin or 4.2 kelvin.

The emissivity of shield is given to as 0.05. The number of layers are 24 layers per centimeter and the solid conductance is 0.0851 watts per meter square kelvin, the layer density so also has been given. What we have to calculate is boil off of liquid nitrogen and liquid helium on per day basis. So, many liters per hour we have to calculate and converted into so many liters per day.

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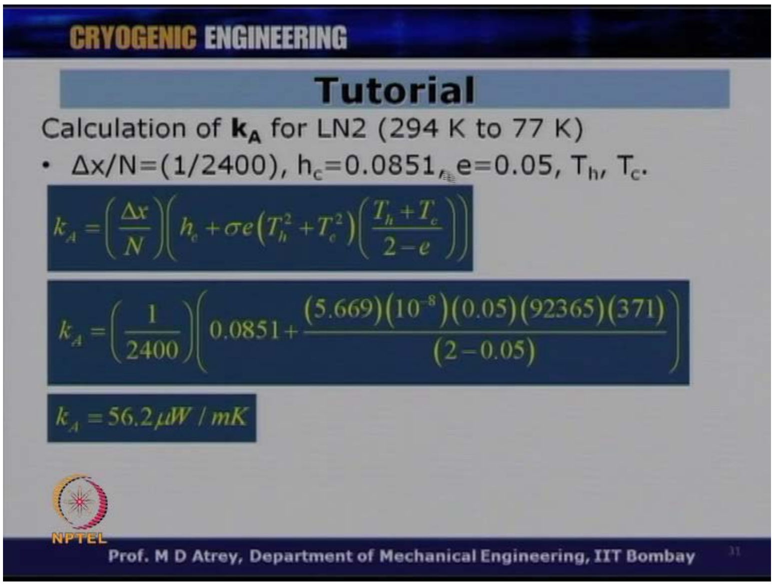

So, what will have to do? We have to first calculate what is the apparent thermal conductivity for the temperature range of 294 kelvin to 77 kelvin which will be important to calculate the responsible to calculate the boil off of liquid nitrogen; so, delta x by N is going to be 1 upon 2400. So, converting into millimeter will have 1 upon 2400 then h c is given as 0.0851, and then will have e is equal to 0.05 as given, and we got a T h and T c specified as 294 at 77 respectively. So, I have got a formula for application to calculate what is apparent thermal conductivity which is equal to delta x upon h h c which is solid conductance. These have been given to us as 0.0851 plus a component which is coming because of the radiation.

So, if I start putting this values now, I will get k A is equal to 1 upon 2400, 0.0851, 5.669 into 10 to the power minus 8 sigma value then e is given as 0.005 divided by 2 minus 0.05, then we got a temperature T h square plus T c square which is given by this bracket, and then we got a T h plus T c as given as 371 which is 294 plus 77 kelvin. Calculating this we get k A is equal to 56.2 microwatt per meter kelvin. So, this is a very important calculation and we got a apparent thermal conductivity for whatever assumption we have got for layer density and h c etcetera. We get a k A of 56.2 for the temperature range of 294 to 77 kelvin. This k is responsible to cause the boil off of liquid nitrogen. So, can we calculate now?

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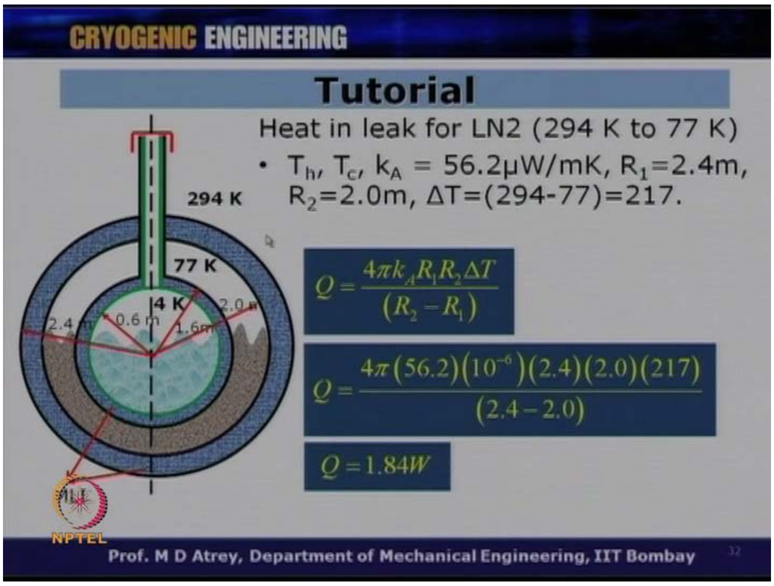

Therefore, heat in leak for liquid nitrogen is going to be given by for these parameters, we have got a 56.2 micro watt per meter kelvin as apparent thermal conductivity, R 1 is equal to 2.4, R 2 is equal 2 this is what has been given, delta T is equal to 217 now here. And therefore, Q is equal to 4 pi, because it is spherical in construction, we got a 4 pi k A R 1 R 2 delta T divided by R 2 minus R 1, putting the values 4 pi into k A value as 56.2 into 10 to the power minus 6 then R 1 R 2 2.4 and 2 delta T of 217 divided by R 2 minus R 1 which is 2.4 minus 2. And if you calculate this, Q is equal to 184 watts. So, heat in leak from ambient to 77 kelvin across this vacuum plus multilayer insulation is going to be 1.84 watt.

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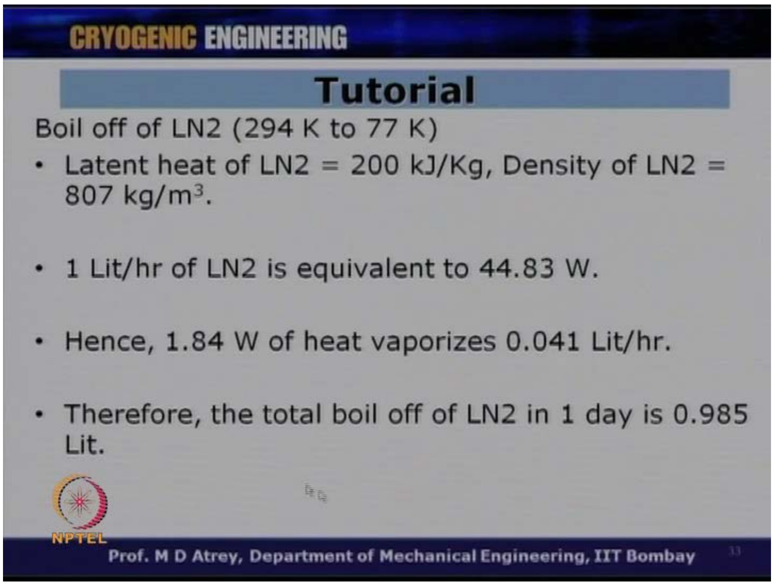

And if I want to calculate the boil off of liquid nitrogen; the boil off of liquid nitrogen for the temperature range of 294 K to 77 kelvin is going to be depending on the latent heat of liquid nitrogen 200 kilo joule per kg, density of liquid nitrogen is 807 and we have shown this calculation earlier. And we know that 1 liter per hour of liquid nitrogen boil off is equivalent to 44.83 watts of heat in leak. In the current case, we have got only 1.84 watt of heat in leak and this would be amounting to 0.041 liters per hour boil off, which is a very small.

So, will have only 0.041 liter per hour as a boil off, and per day therefore will have 0.985 for around let us say approximately 1 liter per day as boil off alright. So, this multilayer insulation if put from 294 to 77 kelvin would cause an approximate 1 liter per day as liquid nitrogen boil off, which is pretty, which is acceptable.

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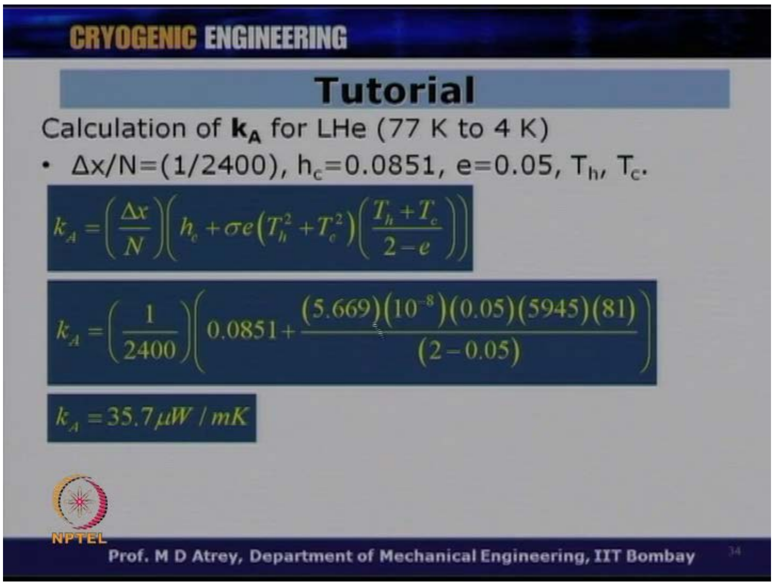

Now, let us go to 77 K to 4 K to calculate apparent thermal conductivity for responsible for boil of a liquid helium. So, here we have got again the same layer density as given, same solid conductance as given, e is equal to 0.05, and T h and T c as 77 kelvin and 4 kelvin respectively. So, I have put those values over here and calculate the value of k A, if I put those respective values. The T e now is going to be T h plus T c is going to be 77 K plus T 1 kelvin and again these two values are also will be different in this case. The apparent thermal conductivity in this case is going to be less now 35.7 microwatt per meter Kelvin. So, in this case now we are calculated the for 77 kelvin to 4 kelvin, the apparent thermal conductivity is 35.7, put those values and get the heat in leak for liquid helium now.

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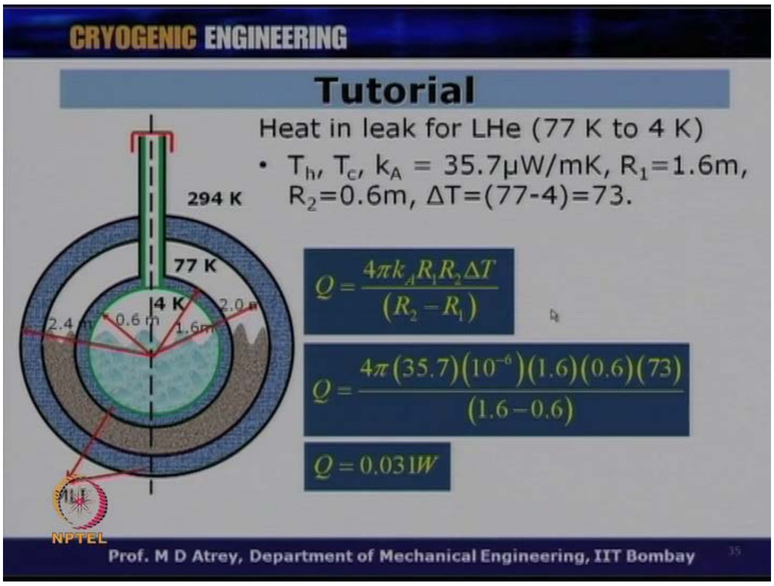

So, heat in leak calculations again would be done; delta T is going to be 77 minus 4 is 73 kelvin. R 1 and R 2 are going to be different, R 1 is 1.6 meter and R 2 is 0.6 meter. If I put this values in the same formula now, I will get Q is equal to 0.031 watts. That means only 31 milliwatt is going to be by heat in leak from 77 kelvin to 4 kelvin.

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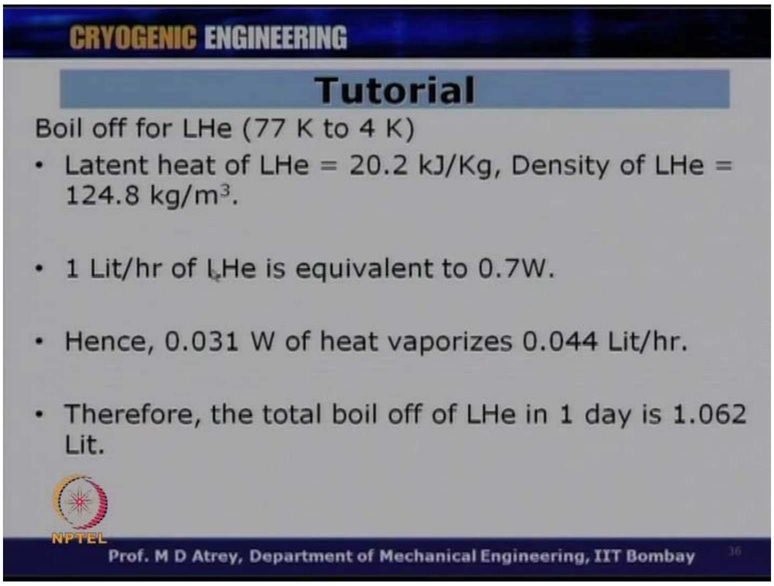

If I want to calculate now the boil off of liquid helium, because of this, I will take into consideration the latent heat of liquid helium which is only 20.2 kilo joule per kg, density of liquid helium is 124.8 kg per meter cube. And we know from the earlier calculation that 1 liter per hour of liquid helium boil off is equivalent to heat in leak of 0.7 watts. In this case, we have got only 0.031 watts of heat in leak and therefore, it will vaporize only 0.044 liter per hour alright, which means around 44 cc per hour of liquid helium boil off.

So, therefore the total boil off per day for 1 day is going to be around 1.062 liter alright. So, boil off liquid helium actually per day is going to be less than is going to be more than that for liquid nitrogen; may not be some Time acceptable. So, but for the given given dimensions, we got a boil off of liquid helium also close to 1 liter per day, and boil off of liquid nitrogen also close to approximately close to 1 liter per day. And this is what the calculation show and this example would show you how to calculate the boil offs and how to calculate the heat in leak due to multilayer insulation alright. This is the way multilayer insulations work; this is the way we have to calculate the boil off helium or nitrogen for multilayer insulation.

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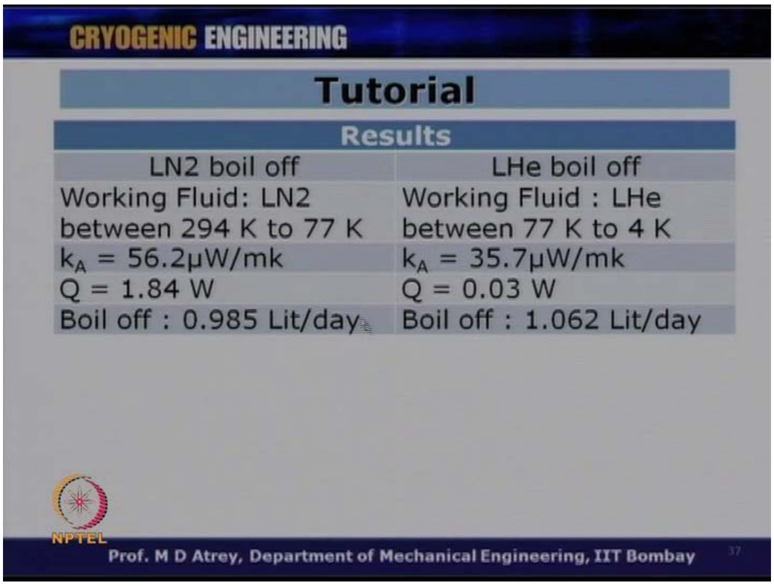

So, to summarize the results for this problem, will get for liquid nitrogen boil off, temperatures were 294 to 77 kelvin, the apparent thermal conductivity calculated was 56.2 micro watt per meter Kelvin, Q was calculated 1.84 watt, this would basically resulted into point 985 liter per day boil off. While for liquid helium boil off, we had a temperatures of 77 kelvin to 4 kelvin, apparent thermal conductivity 35.7 micro watt per meter Kelvin, Q is only 0.03. You can see that Q is so less as compare to what it was per nitrogen. But because of the less latent heat of a liquid helium and its properties, we had a boil of around 1 liter per day for liquid helium. So, this is just to show you comparison that how much boil off for nitrogen and helium would occur if multilayer insulation is used with these dimensions in the present container.

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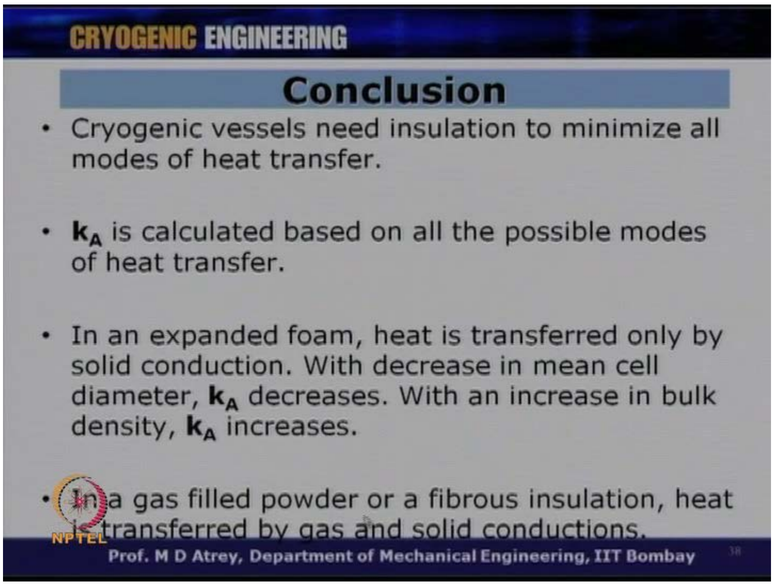

So, conclude, to conclude multilayer insulations or to conclude basically the insulations, we can see different points, whatever we have studied under this topic. So, we gave understood that cryogenic vessels need insulations to minimize all modes of heat transfer. This is what we have studied throughout. k A or apparent thermal conductivity is calculated based on all the possible modes of heat transfer alright. It takes into consideration, conduction, convection, radiation, and therefore, we can compare different insulations by having their apparent thermal conductivity for calculation purposes.

In an expanded foam, heat is transferred only by solid conduction with decrease in mean cell diameter we have seen that k A decreases, with an increases bulk density way of seen that k A increases. In a gas filled powder or a fibrous insulation, heat is transferred by gas and solid conduction alrigh. So, we have to take care of this two aspects or two modes of heat transfer in a gas filled powder or fibrous insulation.

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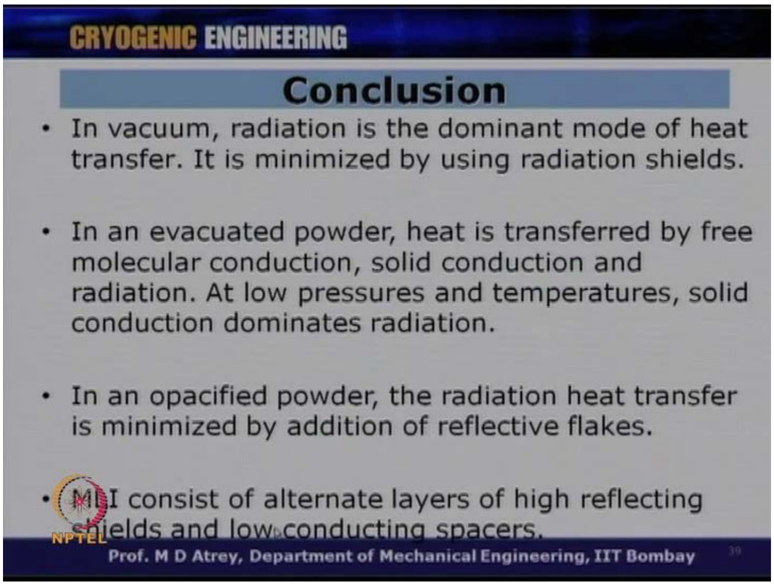

In vacuum, we have seen that the radiation is a dominant mode of heat transfer and it is minimized, it can be minimize using radiation shield. But we know that having radiation shields, it will not be a practical solution for various cryo containers. In an evacuated powder, heat is transferred by a free molecular conduction, solid conduction and radiation. At low pressures and temperatures solid conduction will dominate the radiation sorry it will dominate the mode of radiation heat transfer.

In an opacified powder, we have seen that radiation heat transfer is minimized by addition of reflective flakes. We have seen that all this insulations can be use up to liquid nitrogen temperature, well at lower temperature will have to go for multilayer insulation. So, multilayer insulation consist of alternative layers of high reflective shield and low conducting spacers.

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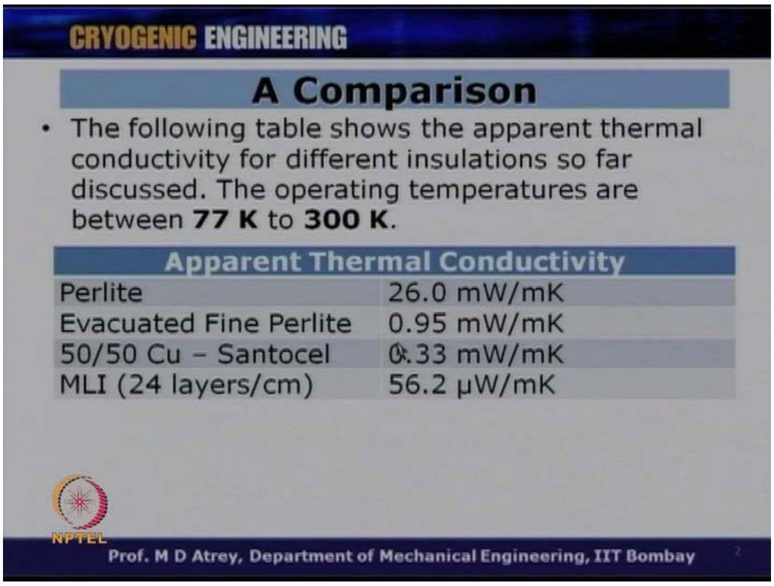

Multilayer insulations are more effective in 77 K to 4 K, also from 300 K to 4 K temperature levels. So, if you come to very low temperature levels, will have to think about having multilayer insulation and that is basically for liquid helium continues due to its properties. When provided with a good vacuum. So, multilayer insulation has to be always be with good vacuum. Multilayer insulation without having good vacuum is of no use, because gas conduction and convection now will cause lot of heat in leaks. And we will also seen that there is an optimum layer density at which k A of multilayer insulation is minimum. So, we got to have this optimum layer density for our applications depending on that we should apply particular layer density for minimizing the heat loss, minimizing the heat in leak.

So, we can see a comparison at the end of all the insulations which we have seen till now. The following table shows the apparent thermal conductivity for different insulations so far discussed. The operting temperatures here taken are 77 K to 300 K. And just to give indicative apparent thermal conductivity values for let us say perlite, the apparent thermal conductivity 26 milli watt per meter Kelvin. For evacuated fine perlite this get reduce down to 0.95 milli watts per meter Kelvin. Then you got a opacified powder 50-50 copper, and this is santocel, and again it get reduce to 0.33 mille watts per meter Kelvin. And then become to MLI just to see the comparison of powder evacuated powder, opacified powder and then we got a MLI having 25 layers per centimeter, and we can see that the apparent thermal conductivity has come down to 56.2 micro watt per meter kelvin. And here what you can see is all the values for comparison of different insulations. Thank you very much.