Introduction to Explosions and Explosion Safety
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Lecture - 22
Case Histories of Explosions Involving Volatile Liquids, Minimum Oxygen Concentration, Maximum Safe Oxygen Concentration

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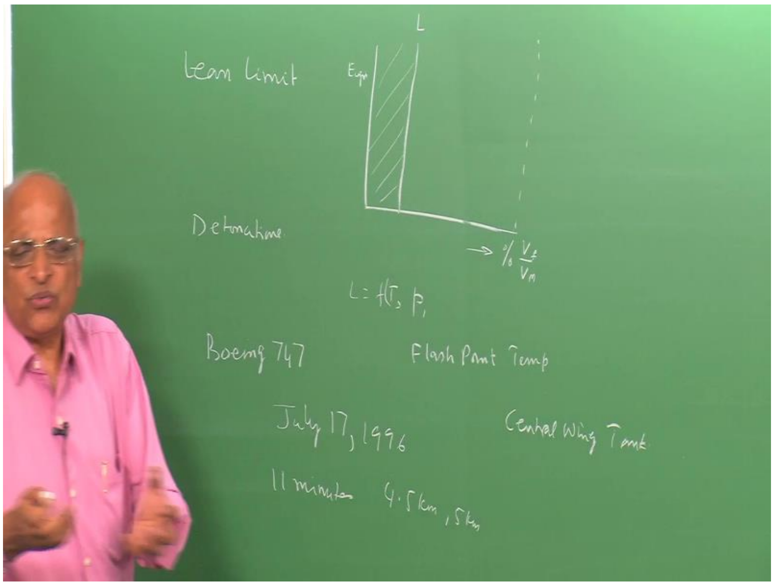

Good morning, you know in the last class we discussed about the limits of flammability especially, we said that the lean limit of flammability, lean limit is an important safety criterion in that you know if you have a spill let us say of a volatile liquid and the vapor comes out of it, and if it is able to form a mixture within the flammable limits, what did these tell? We said supposing we have on the x axis, we have let say percentage volume of the fuel gas which is present divide by the volume of the mixture, they percentage volume by volume, and on this axis we represent something like ignition energy.

We told our self well less than some limit mixture cannot really burn, because the energy released is so awfully small, it cannot support the combustion, and this we said as the lean limit of flammability. And similarly, we said there could be an upper limit wherein the air is so insufficient that it cannot burn again. We categories this lean limit of flammability in terms of we said well L depends on the temperature; it is a function of temperature, it also depends on the pressure which is available. And of course, we said well it is essentially dependent on the concentration.

We derived expressions for the lean limit in terms of temperature and pressure. We also went one step further, and looked at volatile liquids or volatile fuels, and talked in terms of the flash point at which we said at a flash point temperature, the amount of vapor generated from the volatile liquid is such that a mixture which is ignitable can be formed. Now today, let us try to apply some of these things to some problems or to some explosions which are been well documented.

We will also try to work out some simpler problems relating to how to convert the lean limit express it in terms of concentration, express it in terms of equivalence ratios. And thereafter, we will go into this subject of detonations. Having set the goal straight let me start with one very famous explosion which is very well documented. This explosion contain is related to an aircraft a Boeing 747 aircraft, you know this accident happened on July 17th 1996. Actually the aircraft was taking off from the New York that is at the John F Kennedy international airport, and it was flying Rome to Paris.

Now, what really happened? The aircraft took off in the evening as I said it happened on July 17th 1996, you know July is a warm month, it also took off in the evening late evening. Therefore, you know the Boeing 747 is a very safe aircraft, it has something like 4 engines, it has reddened features, and it is difficult to imagine that there was a problem with this aircraft. It took off and 11 minutes into the flight after takeoff, that means when it reached an altitude of let us say between 4.5 kilometers, and 5 kilometers it all of a sudden vanished, it just exploded, all the 230 passengers in the aircraft got killed.

Now, you know it was around let say 11 minutes after takeoff, it was over the Atlantic Ocean, and people recovered the remains of the aircraft. And the damage which was identified was they found out that the that a fuel tank that is a central wing, a fuel tank corresponding to the central wing tank. You know in an aircraft you have several tanks which house the fuel. The central wing tank of the aircraft had apparent lies exploded and caused the damage to the other parts leading to a huge fire ball. Therefore, let me get back to the slide and just explain what really happen?

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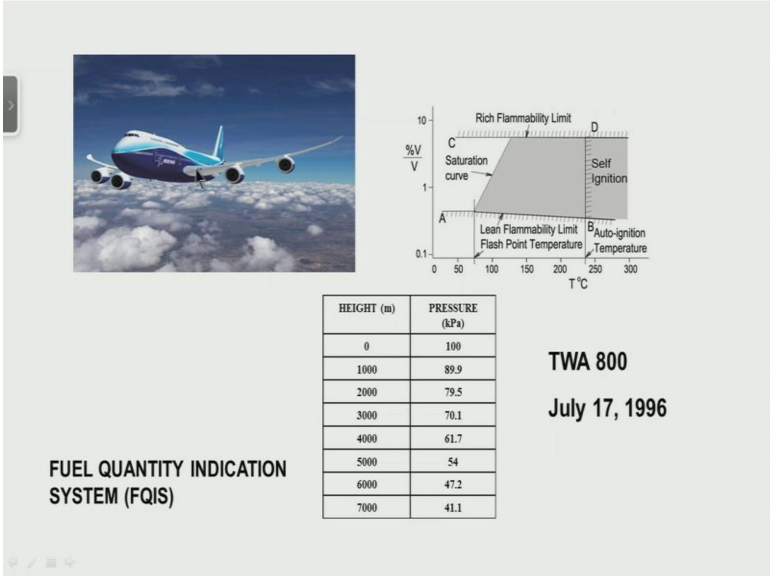

You know if you look at the Boeing aircraft as you see it consist of 4 engines, and what really happened as I told earlier was one of the central wing fuel tanks exploded 11 minutes after fly, and let us try to find out the reasons for the same.

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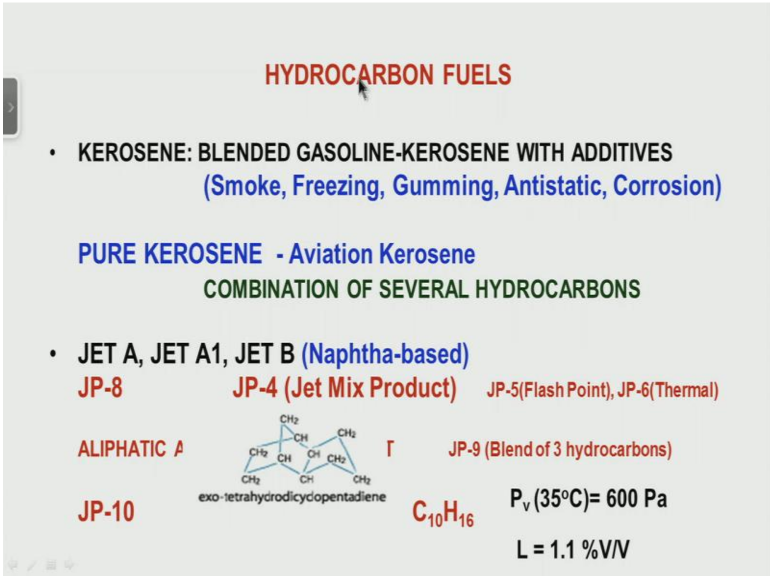

If we let us first take a look at the type of fuels which we use in aircraft, it consists of hydrocarbon fuels and essentially the fuel which we use is almost pure kerosene which we call as aviation kerosene. But it is not just kerosene alone, you add several additives to it, and very often it is a blended product of may be petrol likes gasoline and kerosene.

And it is so treated with additives such that you can bring down the freezing temperature, you can prevent the formation of smoke, you prevent the gumming of the hydrocarbon, fuels, you also ensure that static charges are not built up in the liquid fuel, and also to protect against corrosion you add this additives.

And therefore, whenever you are adding these things that means it is a mix that is a mix of the jet fuels, you call it as a jet mix fuels, and this is what we say is JET A, JET A1 which is used commercially. JET A is used in for commercial flights all over the world, JET A1 is used in US, and you know this is the type of fuel what has been used essentially we can take the properties to correspond to kerosene. But to some extent, the flash point is brought down, and in fact you have improved fuels like we say JP jet mix products, like JP-4 is a product in which you have mixture of hydrocarbons and some more additives added, such that the flash point the thermal properties are improved.

We have J 5 fuel in which the flash point is reduced, JP-6 fuel in which the thermal properties are improved, you have JP-8 which is an improvement, and also you have JP-9 which consists of a blend of 3 hydrocarbon fuels. And one particular aliphatic aromatic substance which is known as cyclopentadiene, and that is it is a chain consist of cyclopentadiene chain, it is essentially exo-tetrahydrodicyclopentadiene. It is a pure substance; it is a pure compound $C_{10}H_{16}$.

The type of fuel we are talking also is JET A, JET A1 for which we can say well the vapor pressure at 35 degrees is approximately 600 Pascal, and the lean limit of the mixture of kerosene vapor in air is something like 1.1 percent volume of kerosene divided by volume of mixture. Therefore, maybe we will take a look at this properties, well we say hydrocarbon fuels are used in aircrafts out of which maybe the properties which we are interested is the vapor pressure corresponding to the ambient temperature the since being a summer month over New York, the temperature is around 35 degree centigrade at which the vapor pressure is 600 Pascal.

Now, we go back to the previous slide, and ask ourselves. Well what could have happened, you have a fuel tank in which I have kerosene, the month is a summer month, the temperature is around 35 degrees centigrade. Well the aircraft takes off, when it takes off nothing has really happened. Therefore when it takes off, well the kerosene is at 35 degree centigrade, vapor pressure is 600 Pascal, the takeoff is at sea level New York, the ambient pressure is around 100 kilo Pascal, therefore the mixture which is formed, if I were to go to the board and just write it out.

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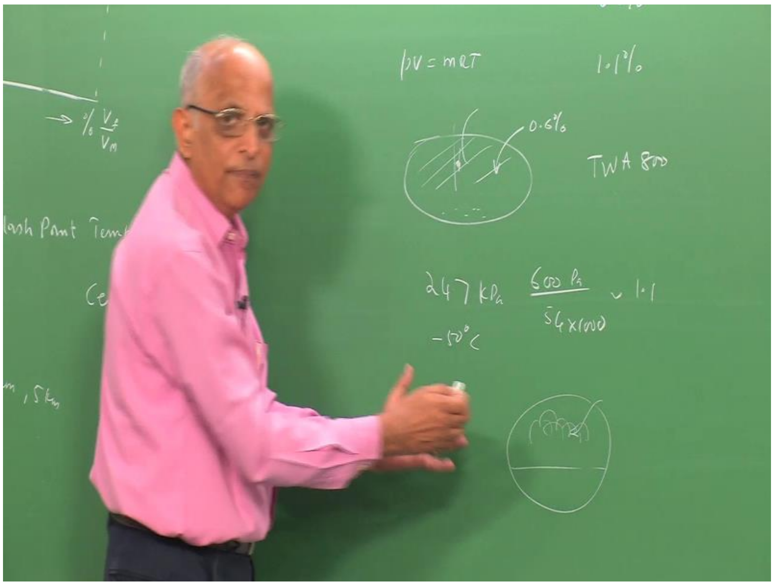

Well I say that the percentage volume of fuel let say kerosene, volume of kerosene vapor divided by the percentage volume of the divided by let say the mixture rather I say percentage, volume of kerosene divided by volume of mixture what I can form? Since the vapor pressure is 600 Pascal, the ambient pressure is equal to 100 kilo Pascal that is 100 into 1000 Pascal, this gives me the value of 0.100 cancels over here it gives 0.006 or percentage wise it is equal to 0.6 percent. The lean flammability limit of the kerosene vapor mixture is something like 1.1 percent.

Therefore on the ground if I have something like a tank in which I have kerosene which is available, the vapor mixture which is formed has a concentration or has a percentage volume of something like 0.6 percent. Whereas to be able to burn it, I require a minimum of let us say 1.1 percent. Therefore, it is safe from the consideration of any fire happening here. When the aircraft is climbing what happens? It climbs let say it keeps climbing, and what happens when it climbs let us takes a look at the table here again.

I plot the height of the aircraft or the altitude versus the pressure as it keeps climbing higher and higher. The pressure of the ambient keep decreasing until when it is at something like 4 kilometers, the ambient pressure is 61.7 kilo Pascal, when it is at 5 kilometer it is at 54 kilo Pascal maybe when I take a look at 5 kilometer when it has climbed, what is the limit of the mixture? Now, it becomes the vapor pressure is still 600 Pascal, why is it 600 Pascal, because that temperature corresponding to a temperature of 35 degrees centigrade on the ground, the vapor pressure of the liquid does not change with height.

And what is why you know the you have a thermal mass which is associated with that tank, during the initial flight the temperature does not change so fast. And therefore, if we assume that temperature of kerosene to be still 35, the vapor pressure is 600 Pascal. And now, you find what is the value of the pressure we said, let us go back to the table. And let us say 5 kilometers it is 54 kilo Pascal, therefore I have 54 into 1000. Well, it is almost near 1.1, and may be with value which we are assuming it is quite possible that the mixture which is formed above the liquid becomes flammable.

And once it is flammable, there are possibilities that you can form a sparker then what is it possibility of forming a spark, let us take a look at that again. You know if you look at any fuel tank what you have, may be the central wing fuel tank or any other fuel tank what happens is you have in the fuel tank, some measurement device to know how much kerosene fuel is available for that you use something known as a fuel quantity indication system that is FQIS. In this fuel quantity indication system, what happens is you have cables running and you when the wires 2 wires of the cable are such that a spark forms in between.

Well, I could have a mixture which is flammable in which I have an electrical spark and it could generate an explosion, and this is what has happened? That means you have a flammable mixture, because of this spark which is generated I could have a flame or a combustion and I have energy realize, and this is what causes the rupture of the tank. That but we will do this problem again when we talk in terms of confined explosions to be able to calculate how much pressure is generated, but for the present from what we learnt about the lean flammability limits?

We are able to tell ourselves well you know at altitude when the ambient pressure decreases, I can form a mixture which is flammable, and therefore there could be a ((Refer Time: 12:57)), and this is what happened in this particular flight? This particular flight was the TWA trans world airline 800 which was from New York to Rome, and this the what happened was you had the central wing tank catching fire, and causing an explosion which got transmitted to the other parts you have a pressure, you have a blast wave, it causes rupture in the other fuel tank, and the entire aircraft gets into a fireball and this is what happened.

You know there are a few things I must also qualify, you know if you talk you in terms of these jet aircraft like Boeing 747 aircraft. Normally it flies at an altitude of something like 10 kilometers 10 to 12 kilometers where in the pressure is even lower, pressure is something like 24.7 kilo Pascal, and the temperature v is around minus 50 degree centigrade. You know the thing is you know yes we are taking of fuel tanks being subjected to low pressure.

And therefore, one of the recommendations was to be able to put some inert agents that means, let us say I have a fuel tank, I could have a mixture which is combustible it is within the limits of flammability, the recommendation to avoid such accident was can I use some inert gases which I put into the vapor mixture, such that I bring down the quantity of the fuel which is available. Sort of I introduce some inert gases such that I shift the concentration of volume of fuel divide by volume of mixtures to this zone which is nonflammable.

Therefore, maybe we should take a look at this, and therefore let us work out one or two small problems on how we make a mixture inert, and go ahead with this. Therefore, in the problem what I do now is? I will do a small problem relating to how we go ahead, and how much quantity of inert gases should we add in order to make a mixture not flammable.

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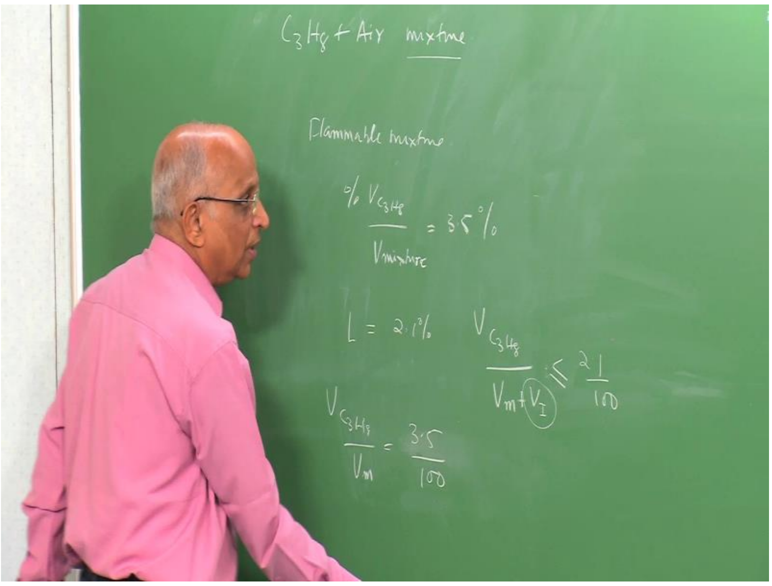

Let me take a small simpler example of propane C3H8 plus air mixture, let me presume that the mixture what I have here is a flammable mixture, let me also assume that the percentage volume of propane that is C3H8 in the volume of the mixture is let us say in the mixture is equal to let say 3.5 percent. You know for propane air mixture we saw that the lean limit of flammability L is equal to 2.1 percent, and whereas what you have in the mixture is 3.5 percent. The question is how much inert do you add, how much inert gases do you add to this to be able to bring it down to this value?

Well, the problem is quite simple, we say V of propane in the mixture what you have V mixture is equal to say 3.5 divided by 100 is the value, and what is it we want to do? I want to add some inert gases to this such that I bring it down to this. Therefore, the next equation what I should get is? Volume of propane C3H8 divided by volume of mixture plus volume of the inert gases what I add should be such that the limit is going to be less than or equal to the value of 2.1 percent. Therefore, what is it I have? Therefore, now I want to find out what is the volume of the inert gases which I add. Therefore, let us calculate this value.

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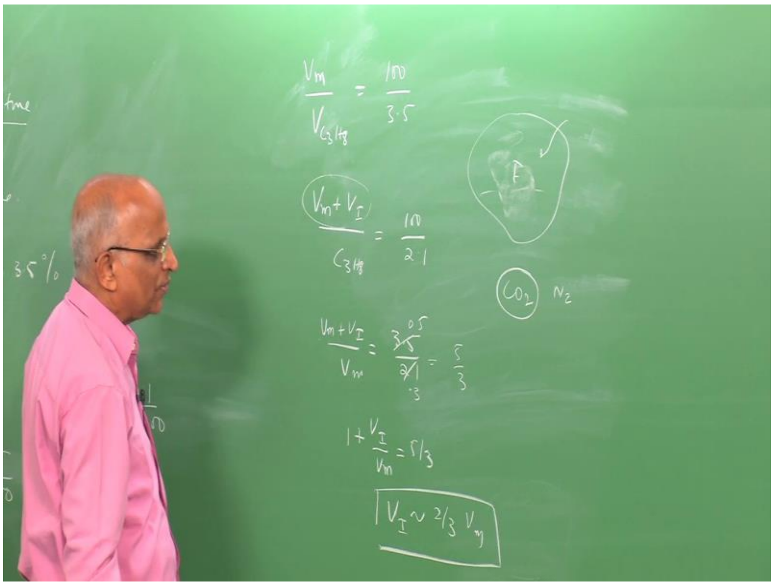

Therefore, I take the inverse of both the equations, and I tell well I have volume of mixture divided by volume of C3H8 is equal to 100 by 3.5. And now I get from the second equation, volume plus volume of the inert gases divided by C3H8 is equal to 100 by 2.1. Therefore, I get the value of volume of the mixture plus volume of the inert gases that is the original mixture mind you to which I have added this, this becomes the new mixture now, divided by volume of the mixture is equal to divide by 1 by the other, and what is it I get?

I get 3.5 divided by 2.1 is the value or rather this becomes 0.5 divide by 7.3, this becomes 5 by 3 or rather I get from this 1 plus V I volume of inert gases to be added, divided is equal to 5 by 3 or rather volume of the inert gases must be around 2 by 3 of the volume of the mixture, this is the amount of inert gases which remains to add. Therefore, if I have a mixture let us say in a fuel tank or someplace, wherein I have the gases which are flammable, how much of the inert gases do I have?

It is becomes a simple way of reckoning, but we must also remember that if I have inert gas like nitrogen, and the property of nitrogen are similar to let us say the fuel and air over here. Well, the effectiveness is there, but if I can add gases whose specific heat is higher, well it is going to be more effective. And in that context gasses like Co2 which have a larger value of specific heat compare to nitrogen are more effective in as a diluents or as an inert gas.

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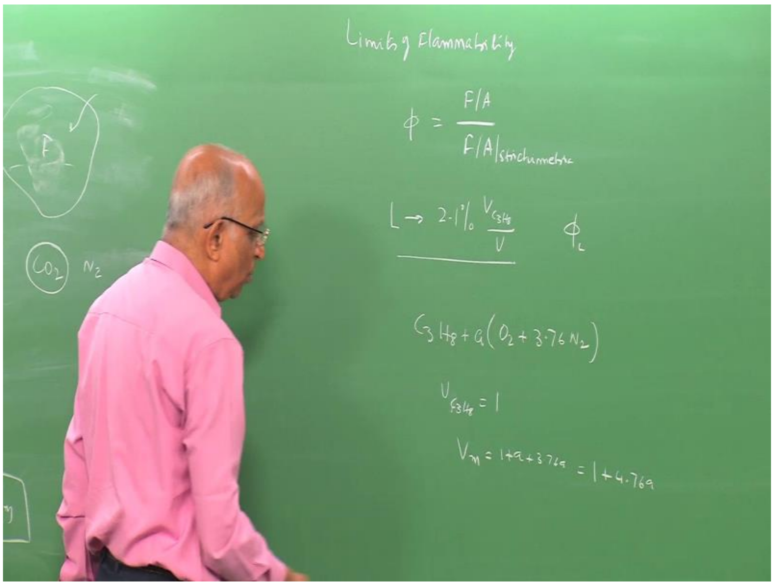

Well, this is the way to do it, but since we are estimating the inert gases and we are looking at flammability limits, the next question automatically comes, can I express limits of flammability in terms of let say stoichiometry see we have learnt stoichiometry we learnt how to calculate the heat realizing chemical reactions, we learnt how to find out the rate of reactions, and for that we use the term equivalence ratio, and what was equivalence ratio? Equivalence ratio was the fuel by air actual divided by mass divided by fuel by air for a stoichiometric reaction.

Therefore the question is, if I say well the lean limit of flammability of propane air is 2.1 percentage of volume of propane C3H8 in the volume of the mixture, can I express L in terms of it is equivalence stoichiometry, what is this value of the equivalence ratio corresponding to L. Therefore for this let us do this problem, because it helps us to understand the relation between may be the equivalence ratio may be the stoichiometric coefficient, the value of the lean limit how far away it is from maximum heat realize zone.

And for that you know, this is the data which is given to me the lean limit is so much, I want to determine what is the value of the equivalence ratio corresponding to L? Therefore, immediately I say well my reaction is C3H8 it is in an air mixture, therefore I have oxygen; each mole of oxygen is associated with 3.76 moles of nitrogen. And well, I have some amount of for each mole of air I have some each mole of propane; I have some moles of air over here. Let us assume I have a moles over here, therefore I have a of O2 and 3.76 this is my total value what I get over here.

And therefore, see moles are proportional to volume. Therefore, I have volume of fuel in this case or volume of C3H8 which is the fuel gas is equal to 1, because moles is 1. The volume of the mixture what I get, is equal to moles plus moles over here that is equal to 1 plus a plus 3.76 of a, a plus a plus 3.76 of a which is equal to 1 plus 4.76 of a, this is the type of a mixture what I am getting. Therefore, what is the value of in terms of volume by volume?

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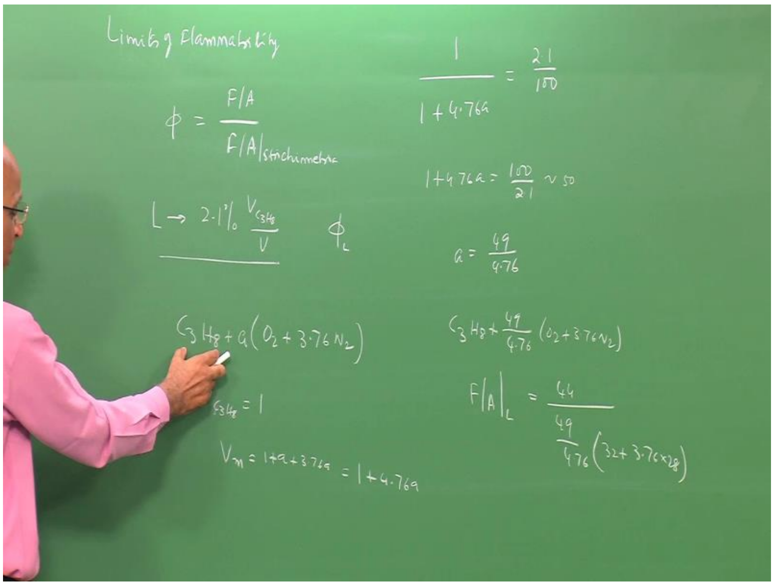

In terms of volume by volume, it is equal to 1 over volume of propane is 1, volume of mixture is 1 plus 4.76 a, and this is volume of propane divided by volume of mixture which is equal to 2.1 divided by 100, this is the value. And now, I solve for a from this equation, and what is it I get? I get 1 plus 4.76 a is equal to 100 by 2.1 or rather this if I simplify it I will just give you the result over here. I get from this if I solve for a, I get a is equal to around let us say 4.76 a is equal to 100 by 2.1 minus 1 which is approximately equal to a is equal to approximating it as 50 over here 49, therefore I have 49 divided by 4.76.

And therefore, my equation at the lean limit of mixture is equal to C3H8 plus I have 49 by 4.76 of oxygen associated with the nitrogen which comes with it, this is my equation this is at the lean limit. Therefore, what is the value of fuel by air at the lean limit of the mixture which is the actual value? Well, I have the molecular mass of 1 mole is equal to 12 3 are 36 plus 8 44 grams, what is the value of the air which is associated, I have 49 divided by 4.76 into 16 2 are 32 grams plus 3.76 into 28 this is the fuel air at the lean limit.

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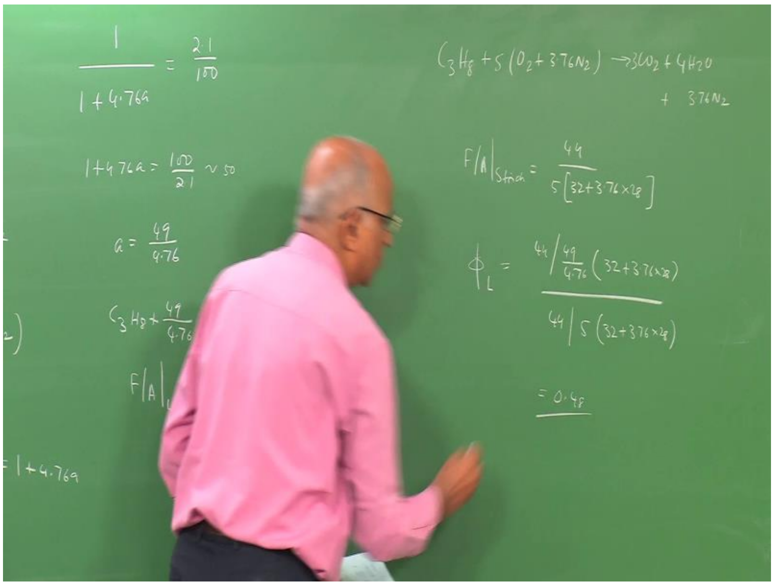

And what will be the value of this stoichiometry, we again go back look at what should be the stoichiometric coefficient and I get C3H8. And a stoichiometric when I have air plus 3.76 nitrogen should give me completely burn product CO2 plus I have H2O that is I have 3 CO over here 3 CO2 plus 4 H2O corresponding to 8 of the h atoms plus whatever nitrogen is coming over here 3.76 into nitrogen, I have to calculate this I need to calculate this. I find well I have 3 2 are 6 plus 4 10, therefore I have 5 over here that is 3 CO2 giving me 3 plus I am left with 4, 4 oxygen comes over here.

Therefore fuel by air for stoichiometry for this particular reaction is equal to again 36 plus 4 44grams divided by air 5 into 32 plus 3.76 of nitrogen which is 28, this is a value of fuel by air stoichiometric. And therefore, the equivalence ratio corresponding to the lean limit of combustion is equal to or the lean limit of flammability is equal to I get I have already determined this is equal to 44 divided by the value of 49 divided by 4.76 into whatever I have written here 32 plus 3.76 into 28 divided by same 44 divided by 5 into 32 plus 3.76 into 28. And if I calculate this value, it comes out to be something like

0.48 is the equivalence ratio. What does it tell let us quickly examine, what is the significance of this equivalence ratio? What did we tell earlier?

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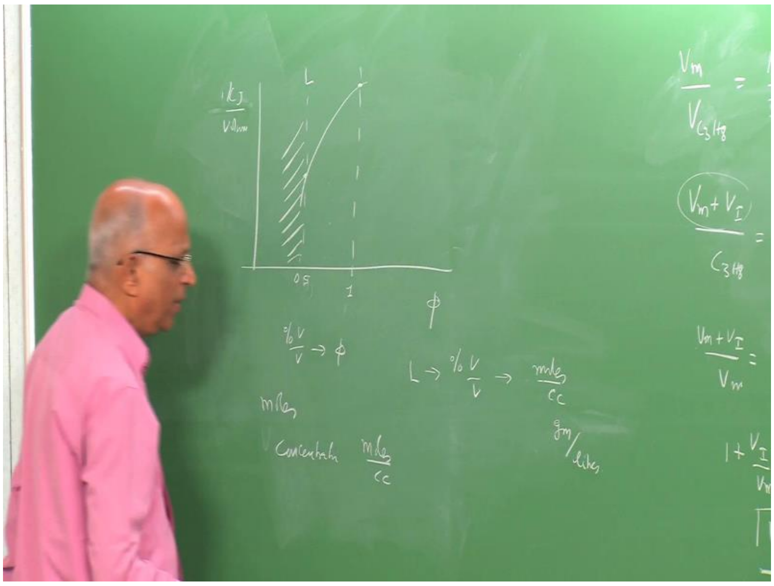

We said when the equivalence ratio is 1 phi, when equivalence ratio is 1, we have completely product of combustion, let us say heat release over here the heat release is a maximum here. And when the equivalence ratio shifts from 1 to something like 0.5, well nothing can burn, that means the temperature drops, because we are looking at heat release let us say in kilo joules per volume or per moles of the mixture, it drops to a value wherein it is not capable anymore. The point to be understood is you know we are telling that may be we are not really looking at very, very lean mixtures.

Even a lean mixture whose equivalence ratio is around 0.5 that is in the fuel lean region is below that, it just cannot burn or the lean limit corresponds to a value around 0.48. Well, this is how we convert the lean limit from percentage volume by volume into something like equivalence ratio. But, you also remember in some problems you know especially when we talk of moles, when we talk of reactions we talk in terms of concentration.

And when we talk of concentration we talk in term of moles per unit volume per cc, can I express the concentration at L in terms or let say limit in terms of percentage volume by volume, in terms of let us say concentration in terms of moles per cc or see moles is also quantity of matter I can express it in terms of grams per volume or grams per liter or milligrams per liter. I would like to do this, and it so happens it is quite simple let us do the same problem again for converting the limit of mixtures or the lean limit of mixtures given as percentage volume by volume.

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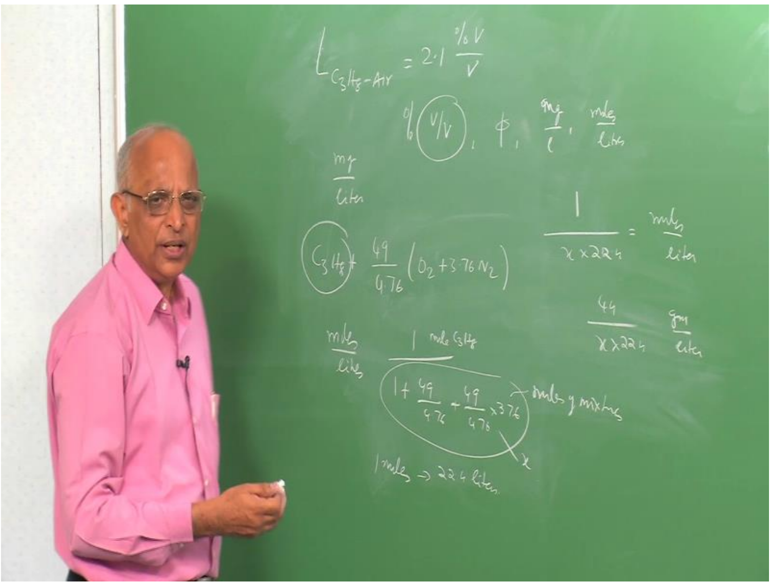

Let say lean limit of propane air mixture is let us say 2.1 percentage volume of propane divided by volume of mixture. I want to convert this in terms of how much milligram per liter is there in the mixture? Therefore, again I look at the equation we have just derived it, let us write that equation under the lean limit I get C3H8 plus corresponding to L we had the equation 49 by 4.76 just write it out into oxygen plus 3.76 of nitrogen this is the mixture what I have?

Now, what is it I find? I want to put it in terms of let say moles per liter concentration in terms of moles per liter. Therefore, moles of fuel is 1, and the quantity of total mixture is how much 1, that is 1 mole of C3H8, and the number of moles of the mixture is 1 plus 49 divided by 4.76 of oxygen plus 49 divided by 4.76 into 3.76 of nitrogen, this is moles per mole of this, this is the total moles of the mixture, and what is the this is the total moles of the mixture. This is 1 mole of propane in the total moles of the mixture, but I know 1 mole of a gas or 1 mole of the mixture will occupy a volume of 22.4 litters.

And therefore, this the total number of moles will occupy this number of moles into 22.4 litters or rather the number of moles per letter is going to be 1 divided by this particular quantity let us say this particular quantity I call x into 22.4 litters, this gives me the number of concentration in moles per litter. If I want to take a concentration in grams per litter, I know 1 mole of propane corresponds to 36 plus 8 44 grams therefore it is 44 divided by x into 22.4 so many grams per litter.

Therefore, you can express the lean limit of flammability instead of volume by volume that is how it is generally done. In fact, it is percentage volume by volume, you can also expressed it in terms of the equivalence ratio, you can also expressed in terms of milligrams per liter or grams per liter or in terms of moles per liter. We should be able to different problems in you having different units and express the same thing. Well, this is from the point we derived all this, because we looked at the explosion of this Boeing aircraft in which kerosene was used one of the central fuels tanks exploded.

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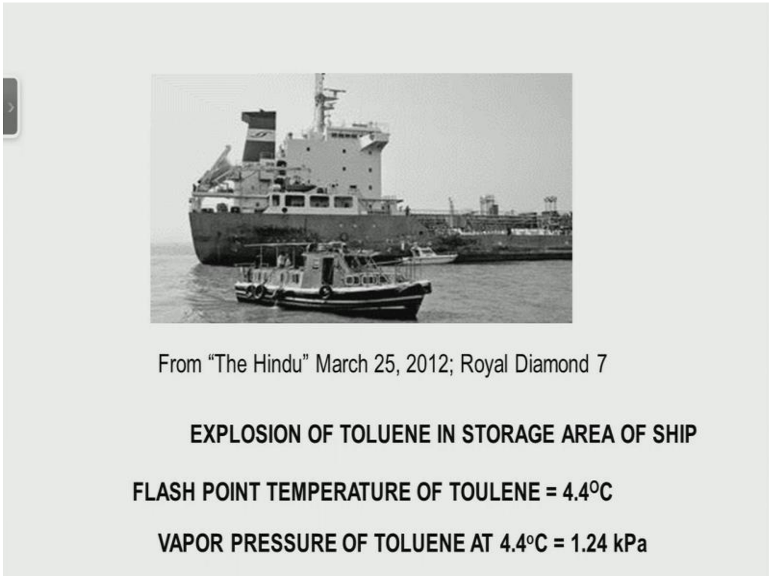

Let us go back, and try to take another look another explosion problem. The second problem which we consider and I show it in the slide here relates to an explosion which happened of in the ship known as the Royal Diamond. This was a Korean ship which was birthed of the Mumbai harbor. This happened on March 25 2012, you know the month always is important to because the month will tell you whether the ambient temperature is high or low, like in the previous example of the aircraft that is the Boeing 747 we noted at summer the fuel tank is somewhat warmer at 35 degrees.

And mind you I forgot to mention one thing here, you know in the fuel tank in the example earlier you know you add the refrigeration system of the aircraft, and the aircraft was slightly delayed in departure, and the people were sitting inside, and the refrigeration system was working. So that you know whenever a refrigeration system is working it the exhaust hot gases are generated, it kept the fuel tanks a little warmer, and that is also one of the criterions which went into keeping the fuel tank warm. Well let us gets back into this particular example.

Well we have this particular ship which is birthed of Mumbai in it is cargo you had toluene, and this toluene if we found at it is something like volatile liquid, if I look at the flash point of toluene, the value is around 4.4 degree centigrade, let me go back to the first slide again. You know this figure we have seen it earlier, here we have the temperature on the x axis; we have percentage volume by volume.

We tell ourselves well the flash point temperature of toluene is something like 4.4 degrees, which means the vapor generated at 4.4 degrees is such that the mixture of the vapor which is generated when mixed with air forms a mixture which is correspondence to the lean flammability limit. Therefore, what is it we are telling? Well the vapor pressure of toluene correspondence to 1.24 k Pa. Therefore, what is the limit of flammability? 1.24 the ambient pressure yes 100 k Pa.

Therefore, the percentage volume of toluene divided by the volume of mixture is 1.24 divided by 100 k Pa which is equal to 1.24 divided by 100 into 100 which is equal to 1.24 volume toluene divided by volume of the mixture. Now, when their ambient temperature is something like 35 degrees centigrade, there is copious amount the vapor pressure is very much higher. Therefore, the amount of toluene which is generated is very much higher; therefore what is being formed let us take a look again, we go back we want to find out how much mixer is being formed?

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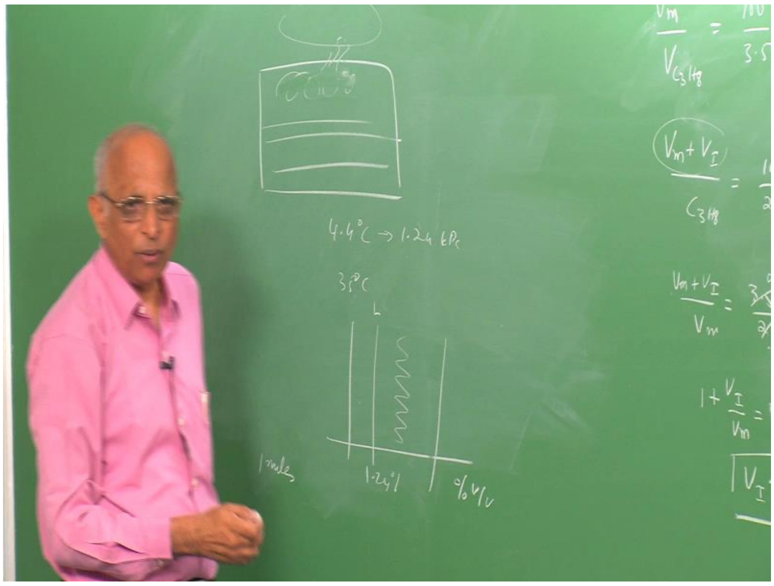

Vapor pressure at 4.4 that is the flash point temperature is 1.24 k Pa, if the temperature is 35 degree centigrade, I have lot of toluene vapor getting generated therefore I have a flammable mixture. In other words, if I plot percentage volume by volume, volume toluene divided by volume of the mixture, may be these are the limits of flammability. The limit as calculated from this comes to be 1.24 divided by 100 into 100 this is the percentage, this correspondence to L may be our mixture is some were here highly flammable.

And therefore, since are highly flammable mixture is getting generated, that means made me there is some leak over year, it forms in the cargo bay the toluene air mixture is formed which is which exceeds the flammability limits, and any part can ignited, and this is what cause the problem. That means the explosion in ship royal diamond was essentially due to leakage of toluene which form and flammable mixture, and that is what cause the explosion. Well, you know one way of stopping such explosions is to as we said is to the dilute the mixture. And very often people use some different terminologies to do that, instead of talking in terms of lean flammability limits let us go back.

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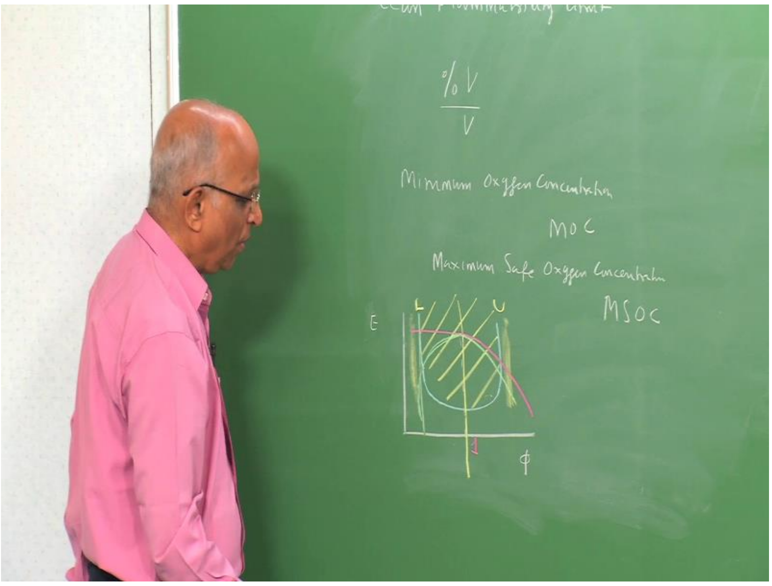

Wherein we are talking of percentage volume of the fuel divided by the volume of the mixture, people also talk in terms of minimum oxygen concentration and this is a good tool that means, see I have to dilute the mixture such that a flammable mixture is not form. Therefore, this minimum oxygen concentration spoken of is M O C also referred to as maximum safe oxygen concentration that is M S O C both refer to the same thing can also be used to quantify a lean limit, how is it possible? Let us again take a look at some of the figure we drew this morning, they I have 5 over here that is the equivalence ratio.

I say well I have the ignition energy over here let say E minimum ignition energy, 5 is equal to 1 stoichiometric. I have the lean limits of combustion coming over here, I have the rich limit of combustion coming over here, I have a u shape curve, and this is the zone which is flammable, this is outside the lean of flammability; this is outside the lean rich limit of flammability u or the upper limit of flammability lower limit of flammability this cannot burn, this cannot burn. Now, instead of well talking in terms of volume of fuel divided by volume of mixture, can I are represented in terms of minimum oxygen concentration to be able to do the same problem.

Therefore, if I say well what is it? If I were to plot the same thing over here, in this figures I want to show the heat release what is it I find? Well, in the value less than 1, 5 less than 1 I have something which is fuel lean that is more air. And therefore in the particular reaction what happens is completely come burn products of combustion are formed between this and this. And therefore, in the particular reaction I have q which is constant, and over here I have unburned gases, and I have air which is not sufficient for me to burn, therefore products of combustion are not there the q drops of.

But, if I look at this heat release, and want to transfer this heat release in terms of the heat available per unit mass of the mixture. Since the mixture keeps on increasing in molar in terms of mole or in terms of volume or in terms of mass, the heat liberated per unit mass keeps coming down, and therefore I get a curves something like this over here. If I get this particular curve, and therefore when the heat release of the mixture is very small per unit volume, well it is not able to support it, and that is why I get the lean limit corresponding to this value.

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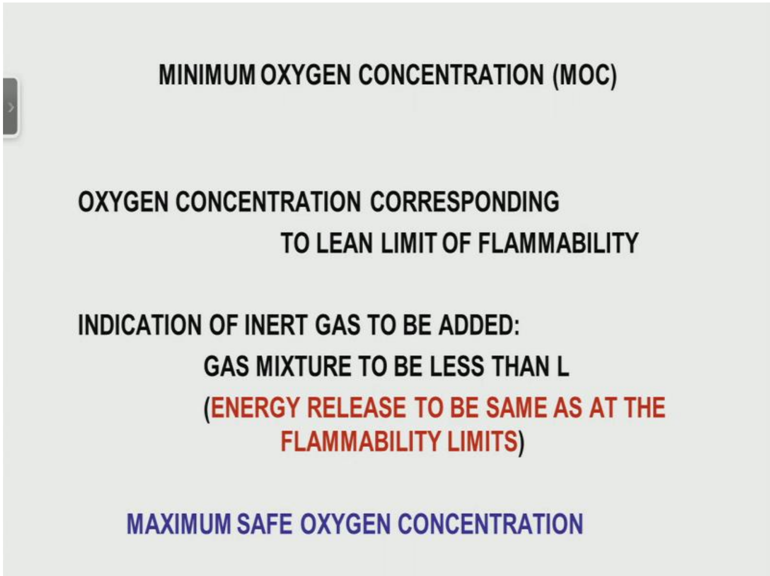

Therefore, can I put L in terms of minimum oxygen concentration, therefore let us go through one particular example, and the lean limit of flammability can also be the therefore expressed in terms of the minimum oxygen concentration that is the oxygen concentration corresponding to lean limit of flammability is spoken of as minimum oxygen concentration.

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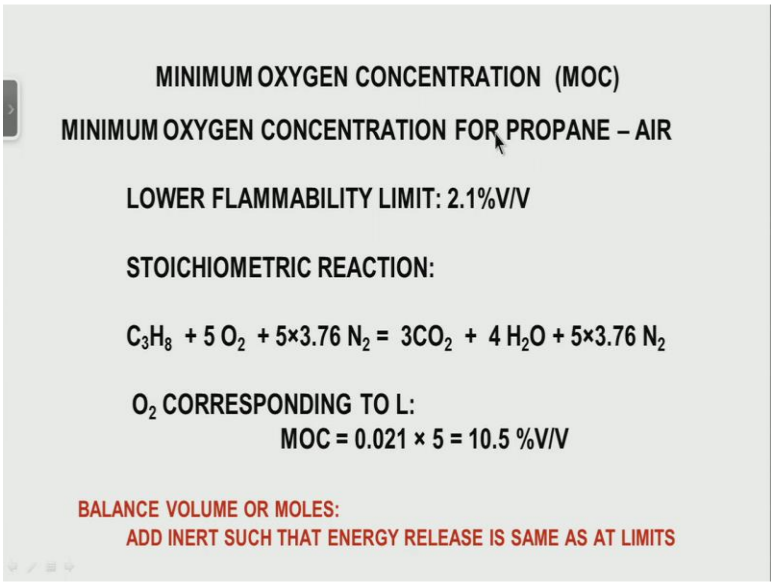

Let us take an example before I come and examine this, you know in the problem which we have been talking earlier namely the lower flammability limit of propane air mixture we said is 2.1 percentage volume of propane divided by volume of mixture. Therefore, if I have a stoichiometric reaction what is it? We said well in the lower flammability region that is just greater than lean flammability limits, I get completely burned products of combustion. Therefore, I first write a stoichiometric reaction C3H8 plus 5 O2 plus equivalent amount of nitrogen gives me products. But now, what is it I say lean limit of flammability is 2.1 percent.

Therefore, the amount of oxygen available in this reaction corresponding to the lean limit of flammability is 5 into 2.1 divided by 100 or rather 2.1 divided by 100 is 0.021 into 5 which is 10.5. And this 10.5 percent of volume of oxygen divided by volume of mixture is what is denoted by M O C, why is it we use this let us again go back to this particular figure which I drew. Let us again examine this, because you know the reason for referring to mean oxygen concentration is the following.

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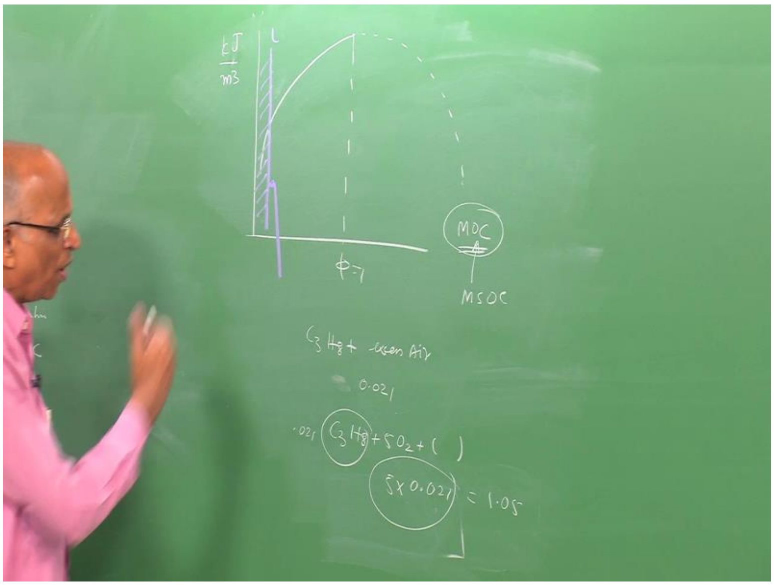

I have stoichiometry over here 5 is equal to 1, I have the amount of heat generated so much kilo joules per let say meter cube of the mixer drops of over here. It also drops of I am not interested in the fuel rich region, because you know fuel rich region really does not corresponded to accidents involving spills, because in most of the spills you formed the lean type of mixers. Let us say that the lean limit of the mixture corresponds to this L, below this it does not really burn, because the heat generated is so small.

Now, what is happening? See corresponding to the heat which is generated over here corresponds to the reaction let us put it down, it is C3H8 plus you know over here I have excess oxygen excess air, and this excess air acts as a diluents and brings down the heat of the reaction. And therefore, I say well the lean limit corresponds to 2. that is 2.1 percentage volume that is 0.o2 1, and if I have I to express what is the if I were to say, well the oxygen what is available, if it is going to be less than in this reaction I had C3H8 plus 5 of oxygen plus the nitrogen content.

Therefore, if my lean limit corresponds to 0.o21, if my oxygen content is 5 into 0.o21 it is less than these quantities, well what is going to happen? The heat which is getting generated is going to be now in a fuel rich mixture, therefore more less heat is going to be generated, and in this particular volume, the heat generated is this itself. Therefore, if I reduce the oxygen concentration less than this particular value which is equal to let say 1.05 or so, you know what is going to happen? It can really cannot burn.

Therefore, the minimum oxygen concentration which corresponds to lean flammability limits corresponds to the value of this stoichiometric coefficient multiplied by the lean limit, and this is how we calculate the minimum oxygen concentration. It is a very useful tool which is used in the industry to act amount of inert gases that means you find out how much oxygen is available in a gas, and how much inert is added to bring it down to the minimum oxygen concentration which we also told as maximum safe oxygen concentration. Let us do one more problem to be able to clearly illustrate how we calculate this.

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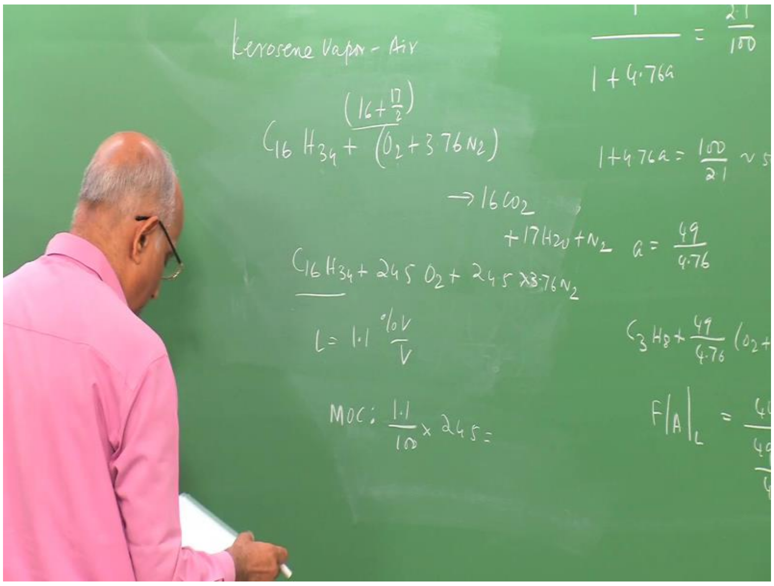

Let me take the example of the minimum oxygen concentration, I want to determine let say for the case of let say kerosene vapor air mixture. Well I want to calculate this well I say kerosene is do decant C16 do decant H34 plus I have oxygen plus 3.76 nitrogen. Since I want to form CO2, I have to add 16 moles of oxygen plus 17 of H2O, let means I have 16 CO2 plus 17 H2O plus the nitrogen coming over here. Therefore, I have 16 plus 17 by 2 of for the hydrogen over here; this is the total moles of oxygen which is available. And this comes out to be 24.5, that is C16H34 plus I have 24.5 of oxygen plus 24.5 of into 3.76 of nitrogen.

Therefore, what is the limit of L? L is equal to we said is equal to 1.1 percentage volume by volume. And therefore, if I were to translate this into M O C, M O C is equal to 1.1 divided by 100 into 24.5 is the minimum oxygen concentration which is required for the kerosene vapor mixture, and this comes out to be something like 26.95 percentage volume by volume. And this is how we do different problems, and we can also relate the lean flammability limit to minimum oxygen concentration and the maximum safe oxygen concentration. Well, this is all about the lean flammability limits, I just want to spend some 3 to 4 minutes on the last part which I said I will be doing today. Having learnt about the flames about lean flammability limits, one of the questions which we often ask is you know we talked in terms of blast waves being formed.

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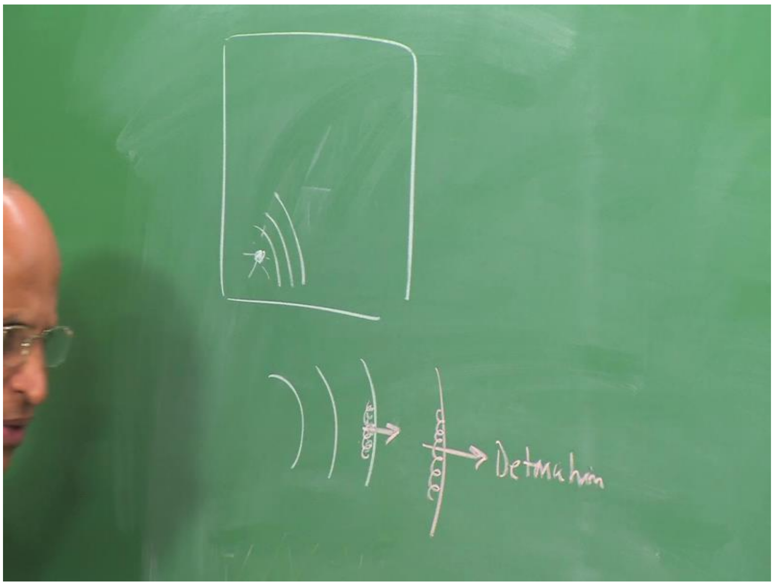

We said I have a mixture of gases; I deposit some energy over here. When I deposit some energy, the energy is deposited very slowly. Well, the heat gets moved out, the concentration moves out, and a flame is being formed. We looked at the flammability limits, we looked at energy required for ignition and so on, but if the energy release is somewhat fast sort of instantaneous. Well a shock wave could be formed, and behind a shock wave well the temperature is quiet large.

If the temperature is quiet large, and it is an explosive gas mixture, the chemical energy which is release behind the shock wave could drive the shock wave such that, now you get a shock wave driven by chemical reactions. And if the chemical energy release is such that it can overcome the work done during expansion of the gases behind the shock wave, I can make the shock wave travel at a constants speed, and this type of wave we spoken of as a detonation wave.

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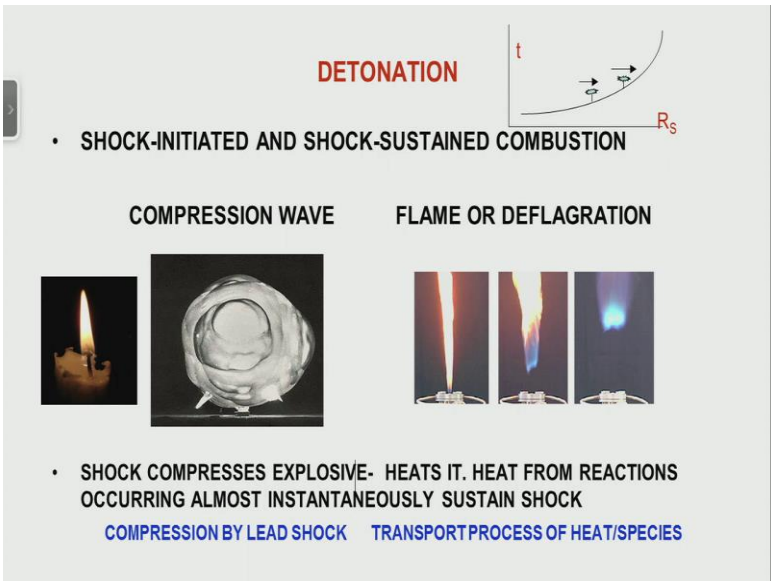

I just show the last slide we you for a detonation, and why I do this today's may be in the next class onwards, we will start taking the look at detonation. Well, instead of having something like a flame which is a candle over here which goes at slow speed or I have some gases which are coming, and the rate at which the gasses is coming is the rate at which a flame speed is available. Instead of having this if I can form something like a blast wave we saw this street diagram earlier.

If the temperature behind the wave is quite high, well you know the pressure is already high behind a blast wave, and now the temperature is high. Therefore, I have something like a compression instead of having an expansion in a flame, I have something like a compression, and this compression that is you have a huge compress type of gasses which had been form. And this shock compressed explosive is or a shock compressed movement of the flame front is what is referred to as a detonation.

In this case, you do not have transport of gases like what we had for a flame, but it is what you have is something like a gas mixture in which you form a shock wave, and the chemical reactions which drive the shock wave which we call as a detonation. In the next class we will take a look at details of how a detonation propagates see and find how it differs from a flame, and why it causes more damage than what a flame can cause.

Well, thank you.