Introduction to Explosions and Explosion Safety

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Lecture - 27
Case Histories of Explosions involving Detonation or Quasi-Detonation

Good morning. In today's class we will discuss a few case histories of explosions which involve detonation. Let me get started with the first one which is supposed to be the worst case history ever.

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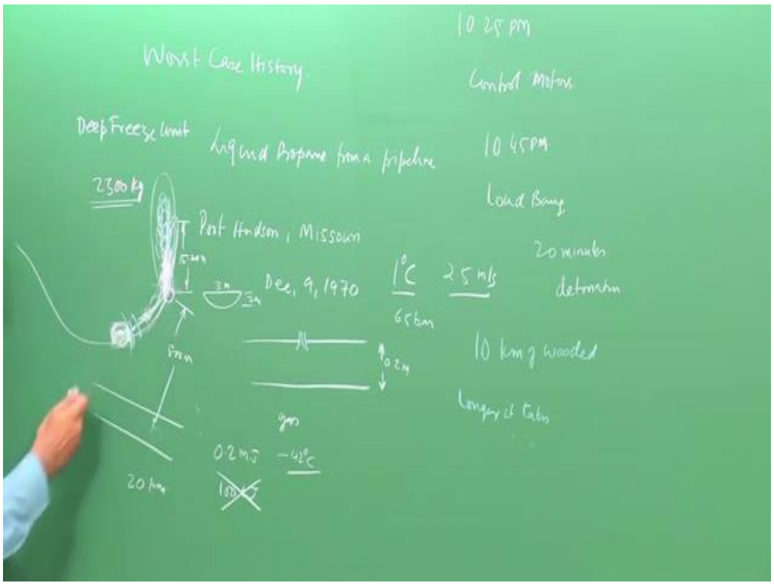

Worst case history ever, this involves in an accidental leak of liquid propane from a pipeline, before getting into the details, let me first tell you when it occurred and what happened. The pipeline ruptured at a place known as Port Hudson. It was in the franklin county, this is in Missouri and the leak happened on December 1970, you know it. So, happened liquid propane was being transported in a pipeline.

This pipeline was of diameter something like 0.2 meter diameter. At a pressure of something like 65 bar and you know from the sight of the place where it was being transported. This particular accident happened at Port Hudson. This particular place was in a valley like for instance you had topography of the place something like a valley.

Something along the slope of the hill you have the pipeline which is sort of buried pipeline. It is transporting liquid propane at a high pressure, why it is transported at high pressure is, you know you propane is a gas normally. It liquefies or it becomes a liquid at minus 42 degree centigrade.

However at high pressure you can still transport it as a liquid. In this particular pipeline which was somewhat old something like forty years old. A small at the weld fracture at the sort of a leak developed and liquid propane started gushing out from this particular pipeline. Let me put it in a buried context and then let us go ahead and see what happens. You have the buried pipeline over here leak develops and liquid propane gushes out of the particular hole or the weld meant, where in the failure has happened.

The moment the liquid propane starts to gush out, upstream up the particular leak people stop the supply, but then there is lot of propane here and something like 2300 kg of propane got spilled from this particular leak. You know when liquid propane comes out, you know the liquid propane is initially at the ambient temperature. Mind you it is a December month.

The ambient temperature was something like 1 degree centigrade being a winter month and there was this wind along the valley. Along the slope of the mountain at around 2 point 5 meter per second this is the wind speed you have the propane gushing out. The moment it gushes out in from the high pressure region, it sees the atmospheric pressure and because of the atmospheric pressure it flashes into vapor.

The moment it flashes into vapor it absorbs that means the liquid flashes into vapor. Therefore, it absorbs the heat and therefore, what happens is even though you have gas which should be there at atmospheric pressure because of the removal of latent heat, you have liquid droplets which are being forms. You have something like a fog of droplets which are being formed and you have a spray.

The nearest place from which people could observe was, something you have a highway, which is something at a distance of around 800 meters away from this particular place where the leak develops. Therefore, a few witnesses observe this particular spray and this spray was something like almost like 15 to 20 meters high. That means you have huge spray of the gaseous vapor, you have the droplets of vapor which are being formed. Well this is what happened and I said the nearest place was the highway.

Then because of the wind conditions, you know this particular cloud. Now, you have something like whitish cloud which is being formed. This cloud moves along the wind speed and the wind speed drags it along the ground. Therefore, you know the atmosphere transports this cloud and we will be studying about atmospheric dispersion at that point. We will again revisit this example, but this this cloud gets transported along the valley.

At a place something like 600 to 700 meters away. You had a concrete warehouse you know you had this building and this was a 2 storey building. In the bottom you had something like 4 or 5 rooms which housed a deep freeze unit. You know in this deep freeze unit you had something like 4 deep freeze units in this thing. As the cloud move you know it was a winter month everything was closed.

Through this sliding doors of concrete warehouse what happened is through this concrete through this sliding doors, the cloud sort of diffused then and you had a mixture of propane with air being formed over here. I will revisit it how the mixture gets formed therefore, you have the cloud which comes in here. May be at the point of spill itself the gushing was so, heavy because of the high pressure. That a pit of width around 3 meter diameter and a depth of something like 2 meter diameter got formed.

That means that is the speed and because of the high velocity it also entering there. Therefore, you have in this sort of spray which is being formed here air and propane available at this air propane blue into this particular warehouse. You had conditions wherein you could have a flammable mixture or even a detonable mixture, but let us revisit this problem. The leak happened when the time was around 10:25p m. It is at night you know the place is not heavily habited and therefore, you have just a few houses and may be essentially a wooded area.

For some time like 20 minutes nothing really happened. The cloud has drifted along the valley and what happened is, it did not see any sort of ignition source or any spark or anything, which could ignite it and it just entered this warehouse, wherein these refrigeration units were there.

In the refrigeration units, you have the control motors of the refrigeration system that is in the deep freeze units, control motors let us say. The heat source in these motors plus the spark from these motors it ignited a flame in this particular warehouse. Therefore, you know to ignite a propane air mixture you need something like 0.2 milli joules of energy.

Whereas, to cause detonation in propane air you need something like hundred kilo joules of energy. Therefore, to have a detonation being initiated in this place is just about impossible and therefore, let us say a flame gets started because of the blockages which are available in this particular room, which is housing these deep freeze units. The flame develops into a fast deflagration and then probably into a detonation. When you have a detonation or very something like a cozy detonation, I will again discuss this a little later.

What happens is the pressure behind it ruptures the warehouse, which means it should have been a detonation to have ruptured this. You have the cloud which is available and this shock wave created ignites this particular cloud over here. What people observe is up till around 10:45 p m nothing really happens. When at 10:45 p m 20 meters after the leak originated, you see a lightning in the leakage area. Just a brilliant flash as it were, saying that something all of a sudden has happened followed by the loud bang.

Mind you before this loud bang from this lightning of the propane air cloud, which is formed over here. Prior to that a bang was heard when this thing got initiated a detonation got formed here. Therefore, you have a detonation which occurred here due to blockages flame to detonation transition, which creates a blast wave and or a shock wave. The shock wave ignites it that is when people observed a lightning in the sky, in the valley.

This cause the detonation and therefore, you have something like a waiting period of something like 20 minutes, after which you create a detonation and this detonation was. so strong, that may be people who have witnessed to this particular accident from the highway. When they were just toppled down and even at a distance of something like almost like 20 kilometers away, it is reported that one of the cops who were driving his vehicle he lost balance because of the wind effect. That was the powerfulness of this particular explosion.

Therefore you find, that in this case the accidental leak of something like liquid propane forms something like a cloud or fog of cloud, which has something like 2300 kilograms of propane. Apparently nothing really happened because of atmospheric dispersion and because of the intense velocity and turbulence, with which the liquid propane is gushing forward. It entrains the air, mixes with air. You have a flammable cloud formed right here, but this cloud keeps drifting gets into the warehouse.

Gets ignited in the warehouse where it meets its first ignition source, forms a flame it becomes a detonation, knocks out the warehouse. The shock from this warehouse is what causes the particular detonation. The detonation was so strong. let us put some numbers into it like 10 kilometers of wooded area around the site, that is got damaged. Buildings around 10 kilometers got damaged and we if we look at it, you know we are seeing that the sky got lit up or lightning sort of thing happened 20 minutes afterwards.

That means you wait it for 20 minutes and therefore, whenever you have a leak you know the longer it takes, longer it takes to ignite, the more and more of the combustible cloud gets formed and you run into the danger of forming a large explosion and this is what happened which means you know for an explosion to occur again redraw what we are learning, what we have learned.

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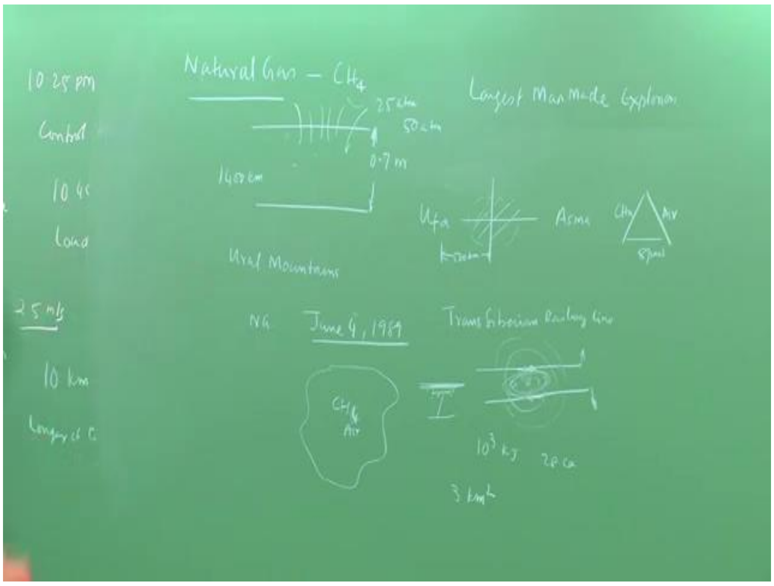

You need a fuel, in this case it is c 3 h 8 propane, you need air to mix together. In this particular case there is no doubt that because of the high level of turbulence with which the spray is getting formed that it get mixed over here. You have a mixable cloud and once the valley gets lit, then what happens is the heat from this, sort of devours you know it feeds into the fuel rich propane which is still available.

You see a red glow of fire which happens afterwards. It consumes the remnant of the propane air or propane rich mixture which is formed. Therefore you have something like a fuel, you have air, you have an ignition source within the warehouse, which starts a blast wave or which starts a detonation. This detonation breaks through the door and windows of this warehouse and ignites the cloud and this is what happened in this particular case.

Well, this is a well recorded case and the atmospheric dispersion has been done. We will do the atmospheric dispersion a little later, but this is one of the instances of a practical explosion, of an accidental explosion. Having said that let us come to the next example. We will look at some other gas. Let us take a look at let us say natural gas. In a natural gas, is widely used nowadays. There is a means you have the gas fields from which the natural gas is taken and is transported in pipelines.

One such pipeline in Ural Mountains had massively. Let us take a look at it, this pipeline was something like almost like 0.8 meters in diameter. It was conveying natural gas. Natural gas is mainly methane c h 4 compared to propane which we just now talked off.

Mind you in this case it was liquid propane, we are talking of gaseous methane over here which is being transported. This was being transported at a pressure of something like 25 atmospheres. The pipeline was designed for fifty atmospheres, the reason I give this is the following. In an overall length of something like 1 to 2 kilometers, may be the pipeline got ruptured and that means it is a massive leak.

The operators who are supplying this pipeline, this was from the gas field in western Siberia. They found that well the pressure has gone down, they pump more and more thing. Therefore, you had a huge spill of natural gas which was being formed. Now, whereby did this accident happened. Let us put some dates into it. This happened on June 4th 1989 in the Ural Mountains and the leakage was something like 1400 thousand 400 kilometers downstream of the gas supply station.

I am sorry the diameter of the pipeline was 0 7 meters not 0.8 meters. It cracked as I said over a distance of 1 to 2 kilometers giving a massive leak. Therefore, what happened you have a massive leak of methane taking place. A huge cloud of methane and during the leak because of the large thing, it does not entering too much of air unlike in the previous case. Wherein you had liquid methane flashing into vapor, drawing lot of because of the high turbulence with which it is getting out.

It is turbulently entraining lot of air in forming a cloud at the exit itself at the exit of the leak itself. In this case you know it is not entraining it is not able to entrain. So, much of air, you have a cloud of methane plus a little bit of air which is being formed. Now, this particular place, where this leak happened, was at a place known as near to a place known as Ufa. It was this it was between Ufa a place and the other place is Asma in Siberia at a distance of around 500 kilometers from Ufa. This is where the spill took place.

In this part of the terrain, you have the trans-Siberian railway you know in in USSR, in Russia you have this trans-Siberian railway line running between Vladivostok in the east. That is near to Japan to Moscow. This is a double track railway line that means you have 2 railway lines, 2 trains can go up and down. At this particular place near ufa you have this trans-Siberian railway as luck would have it, just after this leak got developed. You know you had the leak taking place in this particular region. You have a cloud of natural gas that is methane and it mix partly with air. At this point 2 trains were travelling simultaneously in the opposite directions.

That means you have a train going from east to west, the other going from west to east. Whenever the trains are travelling you have intense turbulence in the region between the trains. This turbulence help to mix the methane that is you should have put a c h 4. The methane and air together you form a good combustible or a detonable mixture. These are electric trains and you have this electric trains. That means you have overhead electrical line, you have spark always available here.

This spark ignited the cloud here and when this ignited, you know the force of the detonation was so large it formed a detonation. It could not have formed directly a detonation because spark does not have an energy. We saw that to be able to directly form a detonation in methane air mixture which is stoichiometry, require something like 10 to the power of almost 3 kilo joules.

Apparently a flame got formed you have the blockages due to the railway carriages over here, wagons over here. In this wagons may be some 500 people were travelling, essentially school children. You know when these wagons are there, it creates turbulence it creates blockages the flame becomes a detonation and in the detonation because of the force of the shock wave. In the detonation something like 28 carriages were just blown off from the track.

Also that track of the 2 railway lines also blow away. That was the force of this explosion and all the 500 people who were in this carriages got killed and that was the force of this particular explosion. Therefore to sum up, we can say that this particular explosion which not only blue off the carriages, but also demolished the railway line and over any area of something like 3 kilometer square. What happened is that the trees were uprooted, the buildings were decimated and this is the force of this particular explosion.

Therefore, what do we learn from this particular example. This is known as the largest ever man made explosion. As I said this happened in the Ural Mountains and it happened on June 4, 1989. Well, that have been case studies of this particular explosion including the dispersion of methane gas. We will look at the atmospheric dispersion later, but what really found is the turbulence created when the 2 trains were moving as fate would have it. We have 2 trains moving through the particular cloud of methane at the same time created turbulence mix with air. You had the electrical spark and we had the fire triangle, wherein in this case you have methane gas.

You have air over here, you have the spark which creates a flame, the blockages of the train cause it to become a detonation and the wagons just get blown off. This is the case of a natural gas explosion which happened on Ural Mountains in June 4, 1989. Since we have with natural gas, let us take one more example of a case study of an explosion this happened in Cleveland.

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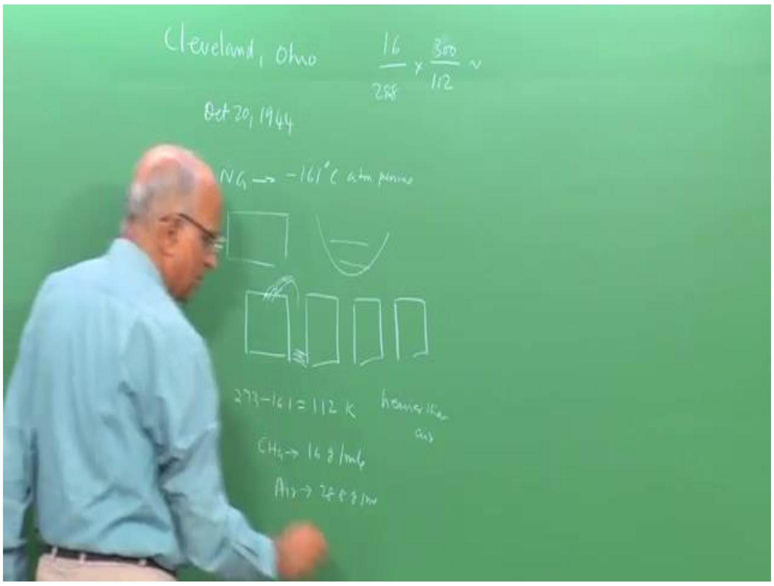

In Ohio, this was on October 20, 1944. You know this involve the same natural gas, but a liquid natural gas. You know when we talk of natural gas which is methane, you know people prefer to transport it as a liquid because it is denser. It is the temperature of the liquid natural gas is something like minus 161 degree centigrade at atmospheric pressure. We have l n g which is liquid natural gas, maybe it is noncorrosive it is harmless liquid noncorrosive.

It does not have a particular smell and this is being this is transported from all over the world in tankers may be through pipeline sand through wagons. The reason being you know you have an insulated container which can hold this particular low temperature thing. In the hallow pressure and you transport it in this case was a storage area, wherein you have tanks something like 4 storage vessels in which liquid natural gas was being stored.

As I said liquid natural gas is stored at cryogenic temperatures 161. It is formed by the mixed refrigeration casket process at these low temperatures and stored over here. You know I so happened one of the containers developed a leak. The liquid natural gas escaped from this case from the storage bin or from the storage vessel. Now, we said well liquid natural gas is at low temperature. Let us put it in terms of kelvin.

You have 273 minus 161 which is equal to 2 over here 1 may be something like we are talking off hundred and 12 kelvin which is the temperature of your liquid natural gas.

You know at this particular temperature, since the temperature is low liquid methane let us say what is the molecular whether it is denser or heavier.

You know if you talk of c h 4, the molecular mass is 12 plus 4 16 grams per mole. When we talk off therefore, compared to air whose molecular mass is something like 28 point let us say 8 gram per mole. It is lighter and therefore, whenever let us say in the previous example. When we say l n g leaks, now it tends to diffuse into the atmosphere being a light gas, but in this case you have the liquid methane which is at low temperature. The gas coming out is at low temperature of the order of this low temperature and because of this low temperature it is much heavier than air.

We can have an expression, we can find out what is density is because the in proportion to the molecular mass. Therefore, you have 16 divided by 288, you have the temperature in kelvin, which is equal to something like hundred and twelve. That means we are looking at the density. Therefore, it is hundred and twelve divided by we are talking of 28.8 here 16 by 28.8. The ambient temperature let us say is 27 degree centigrade, that is 300 kelvin.

Thus this becomes heavier than air and this becomes around 1.5. Therefore, it is heavier than air and therefore, the leak from this of the low temperature natural gas sort of hugs the particular ground.

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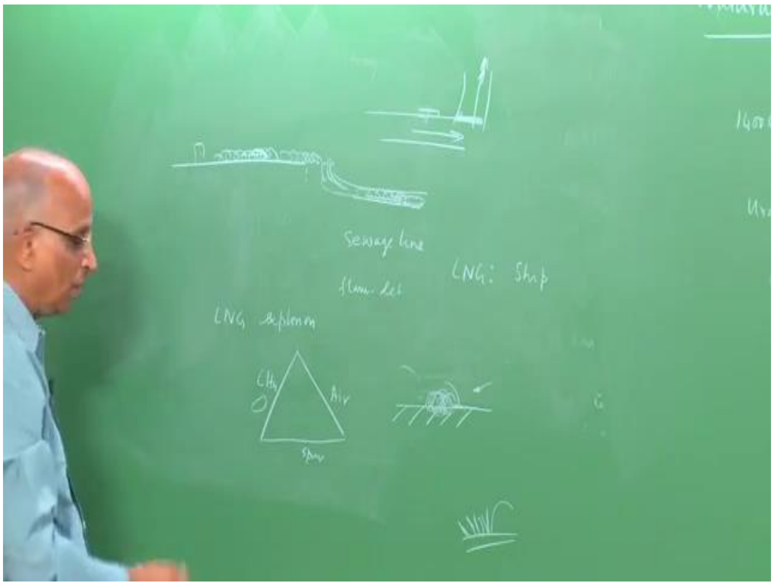

In other words let us draw this again. We have the natural gas at the low temperature escaping from the storage vessel. Being a low temperature gas it sort of hugs the ground. It is on the ground, the conditions of the air are not specified, but perhaps you know it would have been a low wind and the low wind speed. Therefore, the liquid natural gas or the natural gas hugs the ground and travels forward. There was a sewage plant at some distance from the storage area.

In a sewage plant, you know you have these perforations on the ground. You have the sewage gas coming over here you have this process and when this heavy gas goes here it enters the sewage area. Enters the sewage area and enters the sewage pipeline. Therefore, you have natural gas that is methane gas, you have sewage gas you have air in it. All these things get mixed in this particular sewage line when the mixture of sewage gas the natural gas and air are mixed together. You know because of the velocity apparently some spark occurs inside. There is a flame being formed, well I cannot expect to directly initiate a detonation a flame gets formed because of the blockages which are available surface roughness of the pipelines etcetera.

This flame becomes a detonation and what happens, you know whenever you have the sewage lines which are laid, you have the manhole covers which are kept on the road side and the sewage line is over here. The manhole cover sort of sky rocket because of the detonation which occurs in this particular sewage line the sort of sky rocket up. It enters the houses, causes fire in the houses and causes lot of discomfort. This is the case of we say an l n g getting into an explosion.

In this particular case also, we talk in terms of a low temperature methane, mixing with air also mixing with sewage gas in the sewage line and how does it go. It is transported by atmospheric dispersion, the low temperature gas which is heavier gets into the sewage line and that is where the explosion occurs and well the incidents occurs later on. Therefore, you have a spark in the particular sewage line which causes the explosion. Well this is the case of the Cleveland explosion, which happened on October 20th 1944.

In this particular case, in addition to blowing up homes in sky rocketing of the manual covers you know you sort of destroy the township as it were. Therefore, whenever we talk in terms of l n g and you know l n g is an important fuel as on today. It is being transported as I said by ship. You know whenever we talk of l n g leak on the ground. Let us say I have the ground over here, l n g is let us say leaking from a reservoir here.

It falls on the ground, cools the ground and therefore, when the ground gets cooled the liquid natural gas does not increase in temperature and mix with air, but supposing the same leakage happens from the ship. There are special ship available for l n g transport, we have all over the world including the Atlantic Ocean, Indian Ocean.

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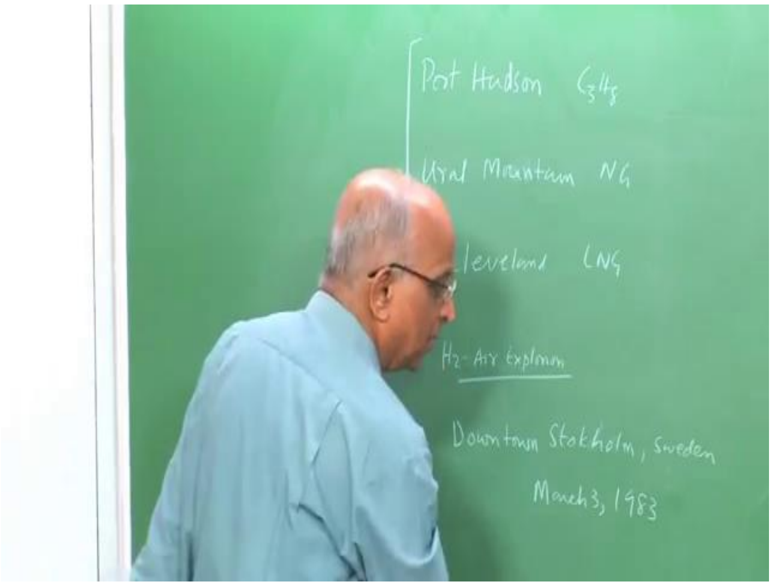

We have birth for ship even in India and therefore, whenever you have l n g spill over water the turbulence in the water may sort of allow the mixing with air. Therefore, the transport of l n g has to be done with caution, based on this particular example and the possibility of an l n g explosion. In all these 3 case studies which I have done, which I have just now gone through, what is it we find. Now, let us quickly put things together in proper perspective. We talked of the case over Port Hudson, wherein you had liquid propane from a pipeline.

We talked in terms of the Ural Mountains at Ufa, wherein you had the natural gas c 3 h 8 as a liquid. You have natural gas and in Cleveland, Ohio wherein we talk off liquid natural gas and all these three apparently caused a detonation which caused lot of damage around, including even to the extent of pushing up the manhole covers. Making them fly like rockets as it were.

Therefore having seen these 3 cases it is now time we focus on 1 or 2. Let us take one more example. Let us take the example of a hydrogen air explosion. You know I deliberately take this example because it is not very sure whether in this particular case we had a detonation or just something like a pseudo detonation or fast deflagration. Therefore, let us take a look at this hydrogen air explosion. This happened in Downtown Stockholm in Sweden this happened on March 3, 1983.

The incident was the following, there was this particular truck, which was carrying the cylinders, different cylinders containing different gases. In this particular accident the truck was parked in Downtown area in Stockholm. You know this truck, you know stopped there to supply gas to different establishments around the particular place.

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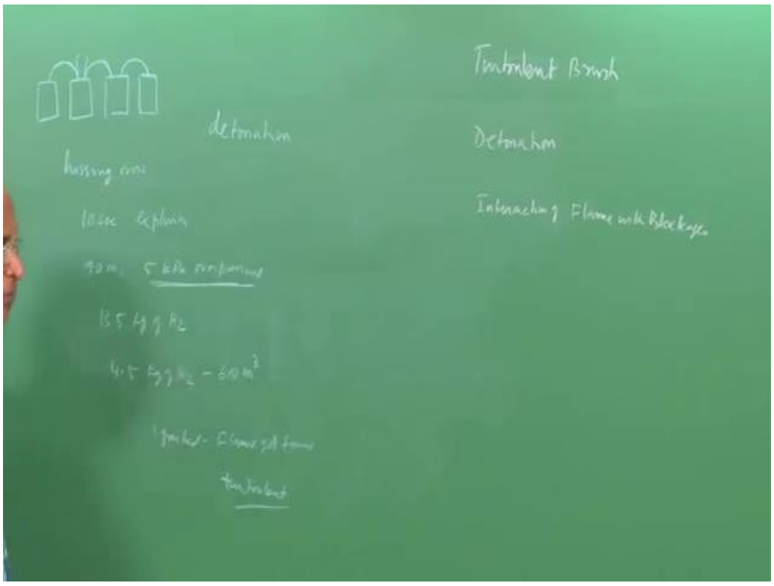

What was there you had in the truck in addition to other gases, you had something like eighteen cylinders of hydrogen at 200 bar and all these things were interconnected together. Something like 18 of them and along with hydrogen gas in the cylinder, there were other gases and the operator was shifting the other cylinders for supply. He found that there is something like a hissing noise which he hears, coming from the cylinders.

Therefore, you wants to investigate it the moment he hears it he goes down, but within 10 seconds he hears some, there is an explosion and what happens is may be at a distance of something like 90 meters away. Based on the breakages of a glass from a building we say yes 5 k p a over pressure was created.

We have studied different over pressures, what causes glass to break we say 5 k p a over pressure can cause it. Apparently what is happened is there has been a leakage and the amount of leakage was something like totally 13.5 k g of hydrogen got leaked. Out of which when the explosion started at 10 seconds apparently something like 4.5 kilogram of hydrogen was available in a cloud of something like 600 meter cube.

Let us take a scenario, you have something like several cylinders which are available, a leakage of hydrogen takes place something like over an area of 600 meter cube. It is possible this cloud gets ignited. Perhaps a flame got formed. When the flame gets formed, it mix the blockages, it accelerates because we saw whenever you have a high speed flow interaction of the high speed flow with blockages creates shock waves or creates expansion and compression waves which are weak shock waves.

In that presence because of the turbulence associated with these wave processes may be the flame becomes turbulent. The acceleration of the turbulent flame leads to something like a turbulent flame brush, which is severe turbulence. Is quite possible that this turbulent flame brush travelling with high speeds could also result in 5 k p a over pressure.

Therefore the accidental leak of hydrogen from these cylinders in Stockholm does not necessarily say a detonation is formed. Therefore, but it is also possible that a detonation of this cloud could have resulted in this over pressure, but it is also quite probable that even if it was not a pure detonation, it was a high speed flame. We could still expect to get this type of over pressure. Therefore, I think before we put this example through.

We must be a little more clear, what we mean by this. Let us say turbulent, brush of flame highly moving at high velocity and what we mean by a detonation, is a detonation formed in this case or not. You know to be able to do that we should be able to understand the acceleration of a flame to high speed. Therefore, let us spend some 2 or 3 minutes on interaction of a flame with blockages.

All what I am trying to say is, it is not necessary that you have these pressure waves and damages coming only from a detonation, but we could also have the pressure waves that damages. In this case you know what happened buildings got damaged and people were thrown off because of the waves created by the particular flame brush or a detonation.

Therefore, it is not that only a detonation can cause damage whereas, in the other 3 case studies which we just now saw, in all the cases a detonation was formed.

In this particular case even a turbulent brush or a flame brush could have caused such a problem. Therefore, what is this turbulent flame brush under what conditions does this get formed, let us spend a couple of minutes on this particular problem.

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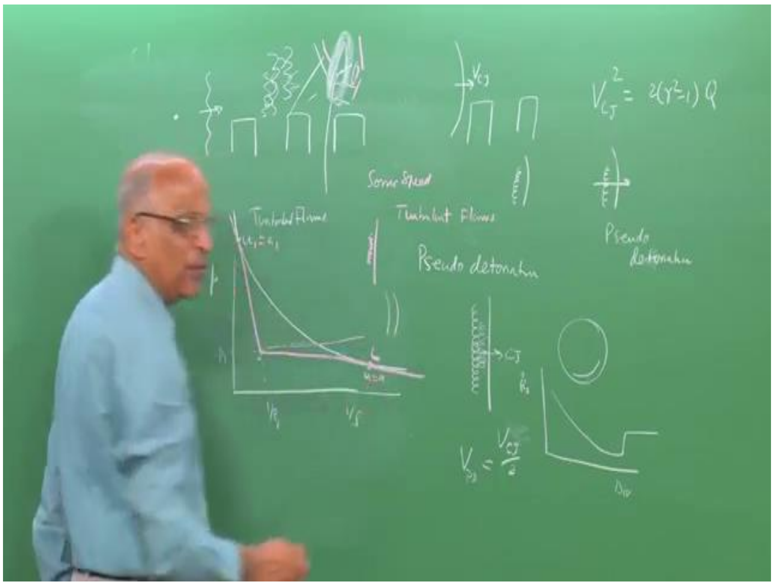

You have blockages which are there, may be in the truck in terms of cylinders, may be outside you have the blockages from buildings and all that. What happens if a flame is being if a flame is travelling, well it initially travels at laminar velocity. A flame is formed here depending on the conditions. This when it interacts over here may be this is the zone of higher turbulence. Whenever you have zone of turbulence the flame becomes wrinkled and when it wrinkles well it engulfs more gas. It becomes more and more wrinkled.

If the status is such that you have the shock waves and or weak shock waves which are being formed in all particular direction you have slip streams, you have vertex and all that. Therefore you have something like an intense turbulence over here. You have something like a flame which is formed, which is highly turbulent. Well we have seen we have distinguished between a detonation and a flame in the reaction hugoniot. Let us plot that figure again, we said well pressure versus 1 over density. The initial pressure is let us say p 1, the initial density is 1 over rho 1. Therefore, this is my initial point, well I have the reaction hugoniot over here.

Therefore, we talk in terms of the upper the Chapman Jouguet points, in the particular plot which I show over here. We say well the chapman Jouguet point, is the tangent from the initial point to the reaction hugoniot over here. Therefore, this is my chapman Jouguet point, which we says upper chapman Jouguet point. This corresponds to a detonation. If I try to extent my hugoniot and then I plot the tangent to it that is the rally line from here.

I get the lower point, well we said you know the region between this to this is somewhat stable is somewhat can be met in practice. Here the lower chapman Jouguet point, here the velocity behind the flame is equal to the sound speed. Just like we have u is equal to a such that u 1 is equal to a 1 here. Therefore, this corresponds to the lower chapman Jouguet point, but what was the characteristics of a flame.

The flame is always such that you have an expansion solution. We cannot get compression solution, if we talk in terms of a flame even if it is moving at high velocities. When you have these blockage and you have the flame accelerating, it has been observed that sometimes the flame is. So, turbulent that it almost travel at something like the sonic speed. That means it travels at a speed corresponding to the sonic conditions behind it.

You know therefore, you are having something like a choked flame or rather the chemical energy supplied to the flame is such that, it almost chokes it and it travels at the sonic speed, but how is it possible that is one question we have to ask, but since we are talking a flame has an expansion solution. How do we get pressure over here. Now, when we say you know we are saying there are shocks ahead of it.

If there are shocks ahead of it the pressure increase and therefore, in this high zone of pressure that means the pressure is no longer atmospheric pressure here, it is high pressure. In this zone of pressure if a flame is travelling and it is travelling at the sonic speed. Well we still call it as something which is a turbulent flame brush, but since the turbulent flame, the common notion is the pressure should be less than the ambient pressure. We also call this as something like pseudo detonation.

In other words a pseudo detonation is a shock front, behind which may be chemical reactions are taking place, but the chemical reactions are such that, it is not able drive the shock front effectively to form a c j detonation. What happens is the net flame, that is the net shock now travels at a speed, which is around, which is such that the speed is corresponds to the sonic speed behind it, which in effect corresponds to the velocity of c j detonation divided by 2.

This is the typically the velocity of a pseudo detonation. That means you whenever you have a shock which forms chemical reactions, but these chemical reactions are decoupled from the shock. You say well it is a pseudo detonation, you still have a compression solution over it. The compression solution corresponds to this particular l point and you call that as a pseudo detonation. Whenever you have blockages, what happens…

Let us assume, I have blockages and in this blockages let us say a chapman Jouguet detonation at v c j is travelling. When the diffraction takes place at the blockages, well you know the gas expands and when the gas expands well I have the shock here. Well the chemical reactions, now the shock expands and therefore, it velocity decreases, when its velocity decreases the chemical reaction gets decoupled. Therefore, the effect of losses from the blockage yeah are such that.

Well I can have a pseudo detonation, but we must also remember, we had developed an equation for c j velocity v c j square is equal to 2 into gamma square minus 1 into the heat released. Therefore, you know we cannot imagine that the heat loss due to blockages essentially cause the c j velocities to drop in, drop to a value around half the value, but it is effectively what is happening is. The decoupling behind the shock and this decouple chemical reactions from the shock is what we call as a pseudo detonation.

Well it is also something like a highly turbulent flame brush, which is being formed. The initiation of a detonation, if we go back to what we discussed about initiation, we always found a shock wave and under critical conditions of initiation well the flame lag behind or the zone of chemical reaction lag behind the shock by a particular small distance which means in practice I could have a pseudo detonation, if I have plot the distance over here.

I say I have something like the shock over here r s dot over here. It decays in strength travels as a pseudo detonation and then becomes a detonation. We did discuss this earlier this is equal to r s dot as a function of distance. Therefore, you know in the case at Sweden, perhaps in the example of Stockholm, wherein hydrogen leak.

You form something like highly turbulent flame brush or a pseudo detonation, which created the wave form. Therefore, it is not essential that you always get something like a detonation to damage buildings. You could also get highly turbulent flame brush which could cause havoc.

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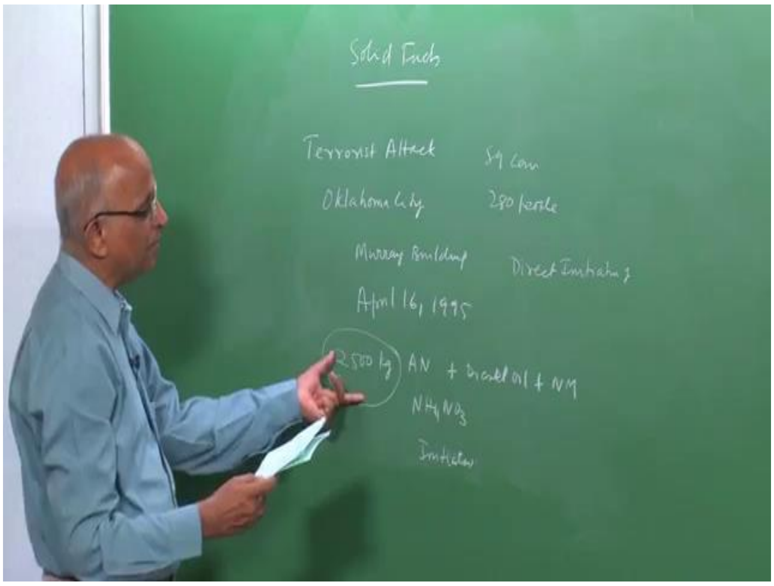

Having said that let us take 1 or 2 small examples, which relate to other substances. Let us take solid substances, solid fuels. I will just concentrate on 2 typical examples. The first example I take is terrorist attack and this terrorist attack happened at Oklahoma City. In this Oklahoma city a nice posh building a 9 storey building, a fatal building known as Murray building, nicely done with lot of glass front and all that, was there.

It was the pride of Oklahoma City and some disgruntle elements in society. They wanted to attack this building and what they did was. They got together on April 16, 1995. I take this example because we have lot of articles on the terrorist attack and Murray building. It came in readers digest also a few years ago. You know, what was done they took something like 2500 k g of ammonium nitrate n h 4 n o 3 crystals, ammonium nitrate n h 4 n o 3 and mixed it with diesel oil and some nitro methane.

See nitro methane is a cleansing fluid. It is also used as a fuel for sports car. This is a fuel this is a fuel this is an oxidizer. They mixed 2500 kilograms of this, parked a truck just outside the Murray building. They made sure that it gets initiated into a detonation by forming a strong shock using some other initiator.

That means they directly initiated a detonation, initiated a detonation in the 2500 k g. This particular the detonation was so strong, that it blow off about more than half of the Murray building totally. It damage something like 89 cars, it kills something like 280 people who were in the building and around. It was the worst ever tragedy one could think off.

You know these are the type of things which havoc which a detonation can do. We must remember that maybe we should take these things a little seriously and make sure that such terrorist strikes do not happen, but getting back to this particular example. This is a case of direct initiation of a detonation. In this particular mixture of 2500 k g and the amount of substance was so large that it just blows off.

The source was the source of this namely ammonium nitrate, diesel oil and nitro methane was kept in a truck and it created, it was forced to create a detonation by a strong initiator and that cause the damage as it were. Well we have such number of explosions taking place one of the recent ones which I want to just highlight before I stop here. Such that we can get started with confined explosions in the next class or confined and unconfined. Relates to the example at which happened last year, namely the Boston marathon.

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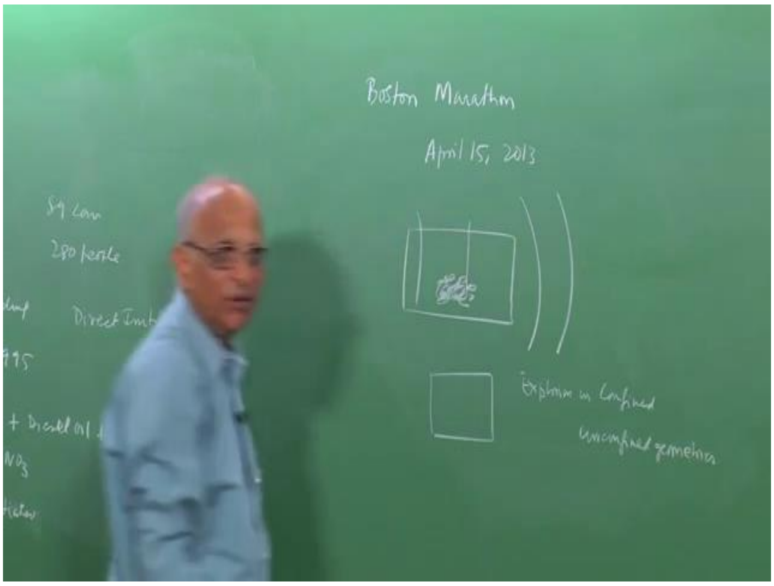

This is on April 15, 2013, you know here what happened is, you had this pressure cookers. That means you had cookers which can hold pressure and that is how we cook our food. In 2 pressure cookers, combustible substances were kept and may be some energetic substances. Compression or detonation was initiated and when high pressure gets developed in the cooker. Well the cooker just ruptures a blast wave is formed.

This blast wave disrupted the Boston marathon last year. It resulted in fatality being three, but more than the fatality the type of damage and the type of people getting injured is something which is very undesirable. Therefore, in this particular case you have a confined vessel of a given volume, in which we start an explosion. In the next class what we do is, we take a look at explosions in confined and also in unconfined geometries. Well, thank you then.

An announcement please, we covered the subject of flames and detonations in as much as they influence the explosions in the lectures 20 to 27. Additional reading material and a set of homework problems, pertaining to these lectures are given in the downloads of this video course.