Introduction of Explosions and Explosion Safety
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Lecture No - 02
Blast wave in an Explosion Prediction from Dimensional Considerations

Well, Good morning. I think we will first recap what we did yesterday we talked in terms of the explosion being define as something which makes a loud noise, a loud bang which is followed by disruption of things in the zone of the explosion.

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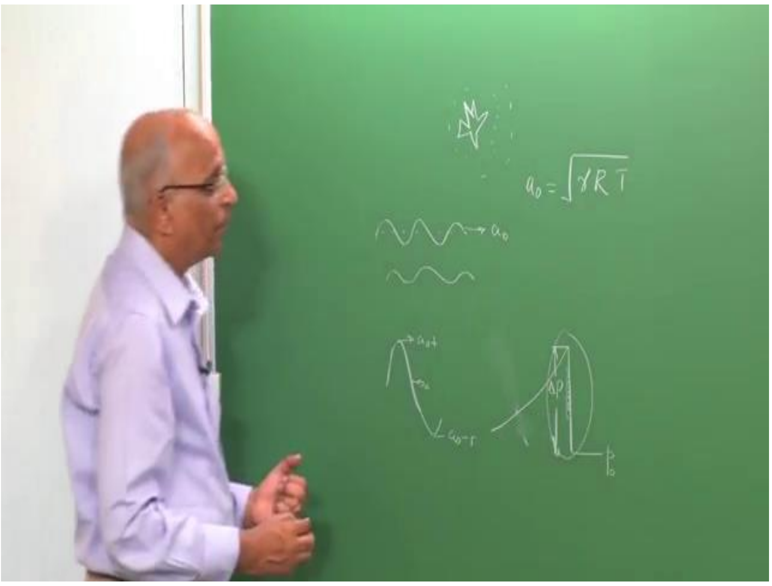

Like for instance, I have an explosion over here, what happens is it, not only makes a loud noise, but also it disrupts the things at the zone of the explosion in and around the zone of the explosion. Why did it happen?

We talked about sound waves, we said well the sound wave propagates through a serious of compression and rarefaction, may be small compression rarefaction about the mean value. Let us say, these are pressure perturbations, any pressure perturbation is associated with a temperature perturbation. We related the temperature perturbation with the pressure perturbation which are there in a sound wave. We also find that there are velocity perturbation in this and the front propagates with a sound speed a 0 in the case of, in the case of a sound wave which propagates as a sound wave.

Now, what happened was we told ourselves when the amplitude of these motions are large like for instance I have large amplitude which is created by some energy being deposited at this particular point which is sort of more instantaneous. I have a larger amplitude, what happened was this the sound speed, where in the at the crust of the wave where in pressure perturbation is high with the associated temperature perturbation is high we found out the expression the sound speed is given by under root gamma which is the ratio of specific heat into the specific gas constant into the temperature.

And therefore, at this point wherein the temperature is higher, you have the sound speed which is larger here at the crest wherein the temperature is lower. I have the sound speed which is less than the mean value here it is the mean. And therefore, this wave became somewhat steeper and ultimately it became something like a shock wave. This is what, we call this wave which was a steep wave as a shock wave and it increase the pressure from the ambient pressure, let us say p naught to a higher value let us say delta p.

Therefore, this is what is there and what happens behind it you have the trailing of the wave behind the front and this I can now represent as let us say, well I the instantaneous release of energy at a point creates a shock front and behind the shock front well the pressure has to go back to ambient and I have something like a rarefaction wave that is an expansion fan behind it and this is what created a sudden pressure rise which we, which we felt as a loud bang.

Now, what happens let us, put some more time on it. Let us spend some more time on this problem. You know you have pressure rise taking place and we also found that because now the events are not gradual, in this case the change in pressure is very small. And therefore, it could be reversible we also found that air being somewhat of an insulator it does not transfer energy, it does not take the amplitudes are small. Then the air being an insulator, the process is adiabatic, there is no heat transfer taking place.

Therefore, the propagation of sound wave is isentropic, but the moment I have a large amplitude and a steep rise in pressure. The events are not gradual, but sudden I have large gradients in temperature, in velocity, in temperature, in velocity and again you have in pressure. And therefore, these gradients lead to heat transfer effects, lead to sheer effects. And therefore, because of heat transfer in sheer some of the energy get dissipated in the particular wave. In addition to the energy getting dissipated, if I were to plot this figure again, what is it I get?

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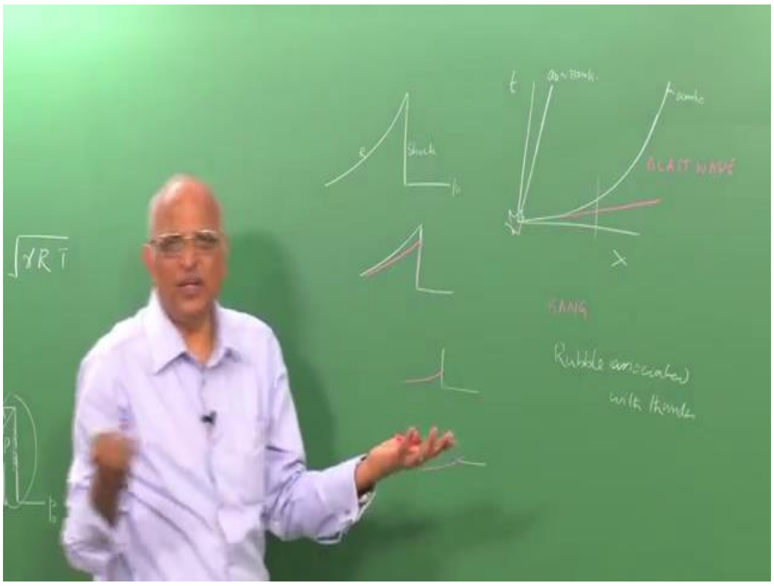

I get well… what will happen, is because of instantaneous release in energy I get a steep fronted wave. This is the ambient pressure and this is the expansion behind it, this is let us say the front of the shock anything sudden is a shock, we found that it travels at speeds greater than the sonic velocity namely super supersonic speed. I have a expansion behind it.

The expansion is what we call as a rarefaction and now the temperature is higher with the result the rarefaction, which moves behind the shock. It moves faster than the speed of this originally ambient pressure well it is 330 meters per second, if temperature is higher rarefaction goes faster. And therefore, what would happen? Let us try to plot it again. You know, since it moves faster as the wave progresses further well the wave progresses further, it goes through some distance, I have the expansion fan, the expansion fan progresses faster.

And therefore, the amplitude of the front now decreases. As it progresses further, it catches more and more with the front. And therefore, what happens is the wave catches in front therefore, the amplitude of the front decreases and ultimately what I get is the expansion fan like this. It has moved further distance over here, let us it plot over here. It has moved a further distance over here and there for you have this and the expansion fan comes over here. Now, with the result the amplitude of the wave motion which is built up or the pressure rise across the front which is compression keeps progressively getting decreased and what did we tell ourselves?

Well in addition to dissipation of the dissipation in energy due to heat transfer due to sheer what happens is now because of the rarefaction fan coming in contact with the shock wave. The strength of the shock wave keep decreasing and ultimately what is it we get? We get something like let us plot it out with a distance x. We had the streak diagram. We had for a sound wave, well this is the speed c naught or a naught at which the sound wave is propagating typically around 330 meters per second in ambient condition.

Now, what is happening initially I got a wave which started at super sonic speed and then the amplitude keeps decreasing that this velocity keeps decreasing. And ultimately it becomes something like this. That means initially I start off with high speed and the velocity keep decreasing, unless until it becomes an acoustic wave in the limit. Therefore, in the near field that is near to the source which release the energy over here, I get a shock wave which subsequently becomes something like an acoustic or a sound wave in the very far field.

Therefore, you know this is how it looks like, if it were a shock which is supported by the energy release, may be if I have a constant velocity shock, may be it would have gone straight like this. But because the rarefaction fan catches up because of the dissipative effects and once the energy is realised there is no energy to drive the shock front it dissipates and this is what we call as the blast wave.

We also told ourselves because the pressure is continually changing, when pressure changes well I have the velocity which is changing, I have a wind effect. Therefore, I have a huge wind which we call as the blast wind. And this is what is the genesis of a blast wind. We can take a typical example, let us say we have lightening taking place, what happens when lightening takes place if you are very near to the source of lightening I get a loud bang, I hear a loud bang as it where, but if I am far, in the far field I do not hear that huge thunder or bang.

But what I hear is the rubble associated with thunder, some sort of rubble associated with thunder. This is what I hear. And this is what is may be in the far field, I hear a continuous rolling noise and in the near field I hear a huge bang. And this is what is the signature of an explosion taking place. This is what we did yesterday. Now, let us go forward, let us try to see whether I can, I can still define my explosion in more detailed way. In some way which is stronger, let us say I would like to model it also, I would like to see what are the controlling factor. Can I redefine explosion in a slightly different way?

All what we said is, we can now say when a blast wave is formed, by energy being released at the source, somebody releases some energy at the source. If a blast wave is found, we said well it is an explosion. Therefore, now we tell ourselves well conversely I can also define an explosion if energy release at the source is such that a blast wave gets generated, then I call the energy realised to be explosive. That means, I indirectly tell myself, if a blast wave gets generated by some sort of energy release and let us say this energy release is E naught joules.

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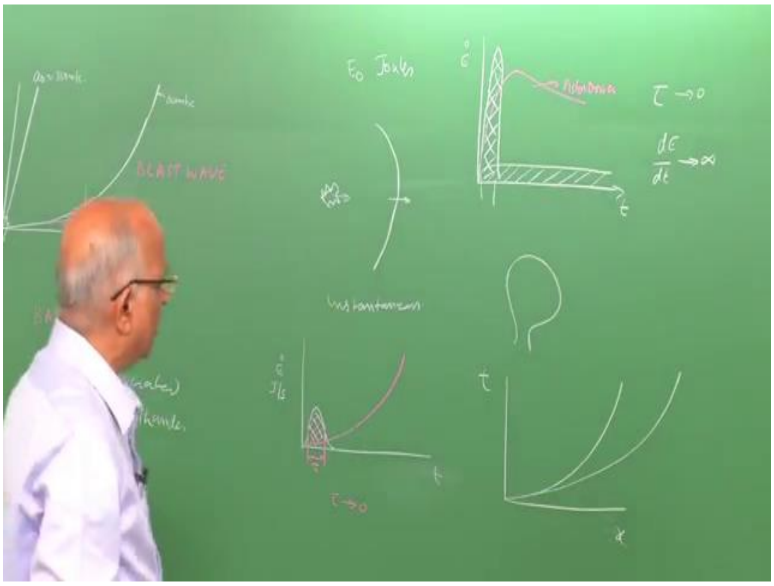

At some particular place and if I am able to get a wave, we define the wave we said wave only transmits or carries energy from the source. It does not physically carry the material from the source into the wave and this is how we defined a wave.

And therefore, we say if the energy release at the source is such that it creates a blast wave, well we can say an explosion takes place. As per the parlance or as per the definitions, normally this energy release must be fast or instantaneous. What you mean by instantaneous? Well let us consider one or two cases. Let us say, well this is my axis, this is the distance x and now or let us say, I am looking with respect to time because I am looking at the instantaneous with respect to time. May be I deposit some energy, I deposit some energy, I start deposition of energy and I finish the deposition of energy here.

The characteristic time of energy release, I can define by let us say the tau over here. This is where the major amount of energy gets deposited. And now, if the time tau, that is tau seconds over which the effective energy gets released tends to 0 well I say, well the energy is released sort of instantaneously. And what happens? A shock wave or a blast wave gets generated and this is how the blast propagates out. Now, if the energy release is more gradual, what would happen? Let us, let us take a look at that scenario, maybe I tell myself again over here. May be this is my time, this is my value of the energy, total energy which is released.

And here I say the rate, this is the rate of energy released. This is the integral behind, it is the total energy release over here. This is so much watts or joules per second. When I take the energy release to be sized that it is gradual. You know what happens. Like yesterday, we had the example of a flute. Let us repeat this example because if you are clear about the basics we can go forward in any direction. What did I do? I blew into the flute over here. And when I blew in to the flute I do have some kinetic energy which is getting released and this is the type of energy which is getting slowly released in the system.

Now, instead of this I also showed you or I also showed you the example of a balloon. May be I have a balloon, I blew air in to it. I consider now my I store some energy here namely the potential energy over here. And all of a sudden, when the membrane burst what happens is, the stored energy is released over a very small time and this is how the energy gas released over here.

Now, when I gradually release the energy it appears to me like a sound wave and if the, even if the magnitude of energy releases is high, if I were to get the magnitude of energy release to be high and if I am able to form something like a, like a blast wave from it. What is going to happen? The continuous release of energy in this zone is going to continuously drive my blast wave that means the blast wave is driven by the energy source even after formation.

Therefore, it is something like a piston driven blast wave. Something like I keep on pushing the blast wave. In other words, if I were to now plot the value let us say on the streak diagram t verses R s or t verses the distance x over here. I have in one case the blast wave being formed over here when the energy releases instantaneous. When I keep on providing more and more energy, well the blast wave will get affected under this is the type of blast wave which I get.

Therefore, whenever I have a slow release of energy, well what is it I get a sound wave. If it is instantaneous like sharply taking place and it falls down. Well, the energy releases so spontaneous that it drives the blast wave and once the blast wave has taken off, the energy release is 0 and the blast wave is on its own. Therefore, these are the three things and this type of a situation, where in the energy release tau the period of energy release is tau is such that it tends to 0 or rather in this case I have d by d t, t tending to 0, tends to be infinite is what we call as an idealized explosion because the once the energy release is given the shock wave or the blast wave which drives it is on its own.

Therefore, we must learn the difference between an ideal explosion which is something where in you have the energy release taking place over a short period of time. You could have a piston driven type of a solution in which the energy release continually drives the blast wave and if the energy release is small over prolonged period, I get something like a sound wave. Having said this, let us also be clear about the mode of energy release.

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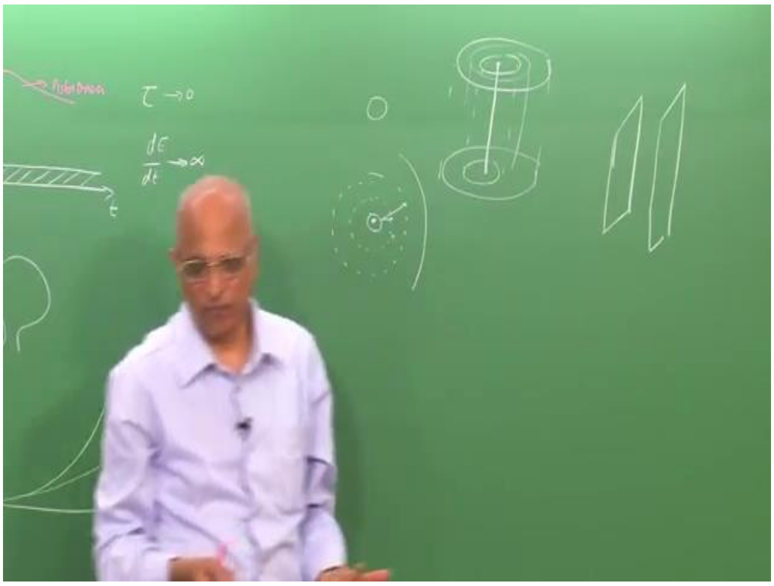

Well, the mode of energy release need not always be as we said in a particular volume. This volume could be a point, may be or could be a sphere in which case I get something like a spherical wave which originates from it.

May be at time t 1, the wave is over here, at as time increases the wave comes here, it keeps on. I could get a spherical shape wave from a point or a spherical geometry over here. If I consider something like lightening or something like a discharge which takes place in a line that means I have if we would have observed lightening taking place in the sky. What happens is all of a sudden there is a line discharge that means I have energy being released in a line.

What is going to happen? Well, the blast wave is going to propagate along this, in the case of a, in as a cylinder. Therefore, I could have in the near field something like a spherical one which propagates out in the near field, I could have something like a cylindrical wave which propagates out. And in the limit, I can also imagine if the energy is released in a plane, let us say something like this and what is going to happen? I could have something like a planar blast wave which moves out.

Therefore, I could have different types of waves namely a spherical blast wave, may be a cylindrical blast wave and a planar blast wave. These are the types of things we could say we could have, let us say a point explosion or a spherical explosion or a cylindrical explosion and a planar explosion. Therefore, this is all about the introduction to explosions, but let us try to go forward. You know what is the problem we are considering? We would like to have a knowledge of how this blast wave propagates. What is the type of damage it does?

You know because our interest is one to prevent an explosion and if an explosion takes place, how to mitigate the effects of the explosion for that I have to first understand the physics of the explosion.

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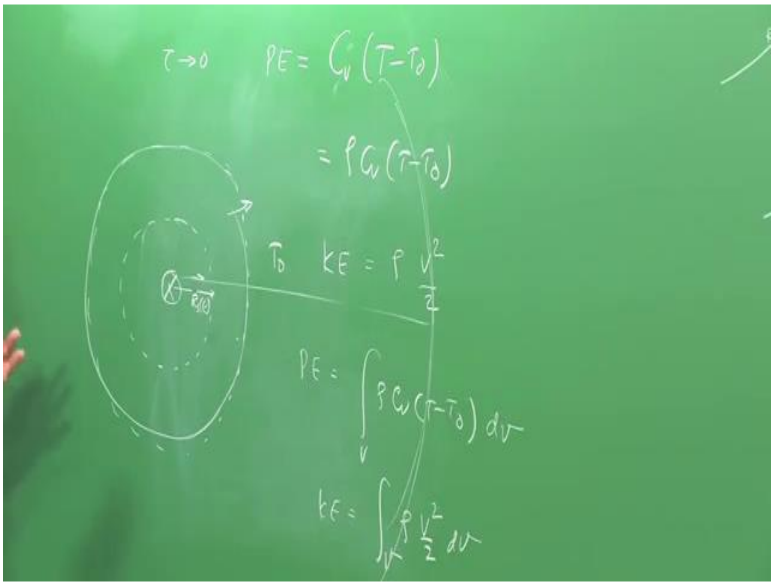

Therefore, let us say well, I deposit some energy E, let us also assume that this energy deposition is instantaneous. Therefore, I have d 0 by dt tending to infinity, that means I just deposited my characteristic time tau over which the energy is getting deposited tends to 0. Then, what is it I am talking of? Well, what is it I have done? We have deposited some energy in a small volume. Let us for the present consider a spherical symmetry and then what is going to happen?

Well, I have a spherical wave which propagates out. May be at time t after the energy is deposited namely the energy gets deposited over a time t and I am interested may be at what is the type of the radius? This is the radius of the blast wave. What is the distance from the centre at time t namely I am interested in this let us call it as radius of the shock wave at this particular time, at time t.

That means a wave gets originated may be at a larger time, the wave is over here. And therefore, what is the conservation I do? See, I deposits some energy here and this energy could be potential energy because I am depositing some energy here and what is the potential energy I have? We know yes, potential energy is a energy let us say associated with the internal energy of your system and it is equal to for per gram of the substance, it is equal to specifically it at constant volume c v into t minus t 0 where in t 0 is the ambient condition. That means it has an excess energy for per unit mass corresponding to this.

Therefore, per unit volume I multiply by density of the medium into c v into t minus t 0 is the excess energy contained over here. Therefore, what is the, therefore this is the potential energy which is deposited. Now, what is happening? I have wave motion and I have velocity of particles behind it. And therefore, this potential energy gets partly converted into kinetic energy and what is this kinetic energy per unit volume? It is equal to rho into v square divided by 2 per unit mass it is, v squared by 2 per unit volume it is this.

And therefore, the energy which is released in the source as potential energy gets continually converted into kinetic energy and part potential energy. And therefore, I tell myself, well the total potential energy is locked with in this because outside this the effect of the wave are not there. This travels at supersonic speed well the medium outside is not affected, only the medium which is enclosed by the lead blast wave or lead shock wave gets affected.

And therefore, if this volume is v, the total potential energy in this medium corresponds to rho c v into t minus t 0 so much joules and the kinetic energy enclosed by the lead shock wave is equal to integral over the volume into rho into velocity square divided by 2. Of course, I have d v here, d v over here. Well, this is velocity. This is volume, maybe I should have written this as small v for volume and this is the velocity over here.

Therefore, what is happening? The initial potential energy which is there gets conserved into the potential energy in the total medium which is now lower which is now spread out and the kinetic energy in this medium. And therefore, if I can imagine in the far field very far away, what is going to happen? If I were to neglect the effects of dissipation and also the effect of rarefaction catching the shock wave, I can tell myself well this the total energy may be potential energy and kinetic energy which is equal to the initial potential energy in the medium is sort of conserved.

And therefore, this energy is unique to an explosion that means in the far field, I can still characterise my explosion in terms of the total energy which is given. We will look at this a little later, but let us keep this point in mind and proceed further. We tell ourselves well the energy is conserved. Can we make any more guesses or can we talk in terms of the problem in some more detail? Let us try that. Let us note, take a look at this energy which gets conserved over here. You know, I tell myself well the total energy gets conserved and what happens if the energy release is instantaneous. What happens if the energy release is little sluggish.

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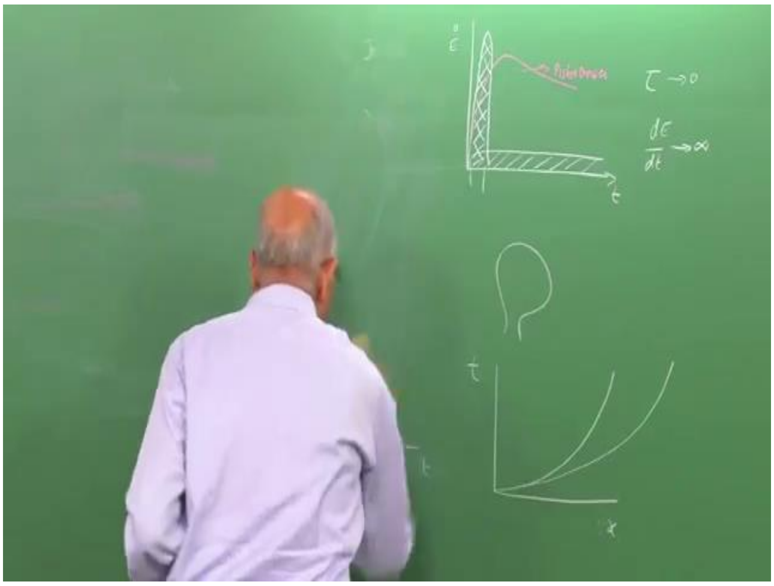

Therefore, let us again plot over here time, what is this? The rate of energy released in one case, the energy released is very fast, in the other case may be the energy release is fast, but over a slightly prolonged duration. In the first case, well this is my characteristic time tau 1 of energy release, in the second case the energy is released may be over a slightly effective energy release over a time tau 2 seconds.

Now, this is the second case now when the energy release is little slower the net energy release is let us say in both the cases is obviously different, may be if it same may be the peak should have been a little lower. But what is going to happen in this case? In the second case, may be because of diffusion of energy the ambient gets heated or rather whenever I have energy release and the medium gets heated.

What happens the medium gets heated and if the medium gets heated the medium is no longer isentropic rather I cannot have the isentropic because now I have heating. Therefore, it is a case where in not being adiabatic and going to have some wastage that means the temperature rise is not going to contribute to my front over here. And this temperature waste becomes sort of my waste energy. The energy from the release goes into heating the medium and when it goes into heating the medium, it does not contribute to drive my shock wave.

And therefore, we say a slower energy release is not as effective as a fast energy release. Well, these are the preliminaries now we go into modelling it and when I try to model it, let us try to model it for a simple situation. Let us see how to go about it. You know in the problem that we are considering, we have energy release at a particular point let us say over here.

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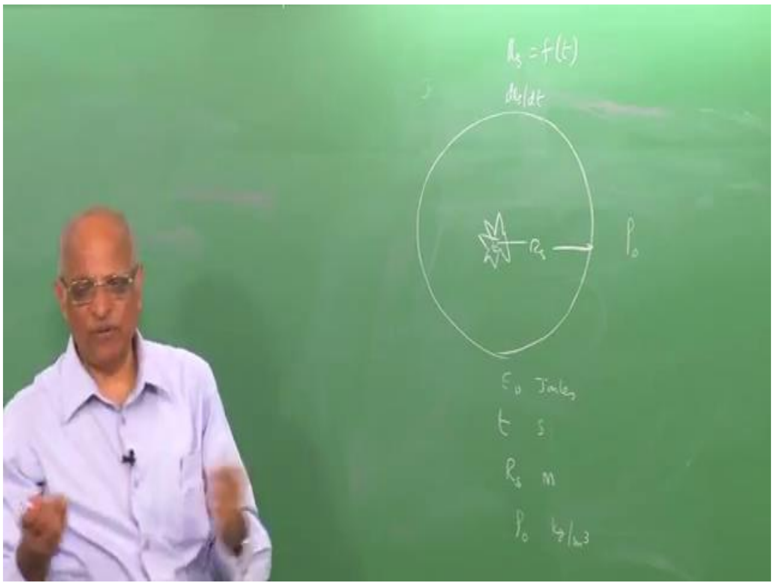

The energy release we say is instantaneous and what happens well at time t I have a shock front and let us say it has a spherical symmetry. At time t, I have a shock front which is at a distance R s from the centre of the source. Let us also assume that the size of this source is so small that it is a point.

Therefore, we have point source which releases energy instantaneously therefore, the time of energy release does not come into the picture because the blast wave is on its own once it is created. The size of the source does not enter the picture because it is a point solution. We call it as an ideal case of an explosion. Well, at t seconds the shock wave is at a distance R s meters. Why is it shown? We have an energy release E naught joules at the source and what is the parameter of the, of the surrounding which influence it. Well, the density of the medium let us say rho naught because it identifies air or any other substance which is there.

Therefore, rho naught is the density so much kilogram per meter cube which for air at ambient pressure is around 1 kilogram per meter cube. And these are the parameter which defines it. Therefore, I tell myself well, I am interested in finding out the strength of a shock wave or the blast wave which is formed when I deposit energy e 0 joules and I want to find out the distance travelled by the shock at time t because if I can find out an expression between distance and time I can always find out the velocity since I know the dependence of R s on time. As a function of time, I can always find out d R s by dt which is the velocity.

Therefore, I want to do this problem, but when I want to do this problem I find well the problem is not as simple as it sounds. The reason being well the shock wave is moving it continually processes more and more of the ambient air point one. Second is well the kinetic energy, potential energy behind it are continually changing. Well, it is totally unsteady problem, totally unsteady and transient problem. And to be able to do this problem, to be able to write the continuity momentum and energy equation using which I solve this problem is going to be complicated. We will do it a little later. But can we do it in a simple way?

In all of us, when we started with our engineering education we start with something know as dimensional analysis and what we call as Buckingham pi theorem. Let us see, whether I can use dimensional analysis to do this problem because I keep repeating this in all the other classes also because the dimensional analysis gives you a good feel for a problem when the problem is complicated.

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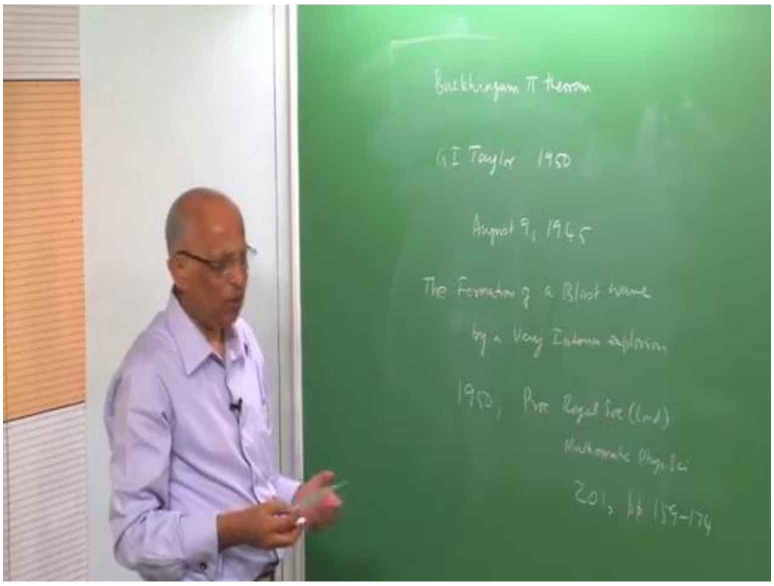

Therefore, let us use the Buckingham pi theorem and see whether I can get some idea about this problem. In fact, at this point I must also tell you that this dimensional analysis and getting a feel for blast wave was first done by G I Taylor in 1950. The genesis of the problem was the following, you know in 1945 we had I think it was in August 1945 at the end of the world war that was when 2 bombs were dropped over Hiroshima and Nagasaki and I think it was August 9, 1945 and what happened, it was a catastrophe. It killed lot of people it mane people and the radiation effects were felt for a very long time.

But the energy which was released from the bomb was not known to anybody and what G I Taylor did was he analysed the problem using dimensional analysis and he was able to precisely point out what is the type of energy which got released in the bomb. Mind you, the thing was kept confidential, it was not open, it was classified, but even then using some data which we will now see, Taylor was able to do. I would strongly urge all of us to look at this paper. I have this reference here with me.

Well, the reference is the title of the paper which G I Taylor publish was the formation of a blast wave by a very intense explosion. As I said, it appeared in 1950 in the journal of proceedings of Royal Society London. It came in the mathematical and physical series of this proceedings. The volume number is 201, it is between pages 159 to 174. It is available on the net and it is a beautiful paper. I would strongly urge you to read it. It gives you a feel for how to go about doing the dimensional analysis which we will now do. Having said this, let us go back and try to see how we do the dimensional analysis. We told ourselves well we have the energy getting released E 0 joules.

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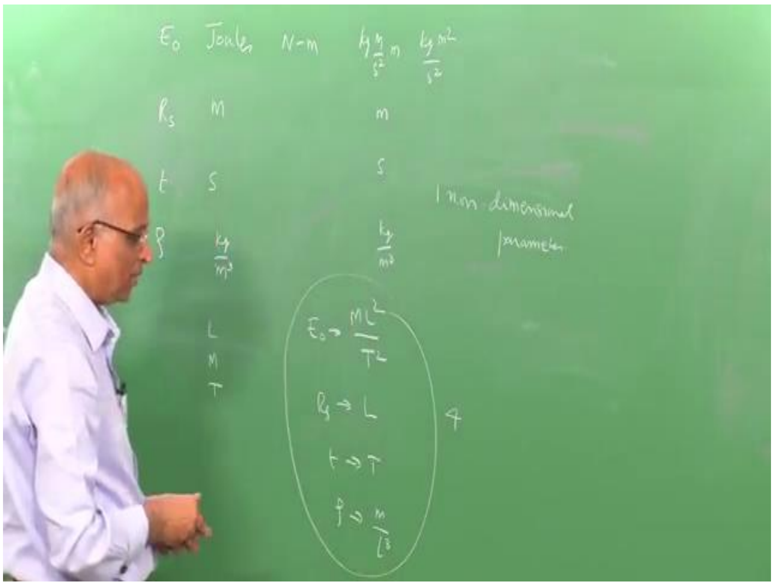

We have we want to find out the distance, the shock wave is from the source at time t seconds. The shock is propagating in a medium of density rho. Well R s is in meters, time is in seconds, density is in kilogram per meter cube. Let us put the dimensions together joules is force into distance Newton meter. What is Newton? Newton is equal to kilogram meter per second square meter. Therefore, it is equal to kilogram meter square by second square that is the unit of energy. Well, R 0 is meters, t is seconds, well this is kilogram per meter cube again. If I were to put this in terms of the dimensions well dimension of meter is length scale linear distance, mass is m, time is t.

Therefore, I could say that the joule energy has units of m l square by t square. The unit of R is distance is equal to l over, here the unit of time is t, t is the unit of time. Well, rho has units of m that is mass divided by L cube. Therefore, you have the dimensions of energy, distance, time and rho as is given.

And now using the Buckingham pi theorem, we find yes we have something like four parameters here and now you know out of these four parameters, I find three of them have independent dimension that means I have four parameters in my problem E 0, R s, t and rho of which three have independent dimensions because I am able to relate may be time is independent, length is independent.

I am able to relate if I have one more I am able to get the other dimensions out, 3 independent dimensions and as per Buckingham pi theorem, if I have four parameters and 3 independent dimensions, I can form one non dimensional parameter. Let us get this value. Let us say one non dimensional parameter we call as pi 1. Therefore, I want to find out this non dimensional parameter.

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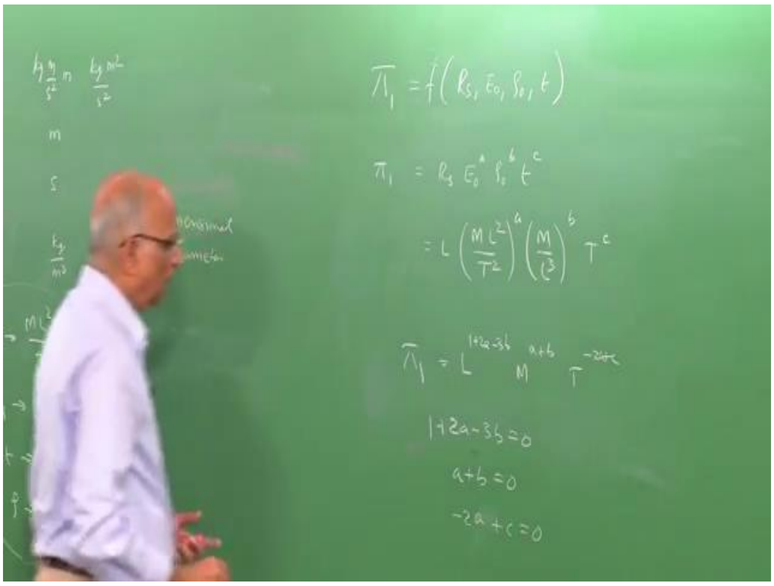

I have let us say this non dimensional parameter pi 1. Well, it is a function of distance, energy release, may be the density, may be the time and if it has to be non-dimensional, well I can write it as equal to I am interested in R s E 0 to the power a rho 0 to the power b time to the power c such that a, b, c and the fact of one are so chosen such that the net dimension of pi 1 is does not have any dimension.

It is dimension less. Therefore, what I do? I immediately put the dimensions of this into this figure. Well, I get l over here E 0 equal to m l square by t square to the power a, rho 0 is m by l cube, m by l cube to the power b T to the power c. And now in order to get non dimensional, let us put all the l together, all the m together, Ii have l into 1 plus 2 a minus 3 b, then I have m, m is a plus b and t is minus 2 plus c is equal to the pi 1 and if this have to be dimension less, well 1 plus 2 a minus 3 b that is 1 plus 2 a minus 3 b must be equal to 0. a plus b the dimensions of m must be 0. a plus b must be 0 and minus 2 plus c should be 0.

Let us therefore get the equation clear. Therefore, I have 1 plus 2 a minus 3 b equal to 0, I also have a plus b must be equal to 0 to get a dimensionless number and minus 2 plus c minus 2 a, I am sorry it should have been 2 a, I have 2 a, minus 2 a plus c equal to 0. Let us solve these equations.

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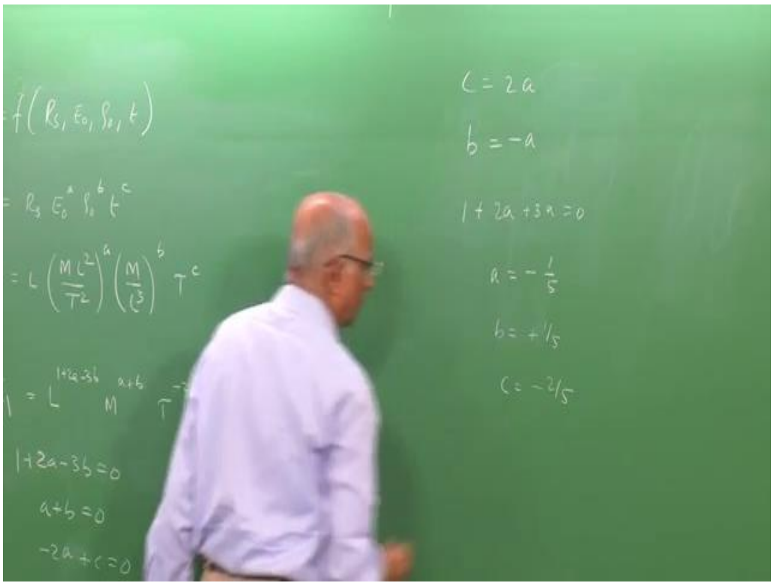

From the third equation, I get c is equal to 2 a, I also get b is equal to minus a. Therefore, I put it in the first equation i have 1 plus 2 a, 1 plus 2a. Now, 1 plus 2 a minus 3 b minus 3 b is equal to plus 3 a equal to 0 or rather I get a is equal to minus 1 by 5. If a is equal to 1 by 5, well b is equal to plus 1 by 5 and the moment I say this c is equal to 2 a that is equal to minus 2 by 5 over here. Therefore, my dimensionless number pi 1 now becomes let us put it together, let us go back.

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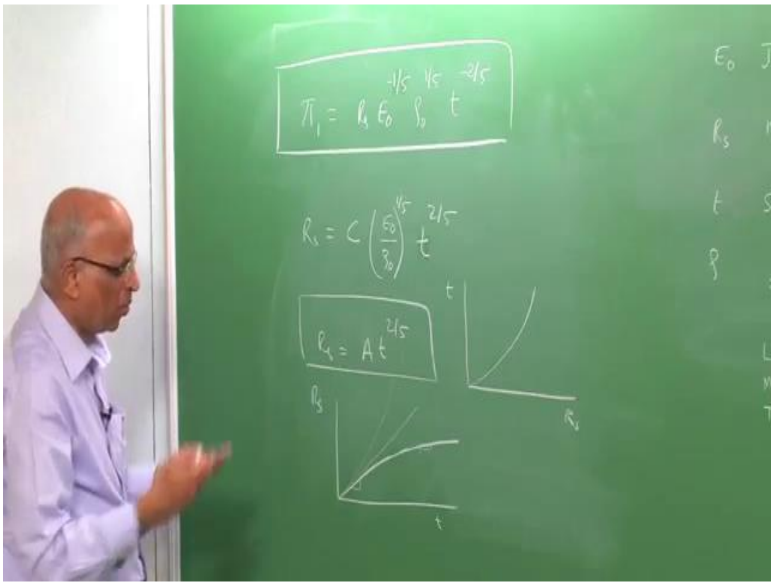

My dimensionless number pi 1 is equal to R s into E 0 a is minus 1 by 5. Then I have rho 0 to the power b, b is equal to plus 1 by 5 and I have t, t is equal to minus 2 by 5 and this is the expression I get for the dimensionless number. Now, for a particular value of the dimensionless number, I can now write the value of R s is equal to a particular value, a constant value let us say c of the dimensional less number. I have c into E 0 to the power 1 by 5 divided by rho 0, maybe I put both this together into t to the power two-fifth.

Now, therefore I find that the distance at time t in a medium of density rho 0 when the energy released is E 0 sort of instantaneously the shock distance R s is given by this particular expression. For a given value of energy release and for a particular medium let us say the blast wave is propagating in air. Well, this becomes a constant I can write R is equal to a t to the power 2 by 5. What is this expression tell us?

Let us try to plot it out whether whatever we have been discussing earlier whether it fits in, all what we are saying is when I plot R s as a function of time well as time increases, the distance R s increases, but if the exponent was 1 well I should a figure like this. If the exponent was greater that 1 well it should be like this.

Now, the exponent is less than 1 therefore, the shock propagates out like this. In other words, in the initial phase for a given incremental time when time is small the shock propagates a larger distance. Whereas at the end may be at a larger time for the same incremental time the distance travelled by the shock is smaller rather if instead of putting it in this figure I put it in the form of streak diagram which we put here, put earlier namely t over here. The distance R s along this well I get the figure like this which is what we thought initially it starts of the high velocity and ultimately it becomes an acoustic wave.

Therefore, this dimensional analysis has been able to give you the type of the radius of the shock at a time t and now using this let us go ahead and do some more analysis, Before we discuss the results again and also discuss the results how Taylor was able to guess the energy release in the, in the bomb explosion over Hiroshima and Nagasaki.

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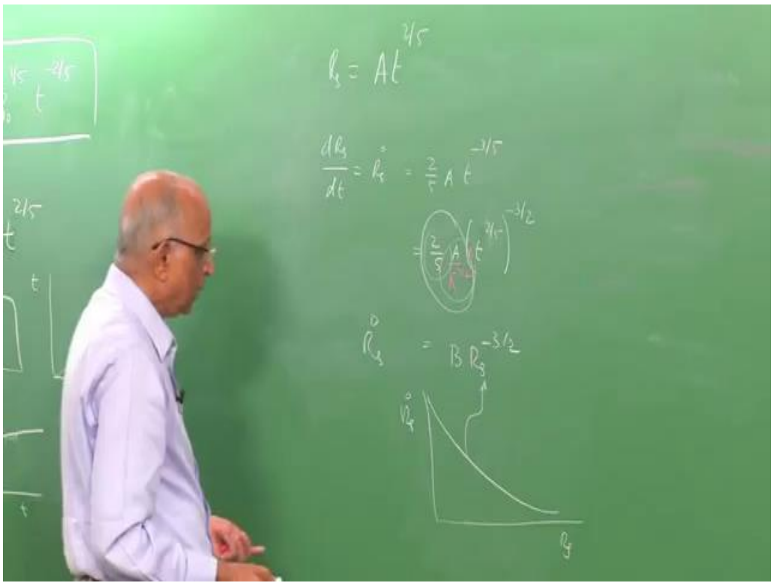

Let us tell yes, we have the expression R s is equal to a t to the power 2 by 5. Therefore, I am interested in the velocity at which the shock is propagating. I have d R s by dt which I say is R s dot, I do not want to carry this differential, the velocity by R s dot d R s by dt which is equal to 2 by 5 a t to the power minus 3 by 5.

I differentiate this and now I want to express the velocity as instead of as a function of time, as a function of distance. And therefore, I can now write this as equal to 2 by 5 a t to the power minus 3 by 2 or let us say 3 by 2 over here into I would like to some more become bring this into the picture. Therefore, I say well I want R s over here, I write it as two-fifth into to the power minus 3 by 2 over here.

Now, I introduce value of a over here. And therefore, I divide this by a to the power minus 3 by 2 over here. And therefore, what is it I have? I have 2 by 5 into I have a over here, I have constant over here, well I can put it as something like this particular value I call it as b and a t to the power 2 by 5 is nothing but R s.

Therefore, I get R s to the power minus 3 by 2 is the value of R s dot. In other words, what is this tell us? Well, I have the shock propagating along the radius or along the distance R s over here. It starts off with a particular velocity and it keeps decaying down according to this particular expression. That means this is R s dot over here and this is how what we said it starts of with a high velocity and keeps coming down ultimately it becomes an acoustic wave.

Therefore, we find that yes using dimensional analysis I am able to get the value of R s, I am able to get the value of R s dot, but now getting back how can energy of how could Taylor determine the energy release in an explosion using this dimensional analysis. Let us put things together again one last time.

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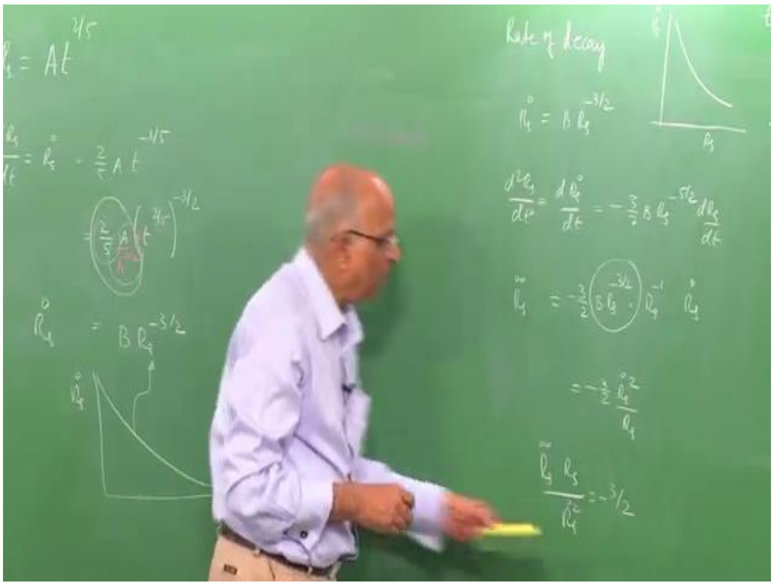

We find yes well R s is equal to c E 0 to the power 1 by 5 rho 0 to the power minus 1 by 5 and t to the power two-fifth over here. This is the expression what we derived. You know in these old cities of Nagasaki and Hiroshima you know in this older cities and all we find this clock towers which are there and due to the explosion when the blast wave hits the tower, the clock stops at a particular time.

Let us say there are two clock towers, separated by a particular distance this stops at a time t 1 when the blast wave hits it. When the second blast wave hits the second one, let us say it is the time t 2. And therefore, the time of these two towers, clock towers are known.

And therefore, I have the distance between them is known therefore, the only variable is a is energy over here. I know the ambient density over here and using this Taylor was able to get the value of E 0 and it came out to be something like 40,000 tones of t n t or in terms of energy it is almost like 100th 100,000 mega joules of energy. I do not clearly remember this, but we will study the equivalence of energy in terms of explosive, we express it in terms of t n t which we will do later on.

Therefore, this simple dimensional analysis shows the characteristics of the wave namely the wave decays out as it progresses faster it starts strongly as we see here starts strongly progresses over here. Can we also make some predictions? For let us say the rate of decay of the blast wave. In other words, what is it we are saying? Well, it decays out, I know the value of R s dot and we said R s dot is equal to b R s to the power minus 3 by 2. Can I get its deceleration that is the rate of decay? In other words, I am looking at d 2 R s by dt square which is equal to d R s dot by d t.

And therefore, I differentiate this expression again. I get this is equal to minus c by 2 b of R s to the power minus 5 by 2 into d R s by d t. This gives me the value as equal to minus 3 by 2 d R s, I can write it as minus 3 by 2 into I now write, yes I have R s to the power 3 by 2. Therefore, I have R s to the power I write it as minus 1 therefore it gives me 5 by 2 again into R s dot again.

Therefore, what is it I get? Can I, can I now write the value of the deceleration, which well this is equal to R s 2 dot. Now, I already know that the value of d R s to the power minus 3 by 2 is equal to R s dot. This is equal to R s dot over here. Therefore, I can write it as minus 3 by 2 into R s dot over here, R s dot over here it becomes R s dot square divided by R s. And therefore, I find that the value of R s 2 dot into R s divided by R s dot square is equal to minus 3 by 2.

Therefore, I get the value of the deceleration and I find well R s dot is the velocity which is positive, R s is the distance and as it progress R s is positive and there is a decay and this is what we say a blast wave continually decays in its velocity as it progresses, as it progresses this is R s dot as function of R s or in terms of a streak diagram may be t verses R s starts with a high velocity and keeps ultimately it becomes a acoustic wave. Well, this is what we learned from dimension less analysis.

And therefore, these dimensional analysis is quite strong, it gives some suggestions. But what are we really interested in? I think let us spend a moment or two of this. See, we are interested in finding out the blast wave which is generated from an explosion and it is this blast wave which sort of equalizes or may be takes the source energy and distributes it over the region enclosed by the lead shock.

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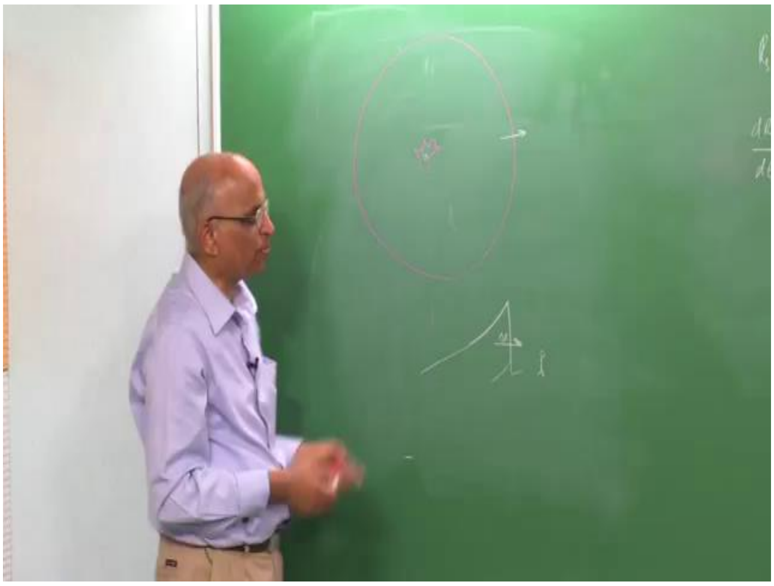

That means we had the explosion taking place over here. We had some energy E naught. This energy is sort of redistributed in this, this is done by the lead shock over her. And what is it we are wanting? We want to know what is the damage which can occur by this particular wave, we are not we know that the matter here is not coming over here, it is only the energy which gets redistributed.

We would like to know, well when I have a wave like this which is coming, I would like to know what is the over pressure, what is the pressure with which supposing somebody is standing here, he gets hit by the wave. What is the type of over pressure which hits him that is there is suddenly a compression which really squeezes him. That means there is an over pressure which affects him and also in addition to the pressure rise delta p which affects him, there is also behind it there is something like the pressure falls we saw this, we found that the end wave is like this. We found that the pressure keeps falling.

Therefore, what are the two factors, what are the factors which we must consider when describing a blast wave? To be able to quantify how the source energy affects from the explosion affects the building or whatever it is a little bit away from the side of the explosion. Therefore, to be able to do that let us put two things together. One of the factors we said is...

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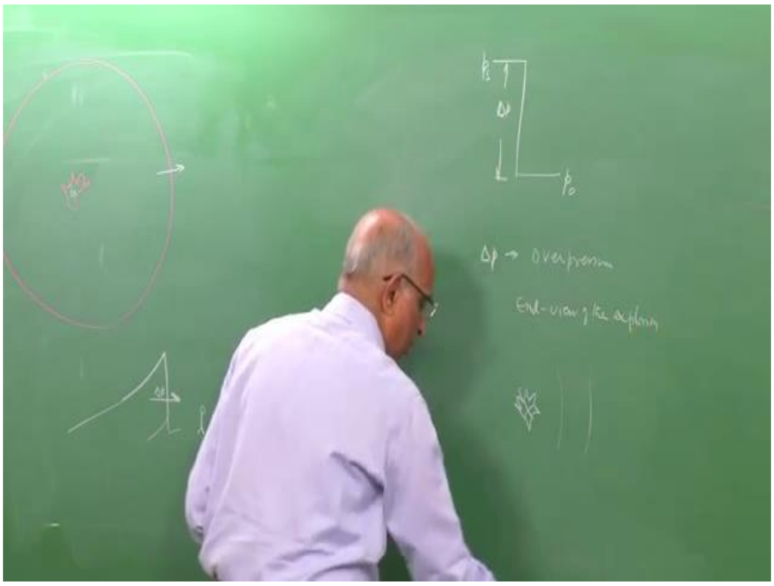

Well you have a shock wave which is formed. This is the ambient pressure P naught. You have a rise in pressure delta p. This over pressure is what we call as delta p. The pressure over and above the ambient, this is the shock pressure P s. P s minus P naught is equal to delta p is literally crushes whatever is in the path of the blast wave and this is one factor which we must consider.

That means we say over pressure. Now, let us try to imagine this slightly, I want to introduce another definition supposing there is a source here where in some energy gets liberated and a blast wave is moving out. Well, you know I stand away from this and I just look at the way the blast wave is progressing. Let me try to put it in a slightly different way.

Supposing, at this point there is an explosion and some wave is propagating out, I stand away from the explosion and see how the waves are looking. That means I get an end view of the explosion and how can I sketch it? Let us try to sketch this.

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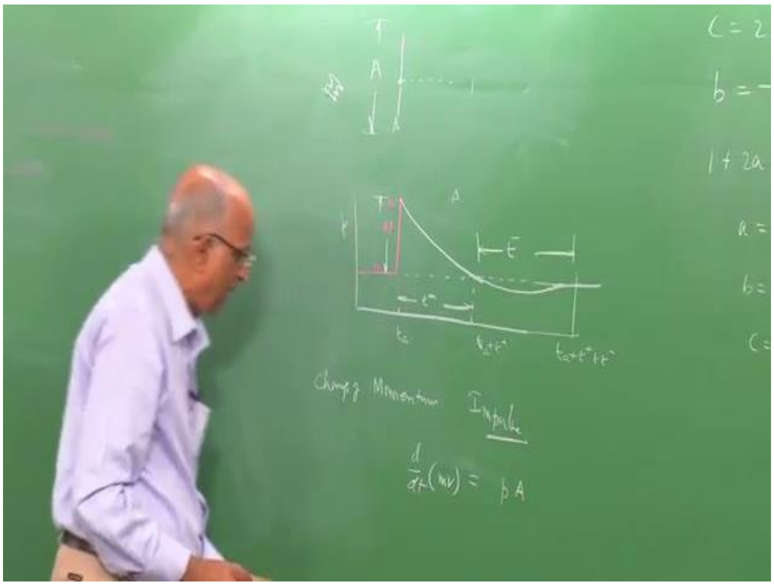

Let us say I have an explosion taking place, a wave, shock wave travels out. May be I am standing away from this and I am looking at the end view of how the shock is propagating. What is it I see? Well, initially if I were to look at the pressure dependence and I am looking as a value of time. Maybe at time let us say at time t the wave comes at this particular point, I am interested, I am concentrating out at this particular point. At this particular point, the initially the pressure is ambient pressure. Let us say, I show the ambient pressure in red.

Well, after the explosion has happened at may be at time t a, this wave comes at this particular point. I am focusing my attention standing away from it, at this particular point I am concentrating. When the shock comes over here, I get an over pressure, which is delta p. The ambient pressure rises from P 0 to P s over here and as time progresses the wave further travels a way.

When the wave further travels away, I am left with the rarefaction fan behind it. And therefore, the pressure keeps falling. The pressure keeps falling well it may, it may reach the ambient value or if the momentum is sufficient it can drag it and give rise to a negative value of pressure, but ultimately in long time I have this.

Therefore, the end view of pressure at a particular point let us say a, when I look at the sequence of wave propagation is something like a pressure spike when the time of arrival of the shock wave is t a. May be it reaches the ambient at a time let us say t a plus t plus, this is the positive value of pressure and then I get a zone of negative value of pressure. I have t a plus t plus by plus t minus. This is the region of t minus. This is the region of t plus. Therefore, I find well this is the type of pressure distribution what I must get.

See we said, well there is over pressure delta p which we say will crush the object and now this varying pressure will result in a wind or something like a momentum and how do I get this momentum? Well, we tell ourselves well I want the change in momentum due to the wind effect and the change of momentum, if I say well change of momentum is what we call as impulse. Impulse is change of momentum and now the rate of change of momentum is equal to force.

Therefore, and what is the force? if I have a frontal area, which is let us say area a. a is the frontal area and if I were to take a look well pressure into area is equal to force. And therefore, I can tell that rate of change of momentum that is d by dt of the momentum change, let say p is equal to the force which is equal to p into a.

And therefore, now rate of change of momentum I should have used a different notation here. I say m V is the rate of change of momentum is equal to pressure into the frontal area or rather this particular expression now I can say the change of momentum.

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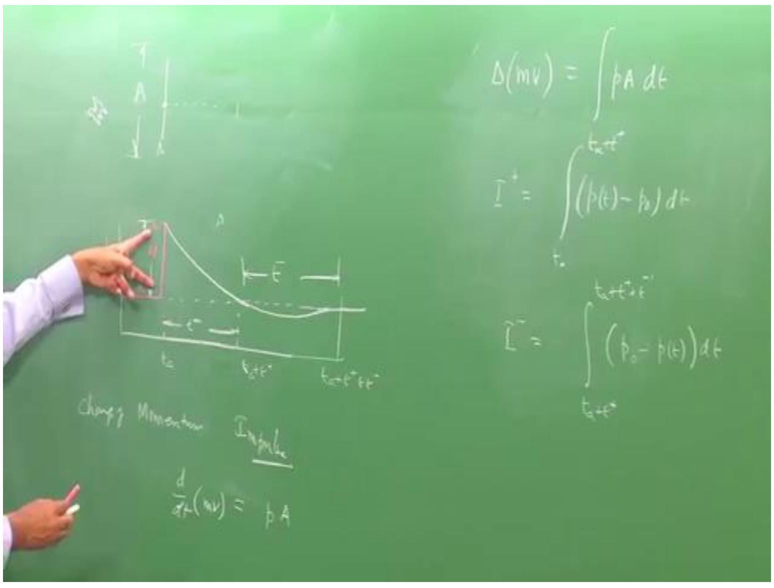

I can say is equal to integral of P a into dt because this is d by dt is this or rather I can say the impulse or the change of momentum associated with this particular expression is equal to the value of the higher pressure that is P at any time.

That means I say the impulse positive is equal to the area because I have area which is I say a constant frontal area into something like P at t minus the ambient pressure in to dt over the time between the arrival of the shock at time t a to the time t a plus t plus over here. And similarly, I get a negative impulse or momentum in the opposite direction which is equal to a into t a plus t plus, this is where I get this particular point. I have t a plus t plus t minus into I get P t. I now get the value, this is lower.

Therefore, I should get the value of P 0 because I am talking in terms of negative impulse minus P t into dt over here. Instead of looking at the area specifically, I can say specific impulse that is impulse per unit area. I can write as this value I can write negative specific impulse per unit area as this and it is this which gives me the blast loading due to wind. And therefore, a blast wave is characterised by the crushing pressure that is the over pressure and these two positive and negative impulses.

We will see that these negative positive and negative impulses could there could be a series of them we will take a look at it. Therefore, what we would like to predict is, we would like to predict the over pressure and the impulse in an explosion to be able to proceed further and this we will do a little later.

Therefore, what I do in the next class is, I continue on this, but before we start describing a blast wave predict the over pressure, predict the impulse and see the effect of the damage. What we will do is we will try to take an example of some of the naturally occurring explosions, some accidental explosions, some intentional explosions such that we are able to relate the physics of explosions with the different explosions as occur in practice.

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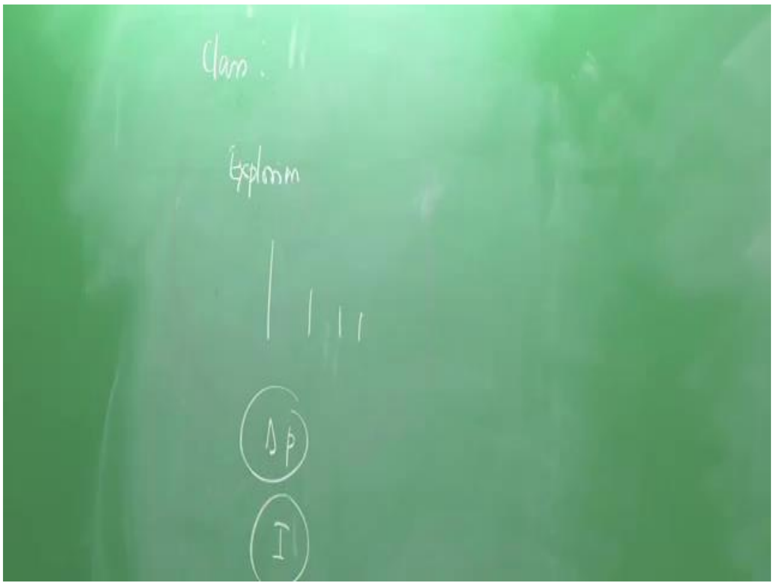

Therefore, in the next class what we will do is with this background, what we have built on explosions namely a loud bang and disruption of things. Looking at the blast wave and blast wave which keeps decreasing its strength, that is a decaying shock wave and the effects like the through dimensional analysis, we were able to find out the velocity. The decaying and also something like over pressure delta p, the impulse what we have.

With this background, we will examine the different types of explosions some typical explosions in eight categories and then after reviewing the different types of explosions we will go back and try to predict the over pressure, impulse and proceed further. Therefore, we meet in the next class wherein we will take a look at the different types of explosion, the different categories of explosion which we said in the last class was divided into eight different categories.

Well, thank you then.