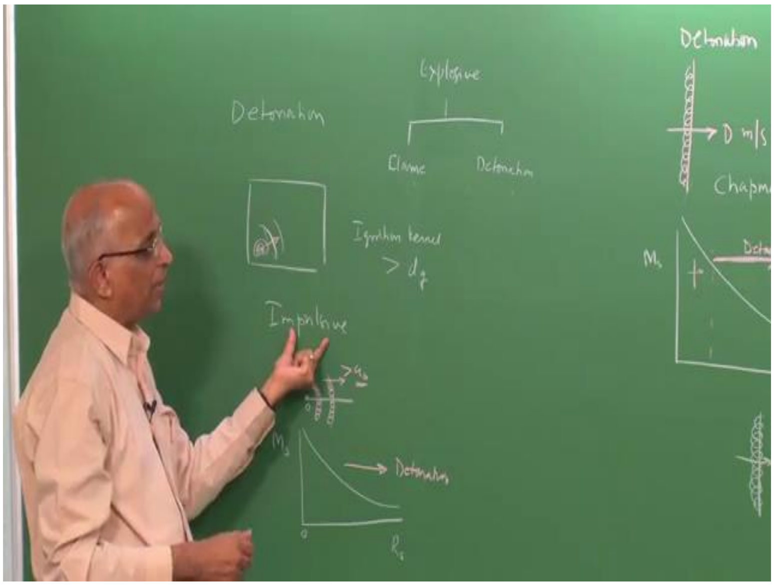
Introduction to Explosions and Explosion Safety
Prof. K. Ramamurthi
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 23
Detonation: Introduction to Detonations
Initiation of a Detonation
Critical Conditions
Energy requirements
Flame to detonation Transition
Quasi Detonations
Run up Distance

Good morning. You know in the last class, we talked about the word detonation and what did we tell?

(Refer Slide Time: 00:17)



Supposing, we have an explosive gas mixture in, let say a container, and instead of igniting it, and how did you, how do we ignite? We deposit some heat source a spark some something which is hot. The heat from the source goes and heats the neighbouring gases, and chemical reactions occur, it heats the neighbouring gases and so on a flame. Maximum velocities are of the order of a metre per second that, is the rate at which the flame propagates out. If the same energy or some energy is deposited, let us say impulsively. By impulsively, what is it I mean?

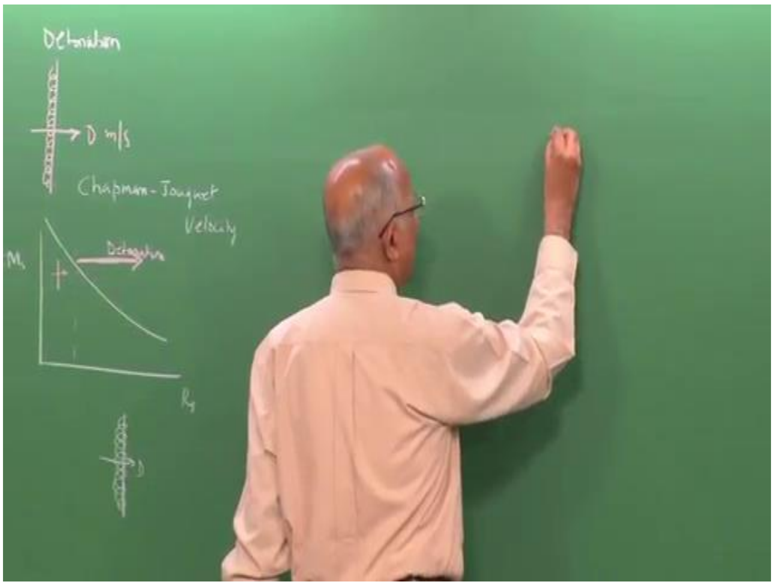
Sort of spontaneously that is over a very short period of time, and we have already learned about it. When some energy is deposited in a medium spontaneously, what happens is, a shockwave get generated. And this shock wave keeps decaying with distance like for instance, I form a shock wave of a mark number ms, this is at point 0. Maybe at point o which is the 0 scale over here. x axis is the distance, the mark number keeps decreasing with respect to time.

And we told ourselves well, a shock wave is form under certain conditions if some energy is deposited impulsively. And if chemical reactions if the shock wave propagates, let us say in the same explosive medium, in which are flame propagates, what is going to happen? You are going to have chemical reactions taking place behind the shock wave, and this chemical reaction is something like which is energising the shock wave.

And this shock wave actually decays with time because it is getting, it is some deceptions happening, some expansion processes are happening behind the shock wave because of that the mark number decreases. But this energy balance or a chemical energy which is released, is able to overcome this decaying influence. Well, instead of the mark number decaying well, it could move at a constant velocity.

That means I have a shock wave which is moving at a speed greater than this sound speed. And mind you, the pressure density increase behind the shock wave, this increase pressure, the increased density is not propagating at supersonic speed, and this is what we call as a detonation. That means, a shock wave induces chemical reactions and this chemical reactions in turn drives the shock wave.

(Refer Slide Time: 02:57)



At this particular sequence namely a shock forms chemical reactions behind it, and this chemical reactions drive the shock in turn is what we call as a detonation. A detonation can propagate at a steady condition provided the losses incurred by the shock, let us say the blast wave due to expansion behind it, may be due to the deception affects. If the energy release can overcome this, it can travel at a constant speed, let us say d meters per second. This d meters per second happens to be a large number because shock by itself travels at a high velocity greater than sonic speed, and if by chemical reaction it can be made to travel even faster.

And therefore, what is going to happen? Let us redraw our figure now, you have M s, that is the mark number of the shock as a function of R s, you have a blast wave which is being formed, it keeps decaying with distance. Let us say by some distance I have, I am able to form sufficient chemical reactions. And let us say it is able to form a shockwave which is travelling at a given mark number and this is what is a detonation. That means, till here the, you have a decaying shock wave, that decaying influence is overcome by chemical energy release, and you get detonation.

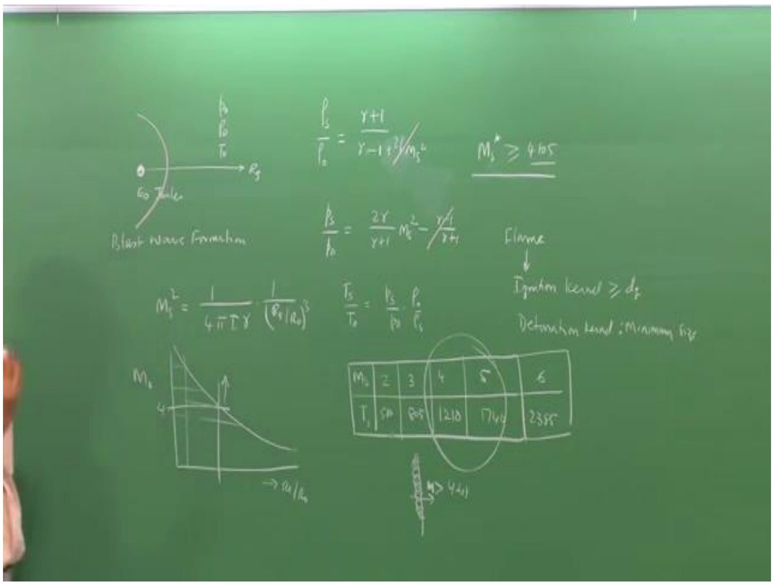
Therefore, a detonation is a combination of a shock which induces chemical reaction, and this chemical reaction in turn drives the shock, and this constant velocity is often spoken of as Chapman Jouguet velocity, you can come back to it. Now, if we are very clear therefore, now we say well, a detonation is a shockwave in which maybe chemical reactions are induced, and the combination of the shock with chemical reactions is what we call as a detonation. I think we have to be a little more clear about it and we have to distinguish it from a flame.

Well, in a flame, it is the transport of heat transport of concentration from the source, which really propagates a flame that means, something heats it you have something like an ignition kernel. And this kernel must be of some minimum size such that the heat loss within it is able to overcome, is able to cause chemical reactions in the adjacently or without itself collapsing. We said ignition kernel size must greater than the quenching distance. So, also can we say something about the energy requirements to form a detonation?

Mind you, we are very clear, these are two different things all together in a mixture, which is let us say an explosive gas mixture, or you have an explosive substance like say TNT or some liquid explosive. I could form, when the energy is liberated slowly, I could form something like a flame which travels at maximum a few meters per second. I could also form a shock wave in which chemical reactions occur behind the shock wave and I could form a detonation. Principally both are totally different, in that this is compression because behind our shock wave we have compression.

In this case, we found it was an expansion. Therefore, these 2 things are totally different, but let us go back and find ourselves, if I can imagine something like an ignition kernel for forming a flame, and we know how to estimate the minimum ignition energy. Can I go ahead and write out what is required to form a detonation, what energy releases their? If the energy release is, let us say impulsive or spontaneous how much energy is required? Let us go back, let us address this problem, it is quite simple, and what we say is well.

(Refer Slide Time: 06:45)



Now, I say I deposit some energy E naught in a particular medium, and what happens? A blast wave is generated, let us say along the distance R s, it could be any direction we again confine ourselves to assumptions that, we are taking on terms of a spherical wave which propagates out. And we say well, I deposit E 0 joules over here well, I say I have already done this problem, as regards the blast wave formation is concerned, have already done this earlier, and what did we find? The mark number of the blast wave is related when the wave is strong.

Mind you, I do need a strong wave because I want chemical reactions to occur behind it. I know that yes M s square is equal to 1 over 4 pie I into gamma into 1 over R s by R naught cube, where R naught is the explosion length R naught, which we explosion length, which we defined as E naught by P naught to the power 1 by 3. Therefore, according to this well, I have drawn this earlier again I draw it, let us say M s as a function of R s by R naught, what is going to happen? is going to keep decaying with respect to time. But now we tell this energy is deposited in an explosive medium, which can sort of burn.

And therefore, what is going to happen well, I have, I have this shock, initially the shock is strong, the shock keeps decaying in strength, maybe initially the mark number maybe 8 5 6 and so on. It ultimately decays to an aquatic wave. And in these regions, I know how to estimate the temperature behind the shock front. Let us estimate 1 or 2 cases, we know well, the density behind the shock, to the density ahead of the shock, if you go back and just check ourselves, we know s is equal to gamma plus 1, where gamma is a specific heat ratio, gamma minus 1 plus 2 over M s square plus 2 over M s square. We will, we will forget this because we are talking of a strong shock solution, we say well, I want high temperatures.

Therefore, I am, I am really not looking at the value of the mark number. Because the mark numbers are high 2 over M s square is equal to gamma minus 1, let us put it down 2 over M s square, M s square is large therefore, 2 over M s square is small compared to this number. Therefore, I can write it as gamma plus 1 divided by gamma minus 1. Similarly, I write that the pressure behind the shock divided by the initial pressure of the medium mind you, I say that the pressure of the explosive gas is P naught, the density is row naught, the temperature is T naught.

To begin with, it is unburned medium. I can write it as equal to we again go back to gamma, gamma plus 1 into the mark number square, minus you had gamma minus 1 divided by gamma plus 1. And we said well, for shock, this is a strong, for a strong shock, for M s being large, this is small for M s being large, this is small. Using these ratios of the density, let us say what did we say therefore, we could create a blast wave, behind the blast I am able to estimate the density, I am able to estimate the pressure behind it.

Using these two relations, and using the gas equation P is equal to row R t. I get that the temperature behind the shock to the temperature ahead of the shock is equal to its ambient temperature, let us say 300 kelvin, I can write it as equal to P s by P naught into row naught by row s. And I can estimate the temperature using these two expressions, I put one on top of the other, and for a temperature naught, for the different values of M s over here, let us say typically strong values. Let us say yes I consider the M s values, I can estimate the values and let us put these values in the form of a small table over here.

What is it I am going to plot? I am going to plot mark number M s, and how the temperature behind the shock changes? Well, if I consider a somewhat weak shock, let us say that temperature behind the shock. If I consider, let us say weak shock, and what it is I get? I get if the shock is weak, let us say 2, the temperature estimated for M s is the only variable, for f gamma is equal to 1.4, the temperature is around 500 kelvin. When the mark number of the shock is 3, the temperature is 805. When the mark number is 4, M s is 4, the value is 1210 kelvin. When the value is 5, the mark number is 5, the temperature is 1740 kelvin.

And the last one, let us say at a value of 6, mark number is 6, the temperature is 2385. You know, we know that when the temperature rises to a value around 1500 to 1600, you have auto ignition of the gas is taking place. And therefore, I can say well, if the mark number of my shock is such that its value is greater than a between 4 to 5, let us say then, chemical reactions will spontaneously occur behind it.

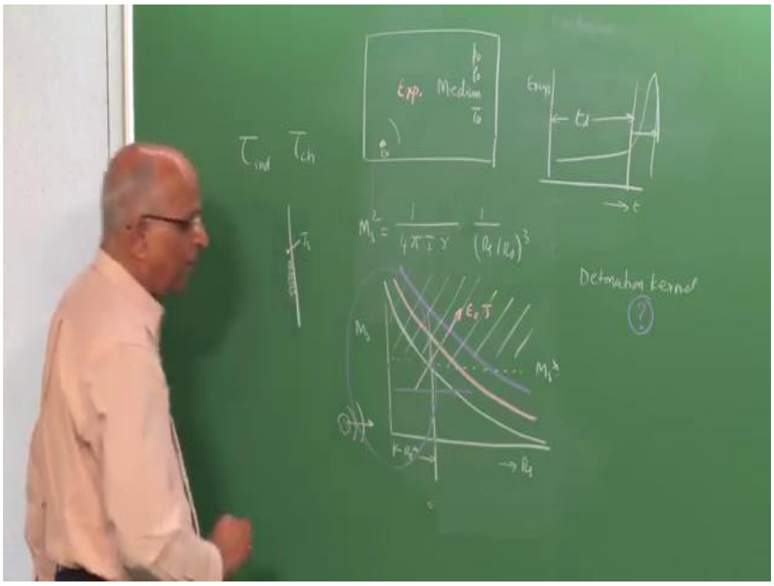
Therefore, if I happen to generate a shock whose mark number is, let us say greater than around 4 that means, greater than this limit well, I can form a detonation. I will tell myself well, there should be something like a critical mark number which I can say is M s star critical, and it is the duty of the energy which is liberated should be able to form a shock whose mark number is, let us say greater than equal to between 4 to 5. In most explosive gas mixture, if I have an explosive gas mixture, we talk which ought to ignite such as, let us say 1000 then, it could be between 3 and 4. If I have an explosive gas mixture which is so inert or something which just not ignites spontaneously, but which ignites only around 2300 well, the mark number should be 6.

And therefore, maybe on an average it is between 4 to 5 and therefore, I can tell myself that duty of the ignition source is to generate a mark number o which is greater than this. But how do I do this? You know I would like to define something like, we were able to say when I have a flame, what did I tell? Well, I wanted an ignition kernel, I wanted a kernel of flame an ignition kernel whose size must be greater than or equal to the quenching distance, for a flame to get started.

Can I also say, for a detonation what is that minimum volume, can I talk in terms of a detonation kernel? Or a seed which is required detonation kernel, which is required to start of a detonation. And if so, can I say what must be the minimum size of this? Just like I say minimum size of a flame kernel is the quenching distance, what should be the minimum size required. And I would like to spend some 3 or 4 minutes on this because this will give us an idea on, what are the type of energy which is required and we will be able to calculate the energy required for a detonation to form.

Therefore, I will spend some 10 minutes on this, or 5 minutes on this, and try to proceed further. Well, we have already said, the mark number in case I am talking of a medium which is not explosive let us again put a medium over here.

(Refer Slide Time: 14:24)



This medium to begin with, let say it is at an initial pressure P naught, density row naught, temperature T naught, and let say it is E naught. And therefore, I know that the mark number of the shock which is generated, I just wrote the expression, let us write it again, 1 over 4 pie I. We said these are integral common strength which denotes the ratio of the kinetic energy of the shock medium, divided by the kinetic energy of the entire medium, where to move at the shock speed 4 pie I gamma into 1 over R s by R naught cube.

But here you know, I also have the explosion link, and I am interested in some energy which is liberated E 0. If I want to put E 0 explicitly, and I want to form the value of M s as a function of only R s and not R s by R naught, for different values of the energy release E naught well, for 1 value I get a curve over here. I increase the E naught significantly and then, I get another curve over here. If I increase the E naught still more, I get the third curve over here.

Therefore, the direction over here is in the direction of E naught joules over here. Therefore, this is how a blast wave decays, as it is formed by energy release in an inert medium. Now, I make this into an explosive medium, and this explosive medium has a say, let us say same pressure, same initial pressure, 1 atmosphere pressure, same initial density, and the same initial temperature, let us say 300 kelvin or so. And now, what is going to happen?

Well, a strong shock is formed, let us say the level I am, I am considering energy release corresponding to the white line over here, and what is going to happen? Well, as it propagates now, the shock is strong, let us say the mark number I denote M s star which corresponds to rapid auto ignition of the gas is behind the shock I form a shock wave. The temperature behind it is T s we have already estimated the value of T s. We said M s is between 4 and 5 and the temperature here is quite large such that, chemical reactions are occurring.

Therefore, in this particular zone of gases which are above this, I expect chemical reactions to occur behind the shock for all these three cases, white line, maybe the particular line here, maybe the line over here. But now, if I say well, you know these chemical reactions, however spontaneously they occur, will take some time to take place. That means, you know even though I create a shock wave, the time for chemical reactions is not instant in it, will take let say a micro seconds, maybe 10 microseconds or let us say millisecond. Therefore, this will take place only when the shock has travelled a particular distance.

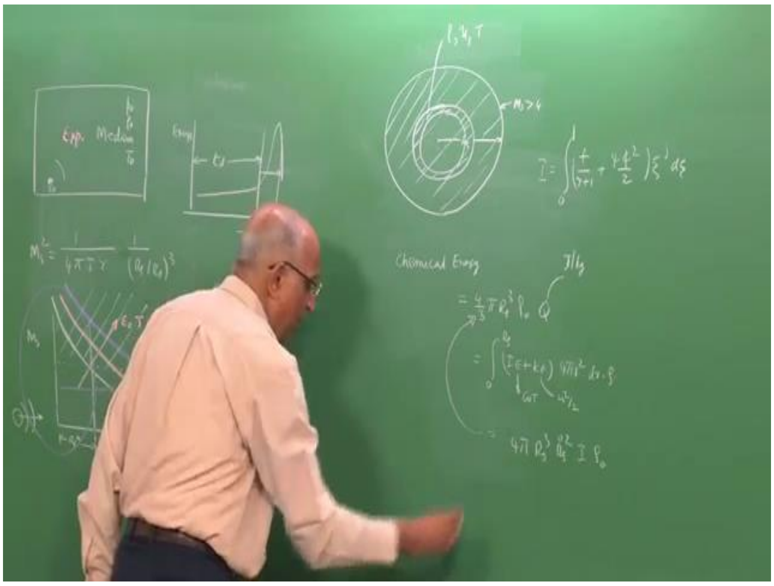
That means, by the time a particular that means blast wave is formed, it travels a particular distance from the source, and by the time it travels a particular distance, maybe the chemical reactions should have started taking place. Because we say well, there is a characteristic chemical reaction time, and mind you in addition to characteristic chemical reaction time, we found that there is a large induction time mind you, let us again go through this. We told ourselves for most of the explosives, the activation energy is large and how does that chemical reactions occur with respect to time, let us say this is time energy release.

Initially there is an induction time in which the chemical reactions get ready, chains are formed, and once the chains are formed, I have a rapid one. That means, I have something like an induction time, which we call as induction time, followed by the chemical reaction time. And this is going to take some time and therefore, maybe by that time the shock travels at certain distance, the induction time should be over, so that that the chemical energy gets released, and the shock that means, there is a need to have a minimum value of R s star.

That means, a minimum distance, and this minimum distance perhaps could correspond to what we are looking for namely at detonation kernel. I think we are still not too clear about it, but let us presume that, yes the chemical energy must be released in the medium, by the time the shock because if they shock. Let us say if he take another instance, if the shock were to decay to this particular value. Well, below this the chemical reactions just take too longer time well, the shock cannot really convert to a detonation.

Therefore, by the time the shock strength reduces to a critical value M s star, it should have moved a particular minimum distance which I can call as a detonation kernel. Maybe I have to refresh this definition again, but for the presence I say it must move a minimum distance away. And this minimum distance away is necessary to form a kernel of explosive gases. Therefore, let us write an expression for this, for the energy release and then, let us put things together and view it in the light of some experimental results. Such that, we can formulate a criterion for starting a detonation or initiating a detonation. Therefore, let us now presume.

(Refer Slide Time: 19:49)



Yes, I have a blast wave, let us presume, yes I have a blast wave which is formed of some size R s, let us say that distance from the sources R s. As usual we make the same assumption row naught is a density, and all that. We also presume, that the mark number of this blast wave, when it is at a distance R s is such that, the value of M s is greater than between 4 or around between 4 and 5.

Such that, chemical reactions take place behind it, that is it is chemical reactions are taking place in this particular medium. Because the blast wave is strong, we say well, the time of the distance travelled is such that, the chemical reactions have taken place. Let us presume well, this is filled with chemical reactions, and if it is filled with chemical reactions, the chemical energy what is available within the blast wave, chemical energy which is available is equal to the volume, what is a volume? 4 upon 3 pie into R s cube, this is the volume, into the density which is the mass, into the chemical energy which is released, let us say cube is so much let us say joules per kilogram is the chemical energy what is available over here.

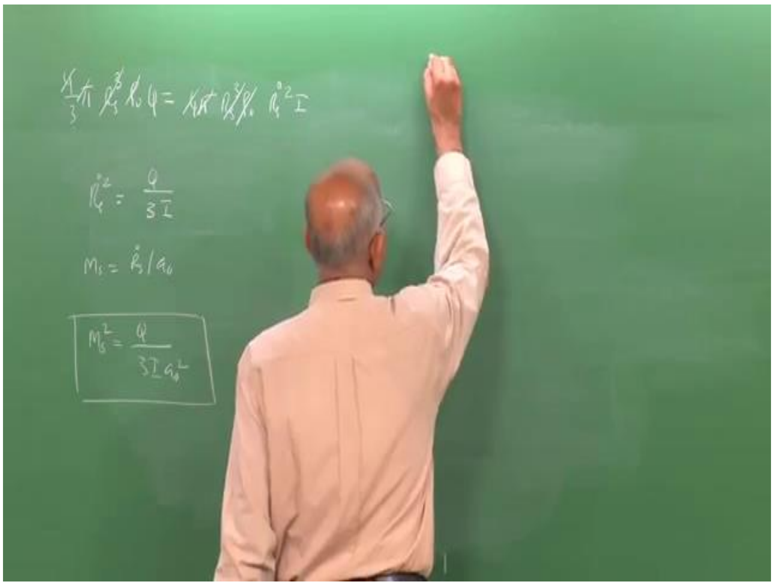
What does this chemical energy do? It increases the temperature of this medium, that is the internal energy of this medium. It also increases the kinetic energy because the shock is moving, it supplies some velocity to the to the flow field. Therefore, this chemical energy gets translated, we are not really considering now that affect of the initiation energy we are considering separately. We are considering just the affect of the chemical energy, and what does it do? It increases the kinetic energy, and the, that is we are, we look at a small segment over here.

Let us say a particular shell, a spherical shell whose density should be row, whose velocity could be u, whose temperature could be T. We have been writing this in whenever we talked in terms of blast waves and therefore, say this is equal to integral of 0 to R s of their internal energy plus the kinetic energy over this particular medium, that is dm over here. And dm, which I can again write it as equal to the surface area of this particular thing, let us say 4 pie r square into dr, into row over here. We have derived this expression, we have derived what this particular limit is, and did we derive it as equal to, I could write internal energy as CvT, kinetic energy is equal to u square by 2.

And therefore, I have therefore, row u square, this became P over gamma therefore, P over gamma minus 1 into row and therefore, row and row got cancelled. And we got this final expression as equal to I that is integral, let me put it separately 4 pie into we got R s cube, into R s dot square, into I over here, and what was the value of I? We said I is an integral is equal to 0 to 1 of f over gamma minus 1, that is the pressure, into density of we had something like sigh phi square, divided by 2, into we had R by R s into d eta. You will recall, we had, we said that this integral is around 0.423 or something for a medium like air.

Therefore, we are able to get this relation, that is 4 pie R s cube into R s dot square into I, and this comes from this particular expression. And therefore, this is equal to this particular value and therefore, what is it I find? Mind you, here row by row naught, I should have got a row naught also over here.

(Refer Slide Time: 23:44)

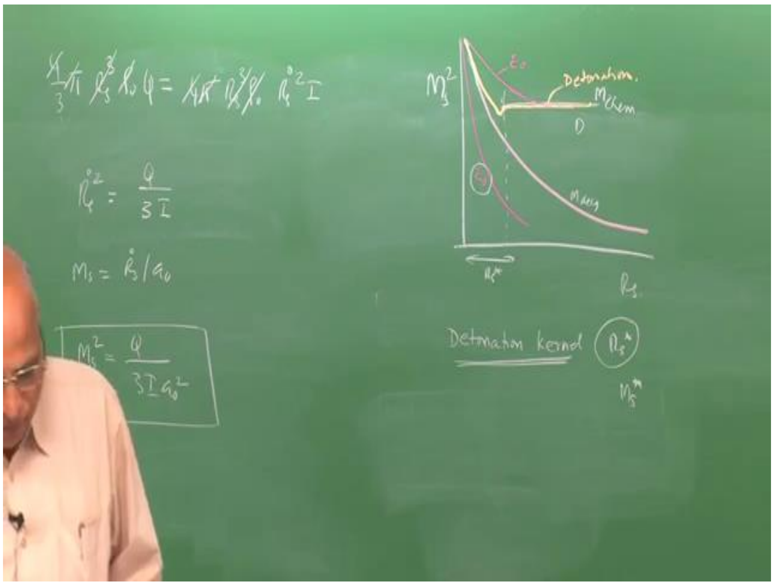


And therefore, when I equate these two expressions, what it is I get? 4 upon 3 pie, whatever I have written here, R s cube into row naught, into cube is equal to 4 pie R s cube into row 0, coming over here R s dot square into I, where I is the integral constant.

Therefore, I find 4 pie, 4 pie cancels on both sides, row 0 and row 0 gets cancelled, R s cube get cancelled over here, and I get the value of R s dot square is equal to, I simply get it as q divided by 3 into the integral particular expression. And now, if I want to write in terms of mark number square, I know mark number of the shock front, behind which chemical reactions are occurring is equal to R s dot, divided by a 0. Or rather I get M s square is equal to q divided by 3 I into a 0 square, where is a 0, we said it is around 330 meters per second.

Therefore, this is from the chemical reactions what is taking place. Well, the blast when no chemical reactions are taking place, it goes as per this particular expression. And combining these two together, can I now say what is the value of the detonation kernel or the kernel of gas which can really form a detonation. Therefore, now I put these two things together.

(Refer Slide Time: 25:22)



Well, I say I have M s square, from as a function of R s, for a given value of energy release, and what happens? Well, the blast wave decays in a under reactive medium like this. When the medium gets to be reactive, and provided I have sufficient quantity that means, the time is sufficient for energy to get released.

Well, the M s square could be something like this. This is for a detonation velocity that, is equal to the value of M from the chemical energy release. This is from the decaying influence if a shock wave that means, the chemical reactions must be able to overcome the decaying influence of the shock wave. And when that chemical energy release overcomes the decaying influence, what is going to happen? Well, it comes like this and gets into a shock.

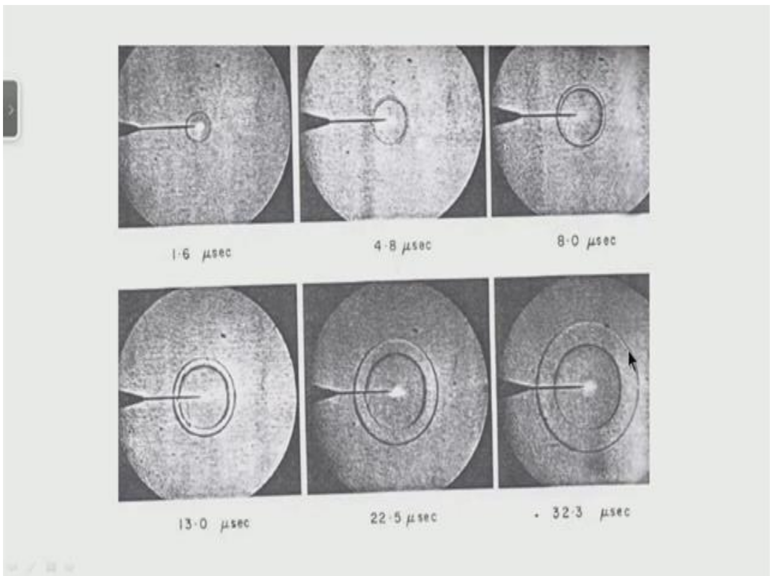
And therefore, I can tell that well, the role of the energy release is initially to form a decaying shock wave, but if the decaying shock wave is greater than some limit well, it gets into this and forms what we call as a detonation. Therefore, you know on this plot now, I say well, I want to include the different values of energy release, and let us see how it will look like, If I have a very small energy release well, it goes like this well, by the time the critical distance is required to release the chemical energy, the shock has decayed to a very low value well, it cannot initiate.

Well, if the energy is very large well, it can directly release the energy and it goes into a detonation. On the other way, on the, in the extreme case that means, this is E naught large well, the energy release is very small. Under some critical condition, it is possible that the energy release, as I have sketch by the orange line, it comes to the M s value energy release takes over, and drives a detonation. And this is how we should be able to imagine or may be have a think model on, how to form a detonation.

Therefore, to form a detonation, I summarise here by saying its necessary to form, let us say a detonation kernel. I still use the word kernel because we are very clear about it in case of a flame. And this kernel size should be a minimum volume, let us say R s star, and this R s star must be formed by the time the shock decays to a critical strength M s. And this R s star at the value of ms star is what we could call as a detonation kernel. And once I know a kernel volume, I can always find out what is the energy which forms this kernel and I can find out my energy release.

Therefore, without, before going further on the theoretical grounds, let us take a look at some of the experiments, and then calculate the energy release. And I show a few experiments results before going forward.

(Refer Slide Time: 28:18)

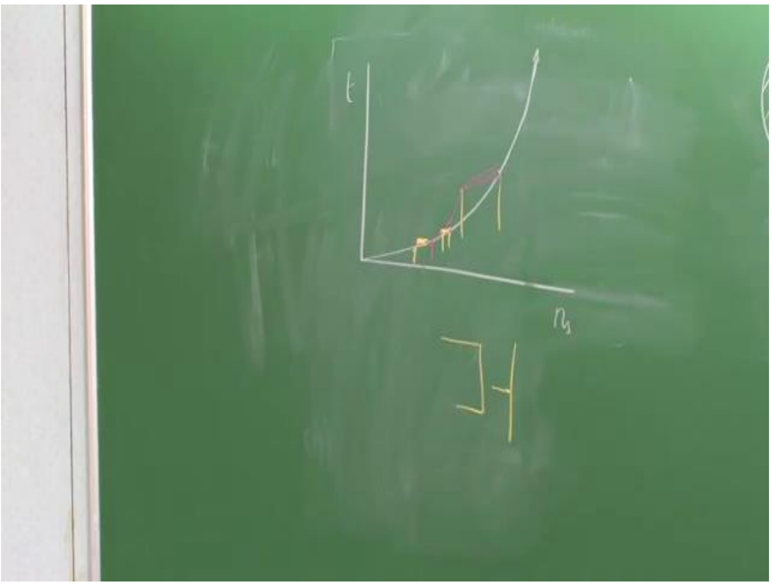


And in the first slide over here, I show some experiments which were done at mcgill university in late60s and early 70s, and what we find is, in this case a lesser spark is use to start a spherical blast wave. The medium used is low pressure acetylene oxygen system, which is diluted with argon again, and what we find is, initially a blast wave is created at a small time, let us say 1.6 microseconds. The shock wave or the blast wave moves forward, it still moves forward at 8 micro seconds, and it keeps propagating of ut. This is the first circle what you see is the spherical shell of the blast wave, which is being found.

In this case, it was cylindrical, but let us, let us assume a 2 dimensional geometry, as the first circle is the blast circle, that is the shock circle. You know behind the shock when the temperature is large, chemical reactions occur and therefore, here you see behind it there is some chemical reactions occurring. The shock weakens, it takes more distance for the chemical reaction to take place. The shock further weakens, we have the shock here, chemical reactions in the second zone.

That means the chemical reactions are further occurring away from the shock that means, the chemical reactions are occurring far from the shock, and these chemical reactions cannot go and supply energy to the shock because it is occurring much later. For the chemical reactions to supply energy to the shock, what must happen? Let us take a look at it on the board. All what I am trying to say is well, let us go back to the street diagram with which we are familiar, which we studied in the blast waves.

(Refer Slide Time: 29:59)

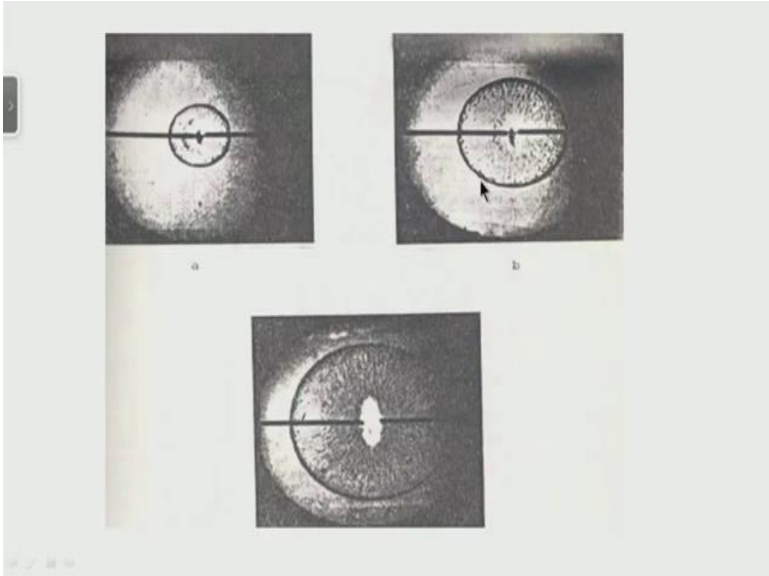


You have the temperature axis, time axis, I am sorry, you have the distance axis. Well, the blast wave gets form like this. In the limit, it becomes a sound wave. Initially I have strong shock wave, and what happens? A particle entering over here is following the shock wave like this, if the particle takes a long time to burn well, it is going to burn over here.

And since, the when it burns over here, the blast wave is already here, it is not able to translate its energy here and keep pushing it, like a piston moving a wave. Whereas, if the wave is going to, if the shock is sufficiently strong, and if it is going to burn right over here, the energy is going to feed into it, maybe a particle entering here will feed into this, and it will push this wave.

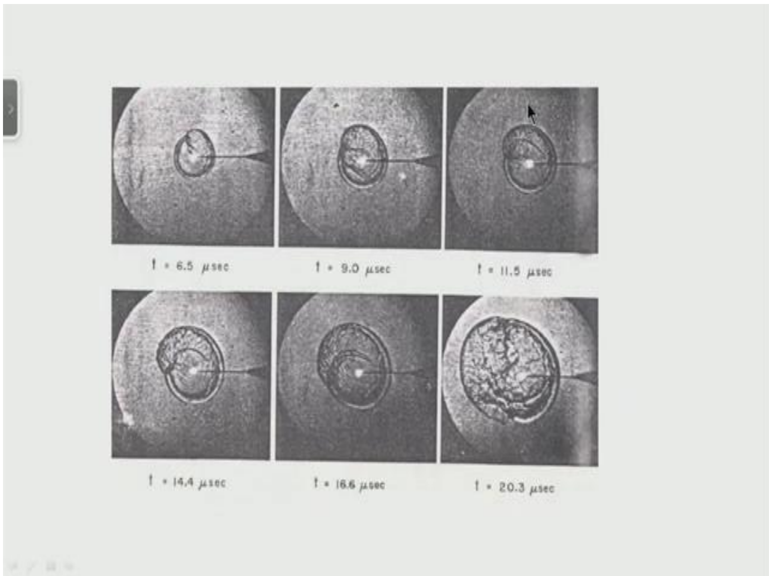
Therefore, I would like this particular distance that means, this particular distance, or this particular distance to be as small as possible such that, chemical energy can really push it. If it is going to burn over here, and there is going to be a say a far away from this zone of chemical reactions well, the energy cannot really push it because it gets into the medium, it cannot really go and push the, push the shock wave, like a piston pushing a wave. Therefore, what happens is, in this particular case the energy release is small and therefore, you find the chemical reactions to decouple from the short front.

(Refer Slide Time: 31:32)



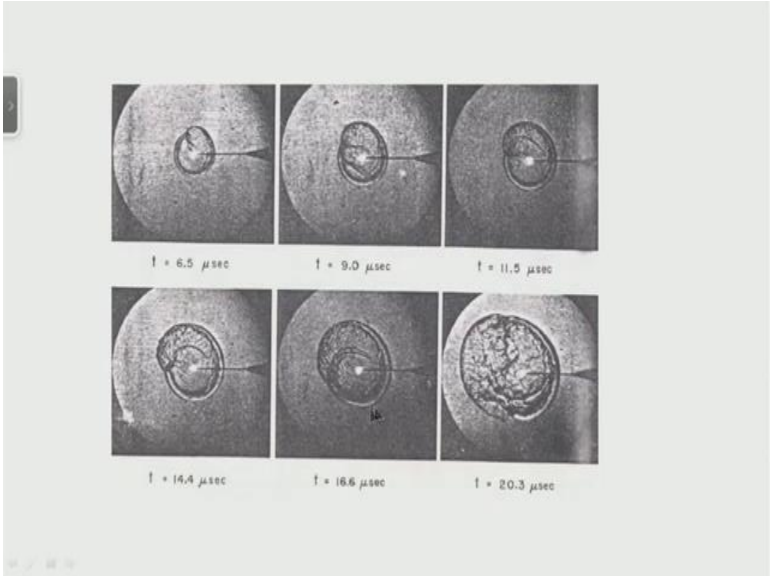
Let us go to the next case, examine in this case the energy is high well, I form a shock here, and the chemical reactions are occurring almost at the shock. And therefore you know you find well, this is the case in which I want, you know the energy is sufficient to form a shock.

(Refer Slide Time: 31:48)



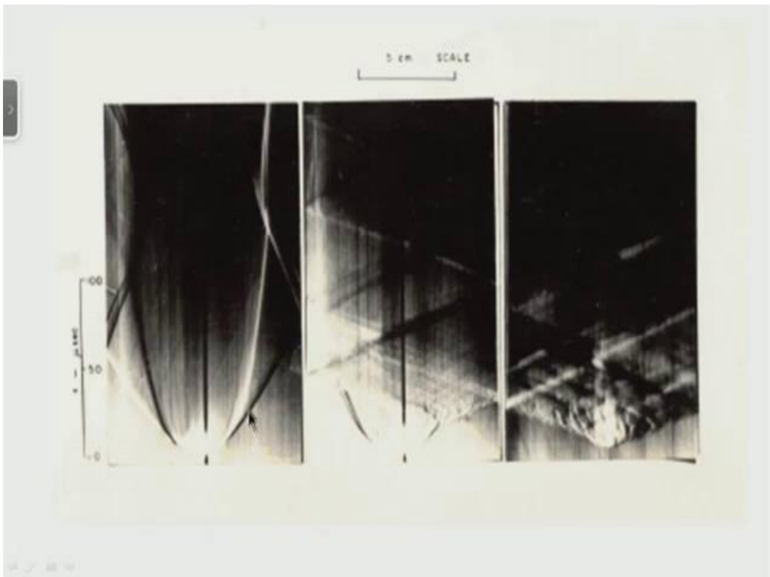
I also show the case wherein, the critical condition that means, initially I form a shock. The chemical reactions occur at some distance away from the shock therefore, it sort of decouples.

(Refer Slide Time: 32:10)



But then you know it really does not decouple like in the first case wherein, it the distance kept on increasing between the shock and chemical reactions. What happens is, at some particular distance it moves as a quasi steady that means, both are moving together, some instability sort of develop. And therefore, what is happening is the whole thing becomes highly messy and the chemical reactions couple with it and they form a detonation. This corresponds, seems to correspond to a critical case.

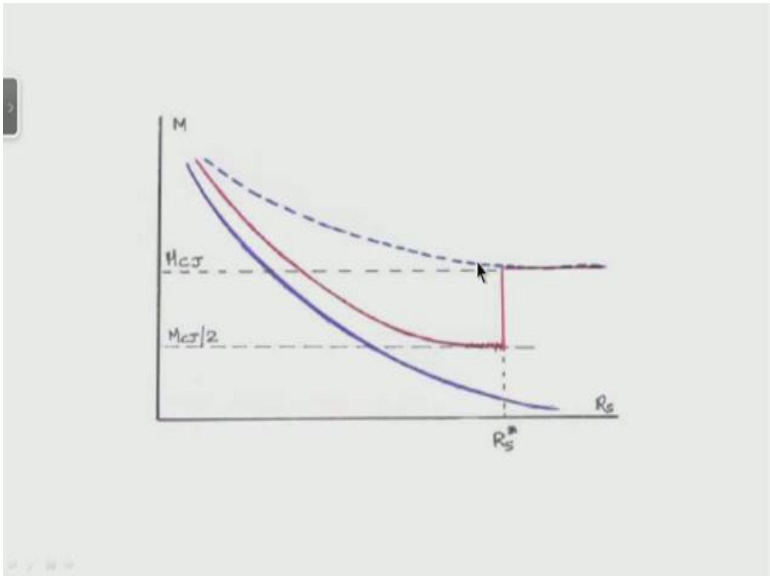
(Refer Slide Time: 32:30)



I can also show it in a sheet picture wherein, maybe when you have the shock, that is the blast wave is over here, it travels forward. You have the chemical reaction zone which are over here, chemical reaction zone over here, blast wave over here. You know that too keep on increasing distance and therefore, the energy is insufficient to form a detonation kernel of some minimum size.

Over here, the energy release is large I have a strong shock wave mind you, here the velocity is much higher. Chemical reactions occur just at the shock front and drive it as a detonation. This corresponds to the critical case where initially there is a decoupling and then, I have both going together and then, forming a detonation. Therefore, these experiments are suggestive of the following.

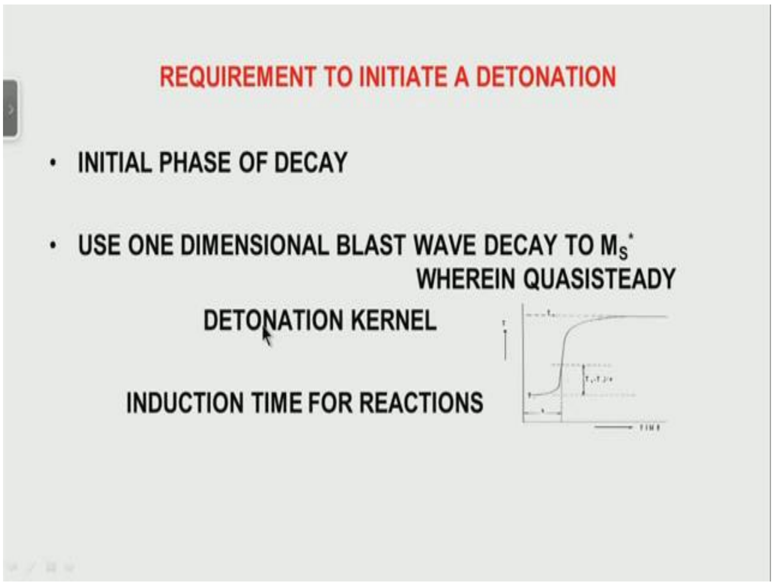
(Refer Slide Time: 33:18)



Well, I have mark number versus the distance, if the energy release is low well, I by the time a core of chemical reactions is formed, the shock wave has decayed to low velocities and it really cannot form a detonation. If the energy release is large E 0, we find this that, this is the direction of energy release, if the energy release is large well, I am able to form a detonation.

Under the critical conditions, it seems to decay to a smaller value and then, maybe go at a constant speed between the two, there is a constant zone of separation and then, it transits into a detonation. We still have to take a look at it, but all what we are saying is, when the energy release exceeds a threshold value, I am able to form a detonation, and this detonation travels at a constant speed, which we said is known as Chapman Jouguet speed and which we have to still model it. But we say well, under certain conditions well, it decays to a smaller mark number, and under critical conditions and then, transits into a detonation. I want to put all these things into a small model.

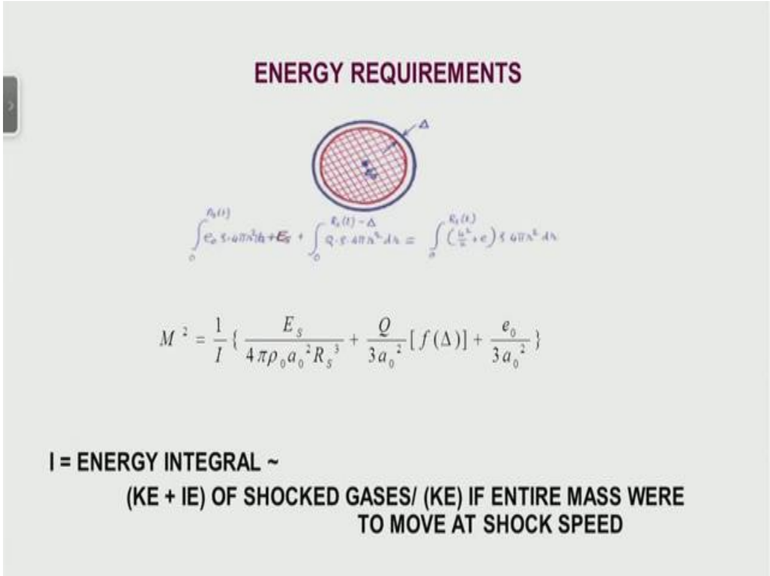
(Refer Slide Time: 34:29)



And therefore, I first try to say based on experiment and based on the constitutions which we discussed before looking at these 3 experimental results, we say well, initial phase is maybe due to the energy release, the blast wave decays. And if the, if the energy release is such that, I can form a detonation kernel under critical conditions wherein, I am just able to maintain the distance between the shock and the chemical reactions to be small wherein, there were both quasi steady and the chemical energy can derive the blast wave.

Well, I can, I can find the critical energy required for a detonation, under these conditions I say well, the distance travelled by the blast before chemical reactions couple is what we call as a detonation kernel. And why do we need this? Well, we need a minimum time for chemical reactions to occur, which we talk as the induction time. You will recall well, on time you have the time axis over here, maybe the temperature over here, and what is we say? Well, the chemical reaction have to take place before the maximum temperatures are reached. Well, this is, this is about the background of the experiments.

(Refer Slide Time: 35:45)



And therefore, now we can write the expressions down. We found, yes we wrote an expression for chemical energy release, when all the chemical energy is released. But now we find well, there must be a distance that means, shock is over here it takes a definite time for chemical reactions to occur.

Therefore, when the shock is at distance R s, I have a distance delta corresponding to the induction distance, over which shock travels. This is the chemical energy release well, this is the energy release from the source over here and these two, this plus this, plus the initial energy release is the total energy release in the medium, which using the same principles what I illustrated for the source and chemical energy release. I can write that the mark number of the front, that is the shock wave front, which is generated by the chemical energy release and by the energy release from the source.

Now, I put it as E s or E naught over here, is given by this particular expression. And I have the value I coming here, I combine the E naught and q over here. I said, it is also a function of the induction time. It is not q by 3 A naught square, which I just derived on the board. It is also a function of this particular distance over here, and I we said is the energy integral, which we studied earlier under blast waves, which is equal to the kinetic energy and internal energy of the shock gases divided by the kinetic energy if the entire mass of gas is were to move at the shock speed.

(Refer Slide Time: 37:21)

$$M^2 = \frac{1}{I}\left\{ \frac{E_S}{4\pi\rho_0 a_0^2 R_S^3} + \frac{Q}{3a_0^2}[f(\Delta)] + \frac{e_0}{3a_0^2} \right\}$$

$$\frac{E_S}{4\pi\rho_0 a_0^2 R_S^3} = \frac{Q}{3a_0^2}[f(\Delta)] =$$

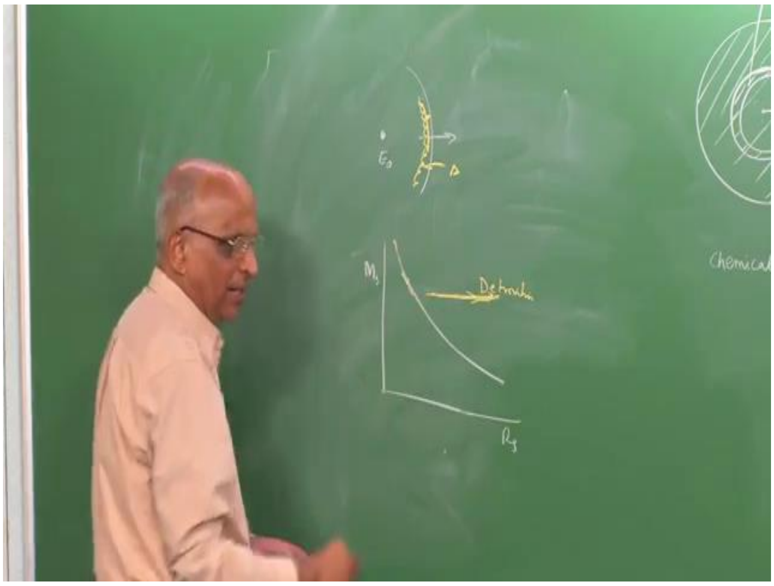
$$\frac{Q}{a_0^2}\int_0^{1-\Delta/R_S^*} \psi \xi^2 d\xi$$

$$= \frac{Q\{1-\Delta(R_S^*)/R_S^*\}^{q+3}}{3a_0^2}$$

Well, this is the formulation of a theory and let us see, what I get. I write the equation again as M square is equal to 1 over I. Source energy term over here, the chemical energy term over here well, I can even neglect this because the initial internal energy E naught, we have been always neglecting it over a blast wave. It is not necessary to consider, and what it is, I now tell myself.

Well, that decaying influence of the shock is due to the source. If it was in an inert medium, M s square is equal to 1 over I into this particular source energy term, it decays as R s cube, and this keeps decaying and the chemical energy release must be able to overcome this decaying influence. Or rather this must be equal to this for the case when the detonation should be formed because what should happen.

(Refer Slide Time: 38:10)



Let me again go back to the board. I have some energy which is deposited in a particular explosive gas. I am forming a shock wave because of this energy which is liberated, if there is no chemical reaction occurring, the mark number of the shock front which is formed, as distance moves will keep decaying.

What does the chemical energy do? We did this calculation, now we have put an induction time, a time for chemical reactions we say it takes place after a particular time over here, this we called as delta in a particular slide which we saw. What it does is, it sort of over comes this decaying influence, and tries to push it forward at constant velocity.

All what we are saying is, the chemical energy release must be able to overcome the decaying influence and make it into a steady propagating front at a given detonation velocity and this is the requirement. And therefore, we say well, the chemical energy release must be able to dominate over the decaying influence and drive a detonation.

(Refer Slide Time: 39:17)

$$M^2 = \frac{1}{I}\left\{ \frac{E_S}{4\pi\rho_0 a_0^2 R_S^3} + \frac{Q}{3a_0^2}[f(\Delta)] + \frac{e_0}{3a_0^2} \right\}$$

$$\frac{E_S}{4\pi\rho_0 a_0^2 R_S^3} = \frac{Q}{3a_0^2}[f(\Delta)] =$$

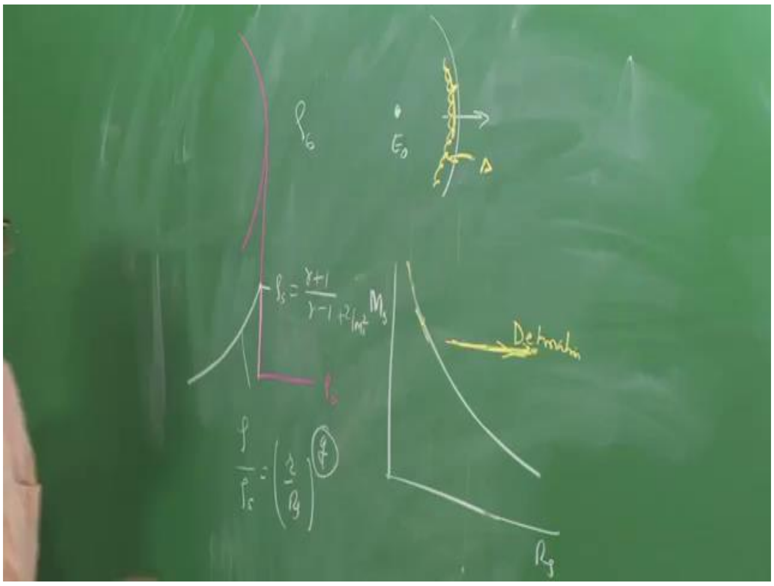
$$\frac{Q}{a_0^2}\int_0^{1-\Delta/R_S^*} \psi \xi^2 d\xi$$

$$= \frac{Q\{1-\Delta(R_S^*)/R_S^*\}^{q+3}}{3a_0^2}$$

And therefore, coming back to this slide we say well, the source energy term must be equal to this for the critical condition. Well, the critical condition is, instead of 0 to R s now, I say well, R s star is the detonation kernel, delta is the induction time or induction distance behind it. Therefore, I have 1 minus delta over R s star into the same you will recall this is the density ratio, this is R by R s over here.

And therefore, I can write this expression as q into 1 minus delta over R s, divided by R s cube into q plus 3. What was q? You will recall, we said that the density ratio behind the density ratio behind a blast wave, let us again go back.

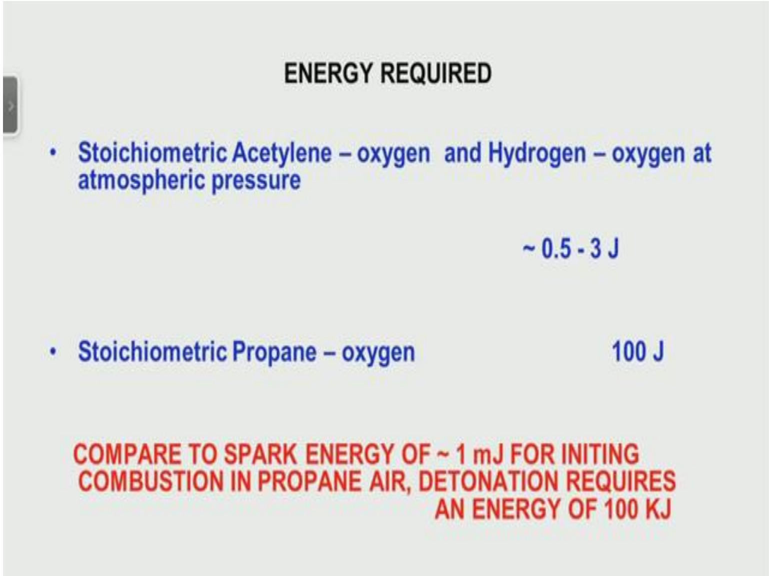
(Refer Slide Time: 40:00)



You had a shock front over here. We said well, at the front what happens you have the initial density is row 0 in the unburned medium over here. You have the density increased to row s, and the value of row s was gamma plus 1 divided by gamma minus 1 for a string shock, for a weaker shock well, I have to over M s square over here.

And what happen it decayed down, we got the slope of this, we said row within this blast wave divided by the value of row s is equal to we had R, that is at any distance divided by R s was equal to q. We found out q is a large number on 15 th, most if the mass is concentrated at the front. And that is the value of q, and if we put this we get well, the equality between energy release and chemical energy release.

(Refer Slide Time: 40:49)



And we are able to now get the value of R star. And from that, if we calculate the value of the energy required, we find that for a stoichiometric mixture of acetylene and oxygen is between 0.5 to 3 joules depending on the pressure. At atmospheric pressure, it is, it is around 2 joules or so.

For hydrogen oxygen mixture it is around 3 joules, maybe the variations is between 0.5 to 3 joules. For stoichiometric propane and oxygen, the energy required is around 100 joules. For stoichiometric propane with oxygen, if I consider air, it is very much higher, but we found whenever we talk in terms of propane air mixture, for the energy required to start a flame was only 1 milli joule.

Whereas, in this case, it is several kilojoules because here I am talking in terms of propane oxygen, for propane air, as I said its much higher. And therefore, you know the energy is of the order of 100 kilojoules for propane air and therefore, we find that the amount of energy required to start a detonation is way-way above the energy required to start a flame.

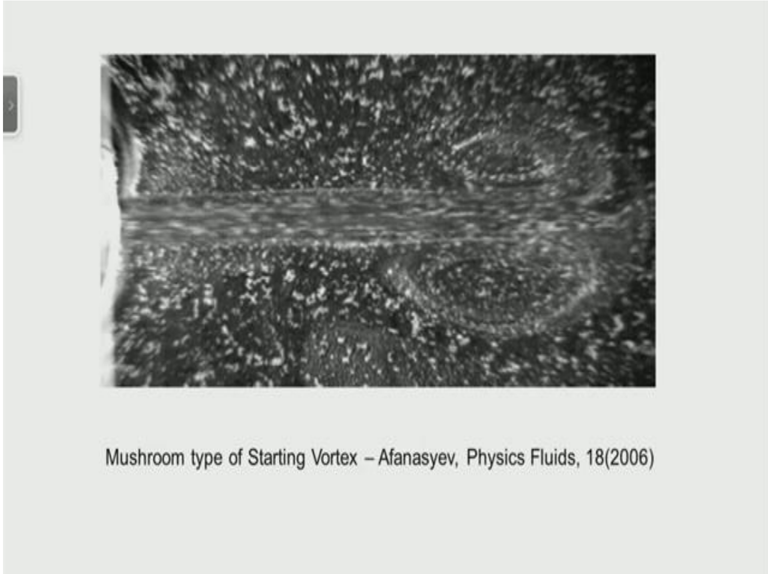
(Refer Slide Time: 42:01)

STOICHIOMETRIC MIXTURE	ENERGY REQUIRED
HYDROGEN - OXYGEN	6 J
HYDROGEN - AIR	3 kJ
ACETYLENE - OXYGEN	5 J
ACETYLENE - AIR	200 J
METHANE - OXYGEN	100 J
METHANE - AIR	100,000 kJ

Having said that, I just show in this particular table the energy required to start a detonation in hydrogen oxygen mixture, we said around 6 joules. Hydrogen air compared to 6 joules, required 3 kilo joules because of the inert affects. You know the thing is that, the induction times are larger, and that is why it becomes 3 kilo joules. Well, 3 kilo joules compares with something like 0.018 mili joules for the flame.

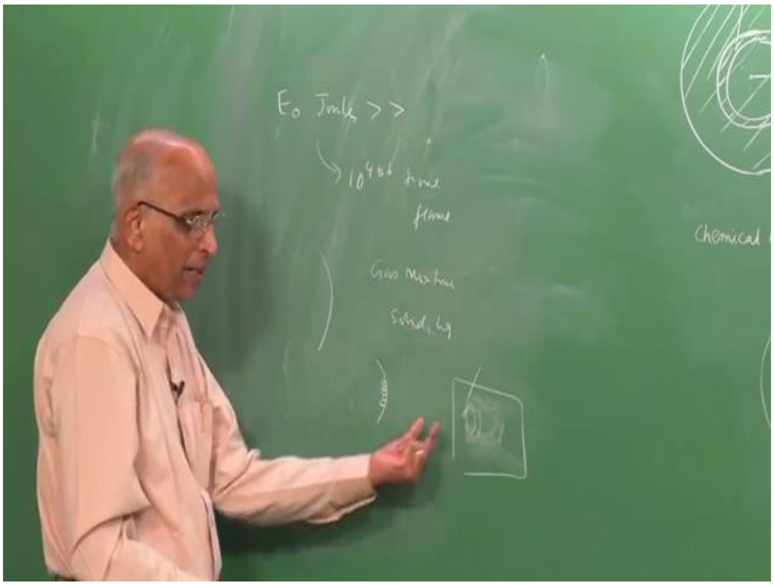
When we talk of acetylene oxygen 5 joules, when we talk of acetylene air it around 200 joules, when we talk in terms of methane oxygen, the energy required is around 100 joules, while with methane air the energy required is something like 100000 kilo joules which means, we are telling that, to start a detonation we require extremely large values of energy. The question is well, you know that means, we have said...

(Refer Slide Time: 42:57)



Yes, we have formulated a theory, let us, let us go back and take a look at what we have said so far. Yes we have understood what a detonation is.

(Refer Slide Time: 43:12)

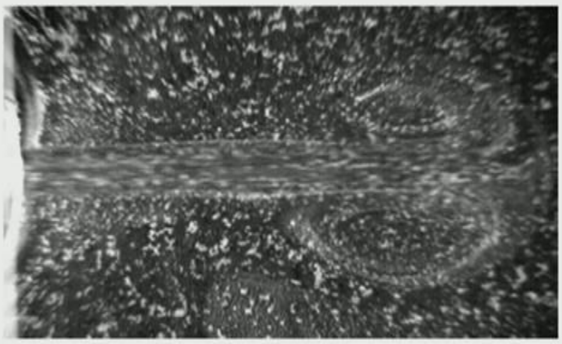


We also know yes, the energy required to start a detonation that is E 0 joules, is very much larger because I need a larger kernel of detonation, compared to a small quenching thickness kernel for a flame. And E 0 is something like almost like 10 to the power 4 times. In several cases 10 to the power 4 to 10 to the power 6 times, what is required to start a flame. Therefore, immediately we will say well, to start a detonation in a gas is going to be very difficult.

Well, it need not be so we will say that, but the point made is, if I have to start a shock wave and form a detonation, I require larger energy release. This is true, not only for explosive gas mixtures, it is also true for explosives like, let us say any explosives substance, which we will study after 3 or 4 classes, like solid explosives, maybe liquid explosives. The energy required to directly form are larger because what we require is to be able to form a shock wave, which should couple with a chemical reactions.

But this as I said need not always, need not be possible because in practice you know, the type of sparks we get, in accidental cases or maybe small mili joules of energy. And if I have something like an explosive gas over here, it is more likely to form a flame and not really a detonation. But then, let us take another look at some of the results, we are taking a look.

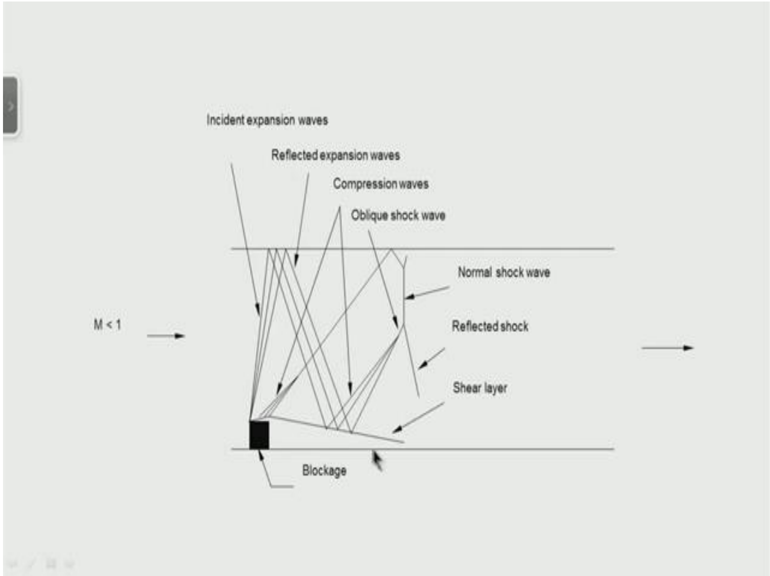
(Refer Slide Time: 44:38)



Mushroom type of Starting Vortex – Afanasyev, Physics Fluids, 18(2006)

You know, if I have something like gas which is flowing in a medium and say some, in this particular case I just consider, let us say a gas flowing through a particular ((Refer Time: 44:50)) over here when it flows over here. Some vortex is formed, something like a starting vortex is formed, something like a, like a shape over here, something like a mushroom shape is formed. And such starting vortex have been widely dealt with in literature such as, this particular author, he published a paper in physics of fluids on the starting vortex.

(Refer Slide Time: 45:21)



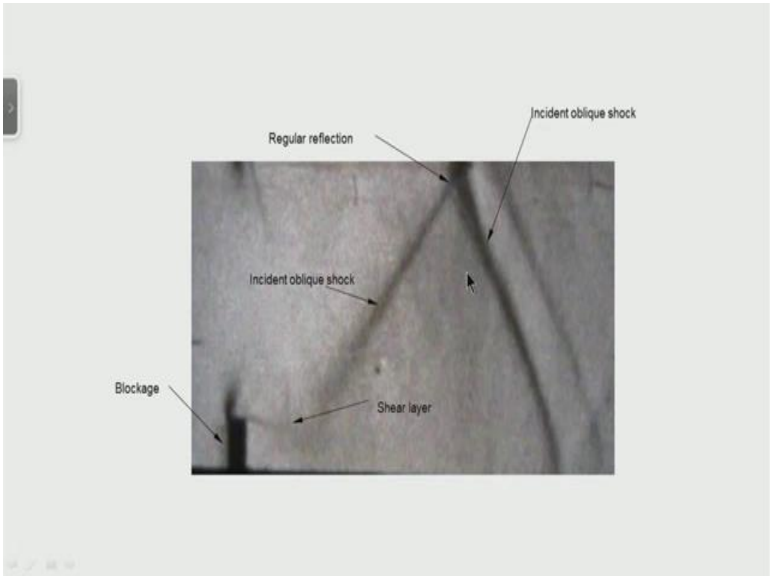
But what I want to say is whenever I have a flame, let us say I have a flame in a mixture that means, I have a pipeline over here, I have a gas mixture, I form a flame which travels slowly. You know, the flame is like a piston, and when I have a flame it pushes the gases ahead of it, and the gases therefore, acquire a velocity. That means the unburned mixture ahead of a flame gets a velocity. And if the flame becomes turbulent, it moves at higher speed and the gas ahead of the flame, which is unburned, moves at high velocity.

And in fact, if I have some blockages or surface roughness on the walls, what is going to happen? This high subsonic flow speed will create expansion waves because the flow becomes sonic due to the expansion of the gases behind the blockage, and I have expansion waves which get reflected. I have 1 thing like a recirculation zone, maybe a vertex is formed over here. I have a sheer layer which separates the zone of separation from the free stream zone.

The expansion waves come and reflect on this sheer layer and since, the impedance over here is ((Refer Time: 46:26)) or the mechanical impedance of the separated layer is less than the impedance of the air of the gas which is already processed or the free stream flow of gases. The expansion waves get reflected as compression wave. See we saw this, you remember? We had the E z value, we talked of gases moving into a higher impedance medium, a lower impedance medium. In a lower impedance medium, the compression waves reflect as expansion waves, the expansion waves reflect as compression waves.

And these expansion waves merge together and form a shock wave that means, they form a shock pattern. And behind this therefore, you have all these multiple shock structures taking place, and because these are all not these could be either a mask.

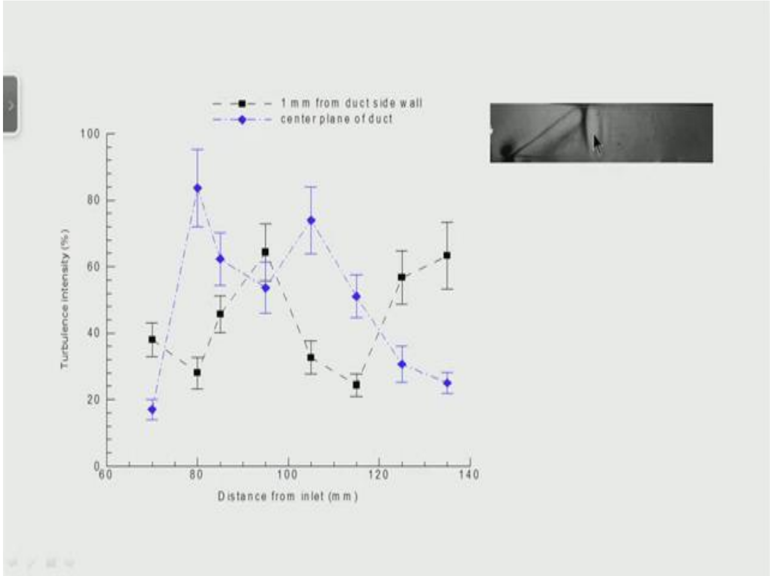
(Refer Slide Time: 47:18)



Term shock, we will consider this in the next class. And we also have, maybe oblige shocks, and because of this the flow becomes extremely, extremely turbulent ahead of the flame itself. Now, similarly, I show a ((Refer Time: 47:24)) picture, you have a blockage here, you have the gases flowing.

Well, you have the shock waves which are being formed, you have a shock wave at the wall, you have the reflected shock wave here, an incident shock wave, you have a reflected shock wave, you have a either you could be a regular reflection, it could be a mark type of reflection. Therefore, you have all the shocks which are possible.

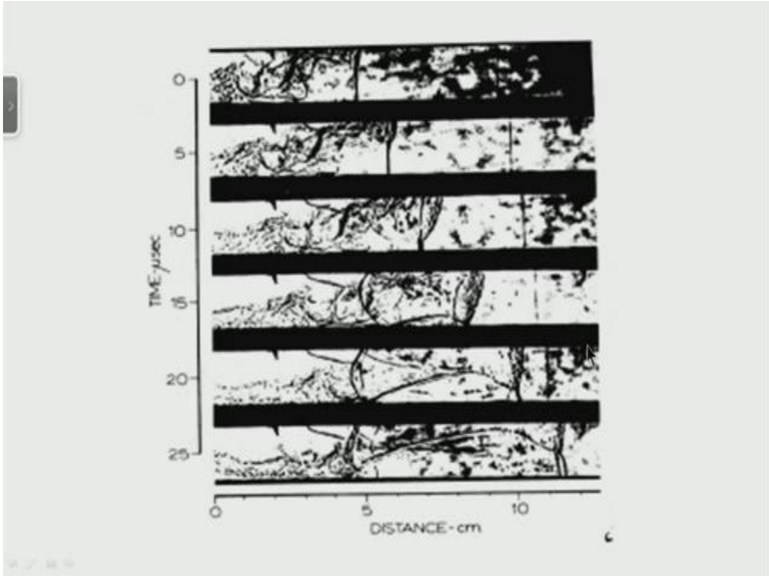
(Refer Slide Time: 47:46)



And these things what they do is, they create high intensity turbulence, know because you have flow directions being changing, you have slip streams over here, you have very high intensity turbulence over here. And this high intensity turbulence and also the length scale of turbulence also increases behind the leap shock wave, which is in the unburned gases.

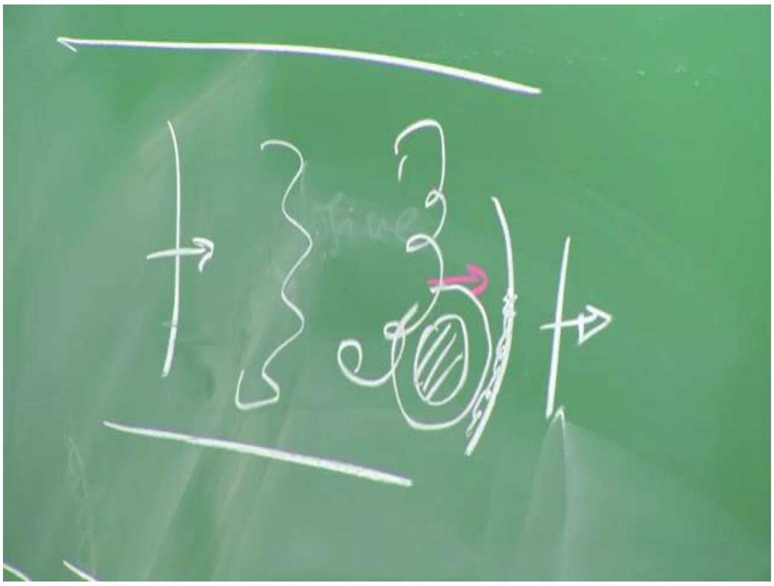
Therefore, you form a very high turbulence flame, which further pushes the gas at high velocity and since, you have the length scale turbulence which is large, you have the flame which is engulfing the unburned gases. And when you have the flame which is engulfing the unburned gases, it sort of implodes, or it sort crumbles together, it capitates sort of, and energy is released. And this energy release could form a shock wave and then, I could have a detonation.

(Refer Slide Time: 48:36)



Therefore, we say well, this is what happens, I have the gas which is flowing, I have the turbulence structure which is being formed, it becomes highly turbulence ahead of it. And ultimately, I have something like a zone of unburned gases, which is enclosed by a particular shock wave. And this shock wave implodes and this thing generates a strong shock wave, which can now couple with the chemical reaction to form, what we call as a detonation wave.

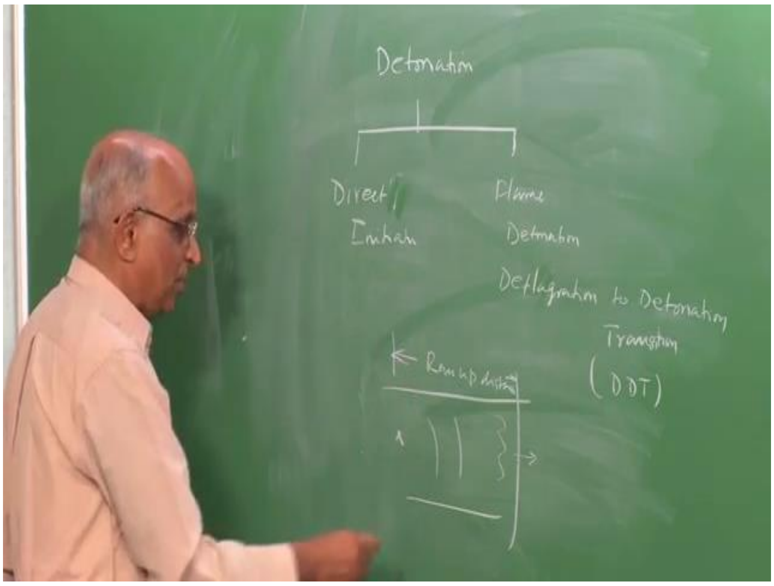
(Refer Slide Time: 49:13)



Therefore, we tell ourselves well, it is also possible for us to think in terms of a situation wherein, I form a flame, and this flame becomes highly corrugated. And ahead of the flame in the unburned gas mixture I have, maybe the velocities are high. And as it becomes more and more turbulent, this flame becomes more and more corrugated until, maybe it forms, it is able to engulf the unburned gases. And when these unburned gases they auto explode, I generate a shock wave.

And now, the chemical reactions take place behind this shock wave because it is quite strong and I get a detonation. Therefore, the formation of a detonation could be from two sources namely, the direct formation of a blast wave which couples with chemical reactions.

(Refer Slide Time: 50:00)

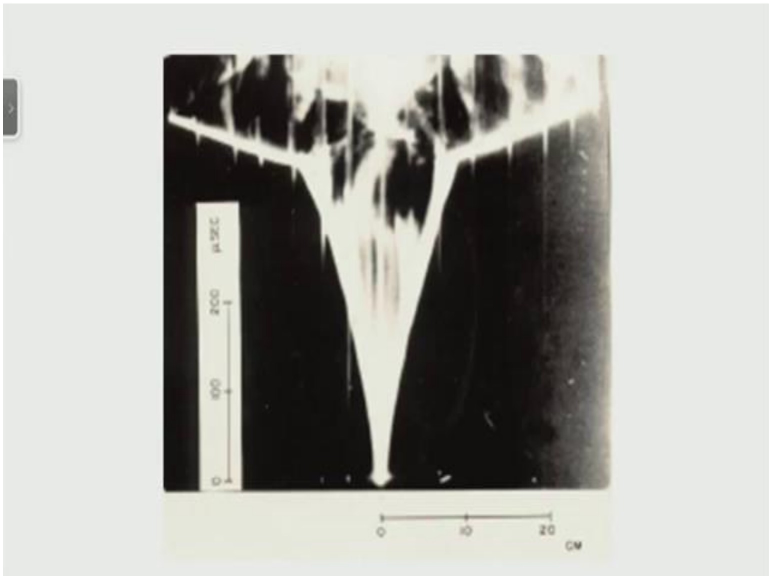


Therefore, I say well, a detonation can be formed by directly from the ignition source, which forms a strong blast wave, which I call as direct initiation. Or I could also form, in which case I could form a flame, and the flame pushes the unburned gases ahead of it form a turbulence gas mixture in which a turbulent flame is formed. The turbulent flame can travel at high speed, it forms a very turbulent flame brush, and this brush if it is able to engulf some gases well, it forms a shock wave.

And then, this shock wave forms a detonation in which case it is an indirect way of forming a detonation, which we call as deflagration a another word used for flame is deflagration that means, a constant pressure flame or a pressure slightly reduces across a flame, we call flame as a deflagration to detonation transition, and this is abbreviated as DDT. Therefore, two ways of forming a detonation is direct initiation, we found that the energy releases are rather high, we know how to calculate the energy release.

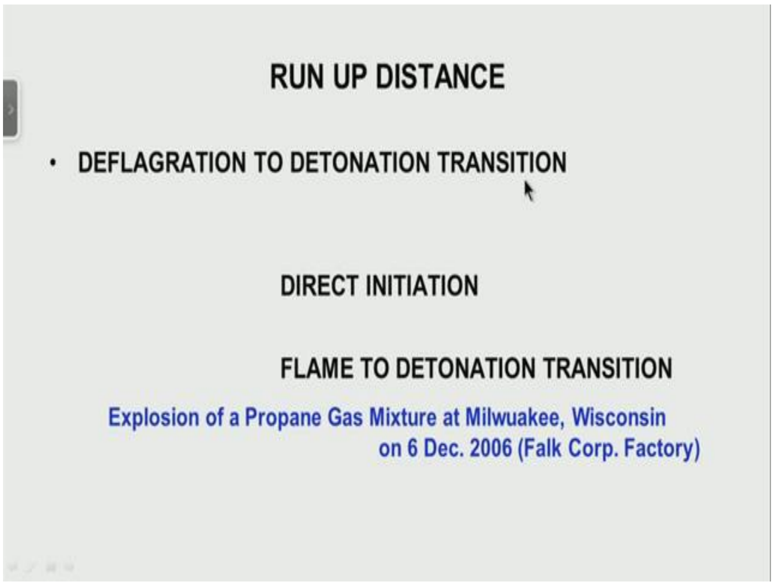
But in this case, I have a flame which forms a detonation. And the distance required from the energy release source, initially I form a flame than after some distance I form, this the distance required is called as the run up distance. And most of the accidental explosions or explosions, which occur with solid explosive, with liquid explosives, with gaseous mixtures, are from flame transiting to this and we will discuss this, maybe in the next class again. To summarise then, I would like to say the following.

(Refer Slide Time: 51:52)



Well, this shows the street picture, initially I have the flame moving over here, low velocity over here, the conditions for detonation are formed well, a detonation propagates at constant velocity thereafter.

(Refer Slide Time: 52:07)



And to just sum up well, the run up distance is for deflagration to detonation transition. It is different from direct initiation wherein, the energy source from directly at detonation. The initiation source forms the flame, which later transits to a detonation.

And in most of the explosive gas mixtures, like we remember, we talked of this, in a particular factory now there was an accidental leakage of propane gas, it formed a propane gas mixture. This was in Wisconsin, and what happened is, this propane gas mixture interacted with the, a flame got formed, the flame push the gases ahead of it. And the gases with were travelling at some velocity, interacted with the machines in this particular machining facility that means, you have the lath machine, it acted as an obstruction or a blockage. The gases ahead of it move towards the particular blockage and it created conditions wherein, a turbulent flame got formed, have further high velocity a gas is got domed.

And gradually a very turbulent flame got formed, ultimately it transmitted into a detonation. We will consider some cases in the next class, and what we do in the next class is therefore, we will see yes, we have learn something about detonation, about how to start a detonation, the two methods of forming a detonation. And what we should be looking at, is at the structure of a detonation. We will see it is not so beautiful, it is not 1 dimensional, it is a multi-dimensional detonation and then, we will take a look at some theories of detonation.

Well, thank you