Indian Institute of Technology Madras
Presents

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NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion
Non- air breathing Engines I

Lecture 6

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We had looked at all the air-breathing systems; now let us take a look at what are the non air breathing systems okay.

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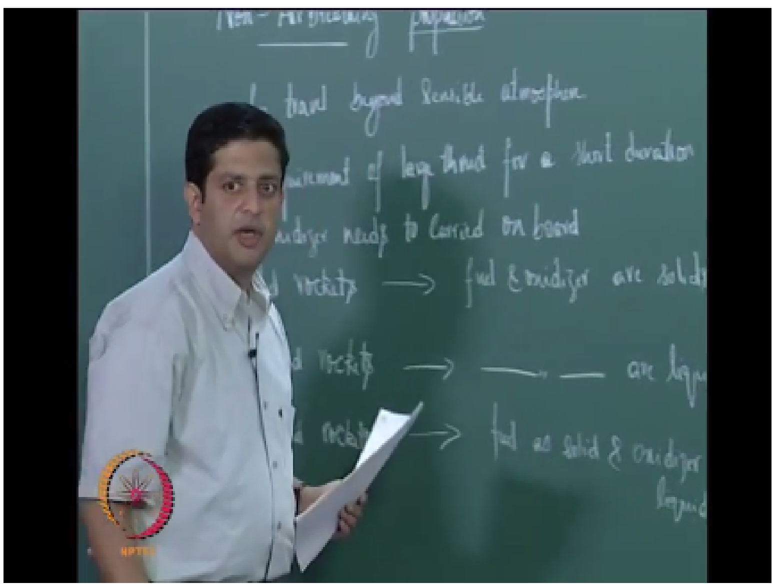

Why do you think we need this I thought we had covered a large Mach number range with the air-breathing system itself, why do we think where do you think we need the non air breathing system okay, that is one part yes for travel beyond sensible atmosphere. The other reason that it exists is suppose you need a large thrust for a very short duration, even within the atmosphere then you tend to go in for non air breathing propulsion okay.

Because if you look at everything propulsion other than the ramjet engine most others are very bulky right, so if you are looking for a large thrust for a very short time you cannot use a large dead weight to propel the system. If you are looking at a turbo jet engine to propel it if you are looking for a large thrust for a short time and you cannot use it and then discard it right. Therefore we tend to go in for rockets or non air-breathing propulsion even within the sensible atmosphere.

Typically missiles tend to make use of this, remember I said any of the ramjet engines are not self-starting and they need to be taken to the Mach number range beyond one for them to be operational, usually rocket engine is used to take it to that because you can get to that very quickly right, if you use the rocket engine. Now most of these airs Ramjet engines are used either as an interceptor missile right then you are looking at a very short response time that you have.

Once the enemy is intruded into a territory you want to find out how to go about neutralizing the enemy right, it has a very short time you have a very short response time that is available to you. So if you have to respond within that time then you need a rocket engine and then air I am getting it okay. Now in non air-breathing propulsion there are three kinds one is solid rockets, then there is liquid rockets and lastly hybrid rockets.

The classification is one based on the physical state of the fuel and oxidizer, remember in a non air-breathing propulsion system you need to carry your the oxidizer on board right see. So in this case the oxidizer carried on board, so in this case here and oxidizer are solids and here fuel and oxidizer are liquids and in this case typically you will have fuel as solid and oxidizers liquid okay. Now just to look at all these systems developed over a period of time.

Remember we started our discussions with firstly fixed-wing designed, how fixed-wing design came about and now it took us a hundred years after that to develop the first flight. So similarly let us look at how these things they award over a period of time now most of you must have played with this Diwali Rockets right, this Diwali Rockets use something known as gunpowder.

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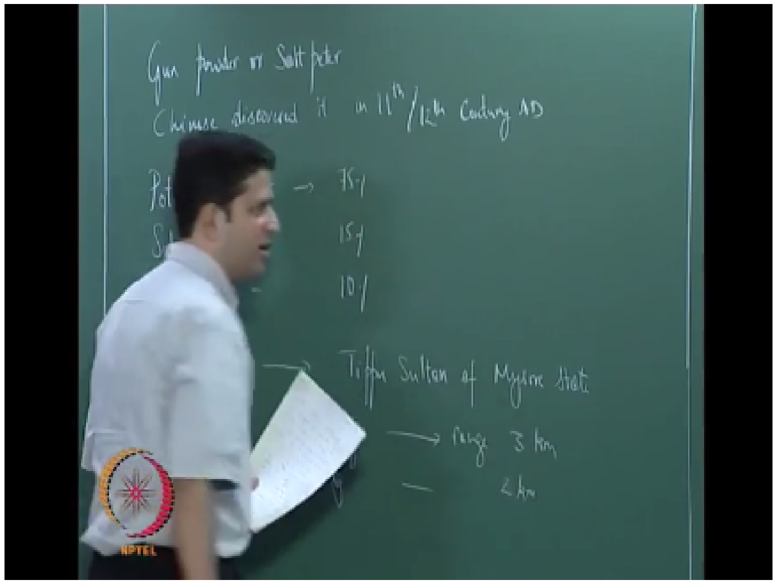

Or saltpeter, now this was discovered by the Chinese around the 11th of the 12th century, so a typical composition of this is it has potassium nitrate around 75% then sulfur15% and lastly charcoal 10% okay. This is a typically composition of a gunpowder and this was discovered in the longer than 12 century after that there we use those explosives but their first piece or first known military use as source to speak as Rockets was somewhere in the 1700 by Tippu sultan Mysore state.

He used this against the British in the third war between the British and the Tippu Sultan, so these were you know he had fairly decent systems but one of them was something like 2 meters long and weighed about 3.5 kgs and had a range of something like 3 kilometers he had another system which was of a shorter range of 2kgs and 1.5 meter and 2 kilometer range. So he had essentially two systems, if you look at what these things did these were glorified current day Rockets right.

But if you look back at a time when these were not known to people okay and suddenly you have something firing and coming at you would be very scared and this would this would be typically used to break up the cavalry ranks, if the enemy is approaching you in a rank formation and if you want to break it up and make them go helter shelter that is when you fire these things at them and that makes them really scared and moron they were not really killing machines as such.
Now after the British won the final war of Mysore around 1799 they actually took all these things to Britain and there was a person by name William Congreve.

He developed these systems further he made a systematic study of them and develop this further and they were used in a few other words fought by the British somewhere in Europe but never really took off beyond that and unfortunately, we do not have any of these specimens that Tippu Sultan built anywhere in India, now they are only available in the British Museum in Britain but after the development by William Congreve it never really took off as a large system they were used in a battles essentially to break the ranks the cavalry.

And things like that and they were later on discarded because liquid rockets became more prominent as the 19th century arrived or the 20th century arrived liquid rockets became more prominent and one would find that liquid rockets began to be developed and talked about I need 20th century and the solid rockets made only a comeback after the Second World War somewhere in the 1950s as large systems.

Otherwise they were relegated to the use of being used as flares in ships right or they were used as useful jet-assisted takeoff, that is if you have an aircraft that needs to take off within a short runway length typically in a battle operations the enemy will first come and try to bomb your airfields, so that your aircraft cannot take off. So then your operational length of the airfield somehow becomes smaller and if you want to take off within that small length then you need an extra thrust that probably the afterburner might not also be able to provide.

In such cases you use these solid rockets and you can drop them as soon as you take off you can drop them, so you do not need to carry them so they are essentially used for flares on ships or jet-assisted takeoff okay and only in the 1950s they started getting developed into large systems okay. Now let us look at what this solid rocket looks like.

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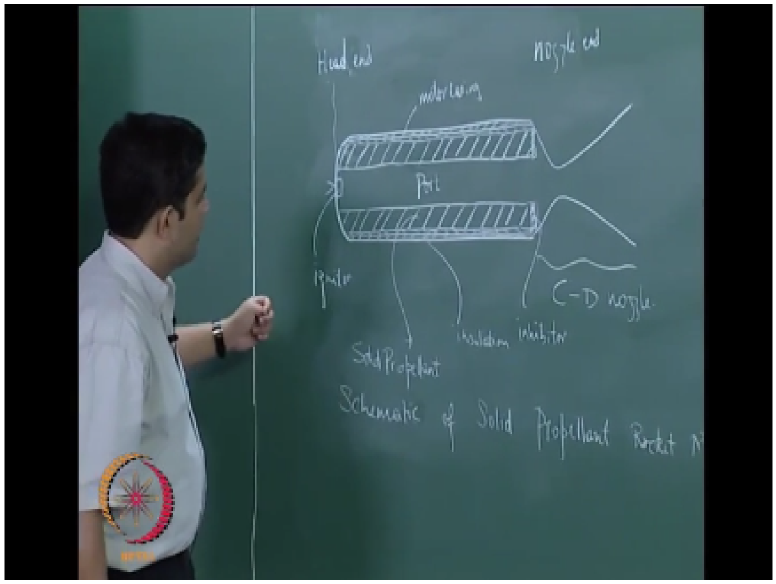

You have an igniter this is known as the agent and this is known as the nozzle and you have a convergent divergent nozzle here okay, this is the solid propellant and this is known as wood okay and you have a layer of inhibitor and this layer here is the insulation and this is the motor casing. So this is a schematic of a okay it has an igniter a propellant green that is the solid propellant green and has a port wherein the propellant burns and the gasses fill up this place and it has a convergent divergent nozzle.

And the whole thing is taste inside a motor casing typically made of steel right or other material metals, all eight people are planning are trying to use FRPs or fiber reinforced plastics here just to save weight and you have a layer of insulation here, what does an insulation do? Insulation prevents heat from being transferred or inhibits transfer of heat okay.

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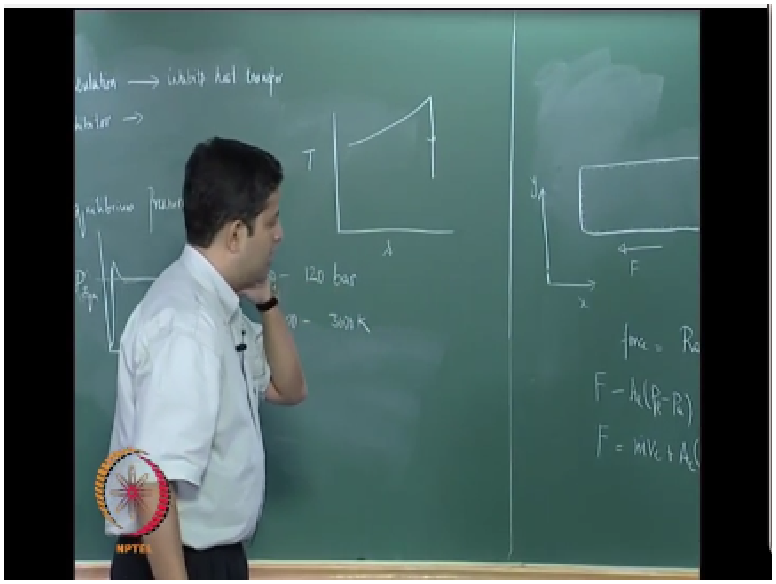

Now there is something known as inhibitor, now what does inhibitor does this although there are high temperature gases here all through this it prevents the burning from taking place in this direction okay, it does not allow burning to take place in that direction that is the role of a inhibitor and typically silicon oxides are used as inhibitors and the igniter is typically a solid propellant itself with a slightly higher loading of metal we will discuss that when we discuss about solid propellants in a little more detail as we go along.

And you have a heat sensitive material here as soon as you apply some voltage across the two terminals this catches fire and as this burns the hot gases and metals fall on the propellant and the propellant gets ignited. Remember a solid propellant has both fuel and oxidizer okay so this catches fire as soon as this starts to burn the pressure inside the chamber keeps on increasing okay because you only have one port and all the gases need to go out through that port and the pressure will keep on rising till the outflow and the inflow matters okay.

And that pressure is known as equilibrium pressure that is if you take a pressure versus time graph the pressure keeps on rising and shoots beyond the equilibrium pressure and comes back to this pressure is known as equilibrium pressure. It pressure increases and increases beyond the equilibrium pressure and comes back to this value, so then this high pressure high temperature gases okay that are formed here typically the pressures can be of the range of 30 to 120 bar in the combustion chamber and temperatures can be in the range of 2600 to 3600 Kelvin.

So these high temperature high-pressure gases are then expanded through a convergent divergent nozzle why are you using a convergent divergent nozzle here? Why not a convergent nozzle because if you look at it the pressure upstream of it is very large and there you have a large pressure ratio between the ambient and the pressure here, so you can expand it through a convergent divergent nozzle and that is why we use a convergent divergent nozzle in any of the rocket motors.

So if you look at a TS diagram for this how will it look like if you were to sketch a TS diagram for the processes in it will there is combustion at high pressure and there is expansion through the right through the nozzle, it is a self pressurized system because of burning the system pressurizes itself it does not need any compressor and the high-pressure high temperature gases expand through the nozzle thrust producing the required moment.

Now let us look at how-to derive the thrust equation for this and remember we derived the thrust equation for a air breathing system let us do the same for this non air breathing system.

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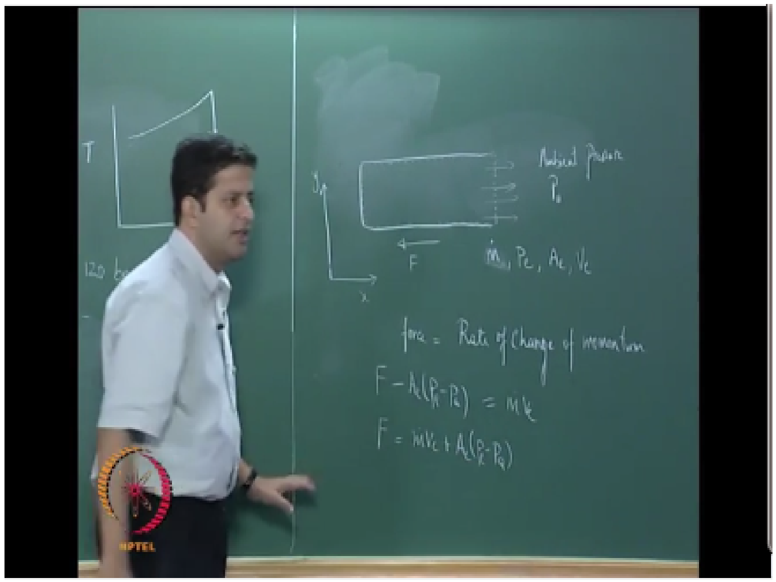

I will take the entire rocket motor as a box and it has only one exit it does not have any inlet because it does not need to take in air so it has only one exit and let me call the conditions here as Rui or let me call the mass flow rate that is coming out as in MDOT and pressure as Pe and area as Ae okay fine and the ambient pressure is okay. Now with this you will you will find that if we were to find the sum of the forces in the x-direction that is the negative x direction that is thrust acting in this direction okay.

Thrust must be =force must be =rate of change right I did not put one more quantity that is the exhaust velocity Ve okay. Now force must be =rate of change of momentum right what is the rate of change of momentum here? Firstly let us look at what are the forces F - Ae Pe - Va right there is a pressure differential across this P_E -P_A and this area is AE, so this is acting in the opposite direction as F so I have taken the - sign must be = what is the rate of change of momentum here m dot x V because there is no intake at all right.

So you have therefore F is = this is the thrust equation for a rocket motor it does not matter what kind of rocket motor view I have liquid or solid or hybrid this is the thrust equation okay. Now if you remember we had defined a quantity called specific fuel consumption right, when we talked about gas turbine engines or turbojet engines and turbofan and similarly we can define a quantity called specific impulse here.

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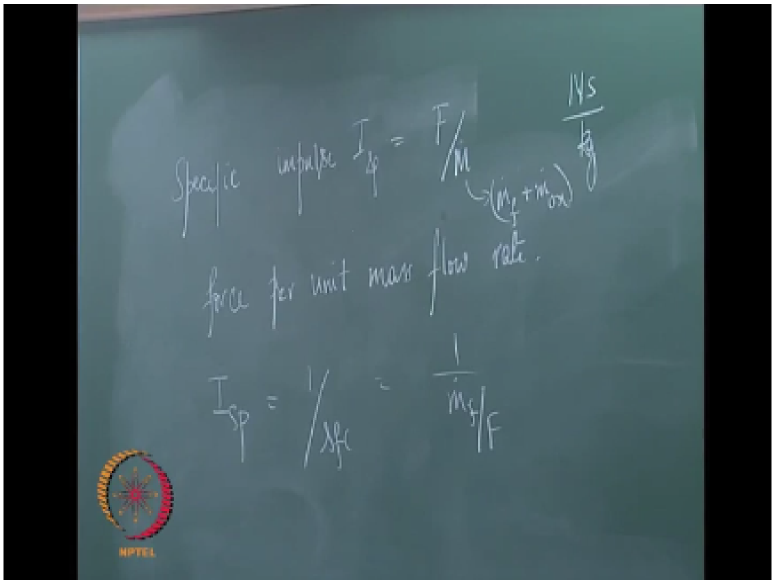

What does impulse? Impulses force into time right, so specific impulses force into time divided by mass okay, so if you look at the expression it is f by m dot that is it is nothing but force per unit mass flow rate and the units of this is Newton second per kg this is the I_{SP} and S_{FC} is I_{SP} is nothing but 1 / S_{FC} if you remember I $_{SP}$ is nothing but mass flow rate per unit thrust mass flow rate of fuel per unit thrust in this case it is the combined mass flow rate of fuel plus oxidizer, this includes mass flow rate of fuel plus mass flow rate of oxidizer.

Whereas S_{FC} is nothing but m dot F / F okay, now a couple of classes back you had asked me how is it that you can say that you get optimal thrust when P_E is =P_A right you had asked me how that is optimal now let us take the case when P is =P_A right.

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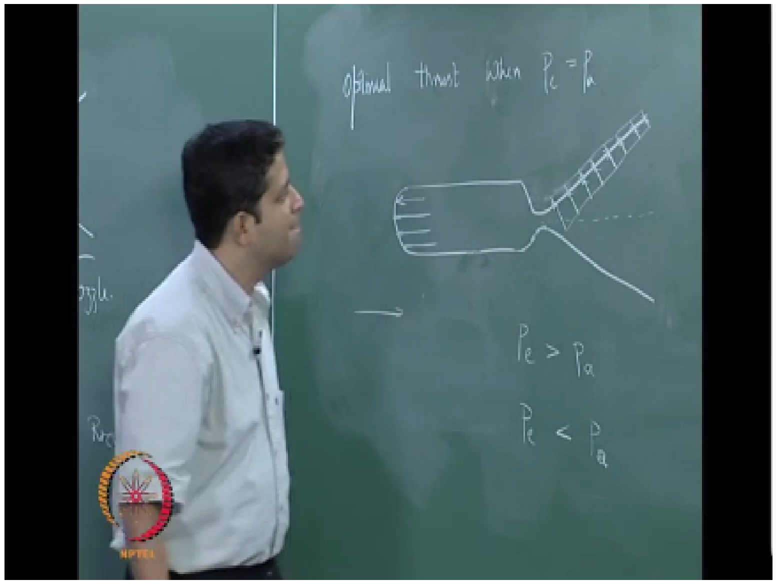

What happens then the flow is said to be optimally expanded if you look at this converging diverging nozzle or I will draw a different sketch here okay, now just like probably some of you are aware of this in aerodynamics you get the lift on the aerofoil by integrating all the pressure over the aero foil okay. Similarly you can get the thrust produced by a rocket motor by integrating the pressure acting on the surface of the rocket motor.

So if you take a look at this the pressure acting on this direction in this direction cancels each other out because of symmetry, so we are only interested in pressure acting in this direction. So you will have pressure acting on this surface and then after the nozzle, what do we mean by optimally expanded? When ambient pressure is = exit pressure, so pressure here is I will draw only the top half it is symmetric about it pressure goes on decreasing as you go from the convergent portion to the exit right.

Pressuring decreases in velocity increases and let me take it that at the exit it is = the ambient pressure okay the ambient pressure is a constant right now this is the nozzle when it is optimally expanded, what happens when Pe is >Pe and what happens when e is < P is what we need to look at. If we are able to show that in both these cases it is less than the thrust produced by this case when $P_E = P_A$ we have proved our point okay.

Now let us take a look at when Pe is >P_A how does that happen if I cut off a portion of the nozzle here right if I were to cut off a portion of the nozzle remove a portion of the nozzle, then the pressure here is > the ambient pressure right but what have I done I have cut off a portion if you look at this the pressure on the inside is > the pressure on the outside, so there is a net force in this direction which you can resolve in these two perpendicular directions.

Now this force cancels each other out because of symmetry and you get only this right, so if I removed a portion here in order to make $P_E > P_A$ I am taking out essentially a portion that was producing thrust which means the thrust is going to be smaller than what it was when $P_E = Pa$ now let us consider the other case when P_E is $< P_A$. Now if you see this the ambient pressure is constant but the pressure inside is decreasing we know the ambient pressure when that happens which side is the net force acting 1.

If you look at the rest of the portion up to this point this is the point where P_E is $= P_A$ right up to this portion the net force was acting in this direction. Now the pressure on the inside surface is less than the pressure on the outside surface so the net force will be acting in this direction which if you resolve will give rise to forces in these two directions perpendicular directions. Now there is producing a negative thrust right.

So if you add a portion of the nozzle so that P_E is $< P_A$ we are adding a portion which will produce negative thrust and therefore it will be not the highest, so the maximum thrust that you can get is when P_E is $= P_A$ if you look at it the other way round one can argue that if P keeps on decreasing is when the velocities will keep on increasing okay and therefore if P decreases and goes to zero is when velocities will reach a maximum okay.

Now let us look at what are they yes in the in the process if we cut that nozzle like we have a super smash colonel down there is another and rocket is flying, suppose we cut that nozzle and only the conversion part is they are little produce negative thrust no just forgetting something yeah. There is a thrust acting here now this surface or say this surface you can yes you are right the pressure here is acting in a in this direction right but this area is there is a small area wherein it is acting in this direction right.

This direction will be > what is on this direction most of the thrust comes from the front part if you integrate the pressures yes, if you integrate the pressures that is if you cut off the nozzle here yes the converging portion if you look at it from that perspective is producing only a negative thrust and a component of it is what you are looking at but there is a throat right and there is a portion in this direction and remember always the throat pressure is much less than the chamber pressure.

So therefore you will get a positive thrust even if you have just a converging nozzle okay, now having looked at how to get the thrust and what is I_{SP} let us look at what are the different kinds of solid propellant that are available to us or that are currently being used.

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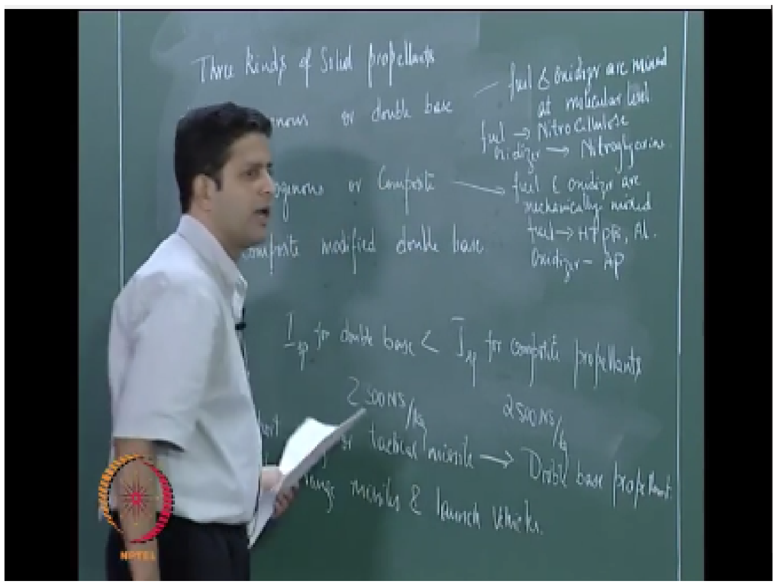

There are three kinds of solid propellants, the first is homogeneous or double base and lastly composite modified double base. Now if you look at solid propellants that are a problem in regards to solid propellant the fuel and oxidizer need to be in close proximity with each other and yet not react, over a period of time. So that is that restricts us from using any solid fuel and oxidizer because they have to be compatible right they should not react with each other.

And in addition they should have good mechanical properties, so that they can be used in large rocket motors. So homogeneous propellant or double base propellant in this the fuel and oxidizer are mixed at a molecular level that is even if you take a small portion of it you will not be able to make out which is fuel which is oxidizer if you take a double base propellant. The typical fuel and oxidizers are fewer less nitrocellulose and oxidizer is nitroglycerin.

They are used nearly in the same proportion and that is why the name double base two basis is what it indicates okay. Now different as different from this in a composite propellant fuel and oxidizer are mechanically mixed that is if you take a small portion of the propellant you will be able to identify what is the fuel and what is a oxidizer and typical fuels are HTPB or hydroxyl terminated poly butylenes and oxidizer is ammonium per chlorate and we also add aluminum in these propellants which is essentially.

If you will discuss this in a great detail a little later in the course, now the essential difference between these two propellants is because this needs to be mixed at a molecular level there is a stronger restriction on this and therefore the specific impulse that we discussed a little earlier is low for if I were to I_{SP} for double-bass is < is v4 composite propellants because in this case you can mechanically mix them there is a lesser restriction and therefore you can find suitable chemicals that you can mix and get a slightly higher performance.

Typically the performance of this is this is around you get an I_{SP} around 2300 Newton seconds per kg and this can go up to 2500 Newton second per kg while I not this one would have thought that because this is superior in terms of performance, we should not be using this at all why do we have both of them still survived. One of the reasons is if you look at in a military application essentially what happens is if you take a composite propellant the composite propellant has aluminum if you see here and this aluminum oxide produces a strong thermal signature.

And in addition the ammonium per chlorate that we using has as in the exhaust products H_{CL} which reacts with water in the atmosphere and also gives a strong exhaust signature, if you are looking at a short-range missile right or a tactical missile as it is called that will film aside you will want the enemy to know from where you have fired it right because then the enemy can come back and hit you, so which is why you will want to use these propellants for short-range missiles or tactical missiles.

So short-range or tactical missiles you will end up using double base propellant okay because this does not have such a heat signature and a composite modified double base propellant is simply you add Hmx or RDX to double base propellant that gives you composite modified double base propellant that will also not have a heat signature but will have a higher performance and therefore it will give you a better performance but I will not have a strong signature like composite propellants.

And sometimes people use ammonium per chlorate also in this okay in the composite modified double base propellant; the typical uses of heterogeneous propellant are for long-range missiles and launch vehicles long-range missiles you do not care about what happens whether the enemy detects you because you are separated by a large distance from the target.

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Solid Rocket motor

Engine	Thrust x t_b, kN x s	Propellant	Propellant mass, tonnes	Chamber pr., atm.	A_e/A_t	I_{sp}, kN s/kg	Dimensions
SAM, Stage I USSR	250-380 x 4.5-3.0	Double base	0.19	30-60	6.0	2.10 (SL)	0.53 m dia x 2.5 m length
Rocket Dyne MK 60 Phoenix	8 x 60	Composite	0.20	-	6.0	2.5	0.38 m dia x 1.78 m length
Lockheed LSM -156	13600 x 120	Composite	317.50				3.96 m dia x 18 m length
PS 1 (PSLV) India	4500 x 100	Composite (14HTPB-6 8AP-18Al)	139.00	60	8	2.5	2.8 m dia x 20 m length

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Now if you look at this table here I have put together thrusts different kinds of propellants and I_{SP} here you look at the last few ones they are very large motors that produce very large thrust this has 139 tons of propellant the PSLV stage one and produces something like 4.5 mega newtons of thrust ok you look at ISPs it is of the first ones are the first two are double base propellants it's around 210 mm 100 Newton second per kg and it can go up to something like 2,500 for a composite propellant okay. We will stop here and continue in the next class where we will discuss about liquid propellant rockets thank you.

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