Rocket Propulsion

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Lecture No. # 34

Review of Liquid Bi-propellant Rockets and Introduction to Mono-propellant Rockets

Good morning. In today's class, I will be dealing with monopropellant rockets and hybrid rockets as a continuation of the chemical rockets. But just to make sure, we are very clear about what we have done so far.

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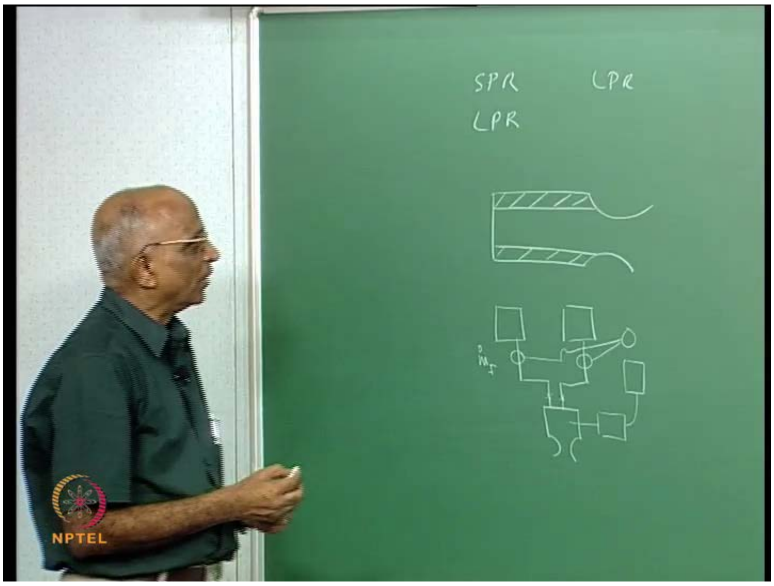

Let us quickly review what are the things we learnt in solid propellant rockets and the liquid propellant rockets. See, solid propellant rockets we have gone into detail, but we said controllability is a problem in solid propellant rockets. What do we mean by that? Once a solid propellant rocket gets ignited, like you have let say a star grain or a cylindrical grain, and once this grain is ignited, it is just not possible to stop the combustion.

Whereas in a liquid propellant rocket, since you are feeding the propellant from a tank into the combustion chamber, maybe by a pump, maybe by gas pressure, maybe regulated or blow-down mode or any other mode stage combustion cycle mode, it is always possible to stop feeding it and you can have control. Therefore, we can say a liquid propellant rocket is more versatile in that control is possible, and not only you can you control the flow, but supposing I have a control system like I want to control the chamber pressure, maybe I put some control here, maybe with respect to compared with something else, and therefore using this control system, I can control the chamber pressure, I have a reference chamber pressure, I make sure that the reference chamber pressure and this are same.

Supposing, I want to control the mixture ratio, maybe I monitor through a mass flow meter, the mass of fuel which is flowing in like let say M dot F which it measures, I can measure the m dot o, I can instantaneously record the value of M dot F by m dot o through a particular circuit, let say I fed this signal over here, I fed this signal over here through a mechanism here, and if I find that the mixture ratio is exceeding I can give a command to these valves or to a valve upstream to slowdown and all that, control is possible. Not only starting and stopping, but also mixture ratio control, maybe pressure control and hence the thrust control.

Therefore, we say a liquid propellant rocket is more versatile, not only is at more versatile it also has higher performance compared to solids, because in solids we add aluminum the molecular mass of the exhaust is high whereas, here if I choose hydrogen oxygen my performance is or my specific impulse is quite large. Therefore, we can say in general the liquid propellant rocket is more versatile, has better performance than solid propellant rockets. But then we say we also see it becomes a little more complex, I have plumb lines, I have tank ages, I have pumps and therefore, it is little more complicated, but I will come back to this. Can we simulate this through theory is something which is questionable? And maybe I will spend some time on it. Therefore, we say liquid propellant rockets are more versatile, and let us take a few examples.

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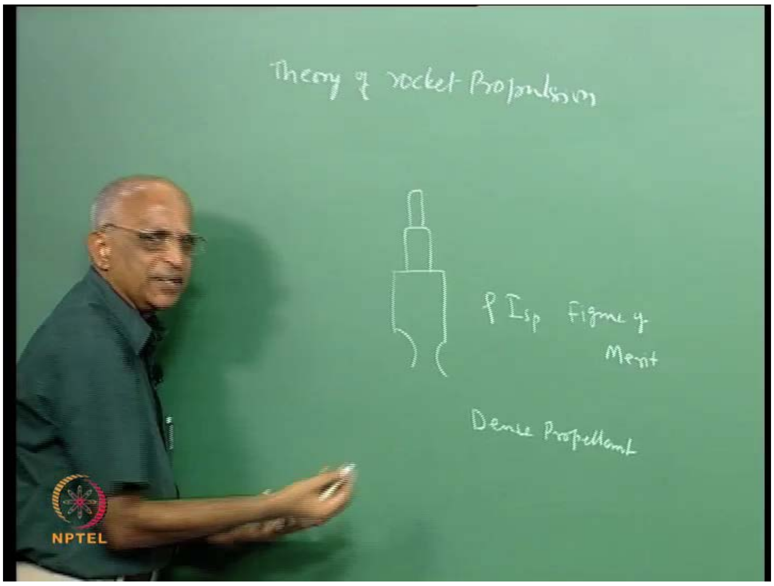

Like for instance, you know when we studied the theory of rocket propulsion, we will recall we said boosters are those rockets which are used during takeoff, and the upper rockets are things which are known as sustainers or upper stage rockets. For booster rockets we found that in addition to I sp, the term like rho I sp becomes important, you will recall and why did we say that? The mass of the cases, mass of the upper stages become important, and under those conditions we derived an expression that rather than I s p the product of the density of the propellant multiplied by I s p becomes a figure of merit of the rocket. Therefore, whenever I choose the booster stages; that means, the stages which first start off, it is essential to use what we say is dense propellants. What do we mean dense propellants? Propellants having higher density, and when I talked in terms of talk dense propellants what immediately comes to my mind is, can I use propellants which are something like dense, like let say UDMH which has a good density, maybe N 2 O 4 as a oxidizer, can I use liquid oxygen with kerosene?

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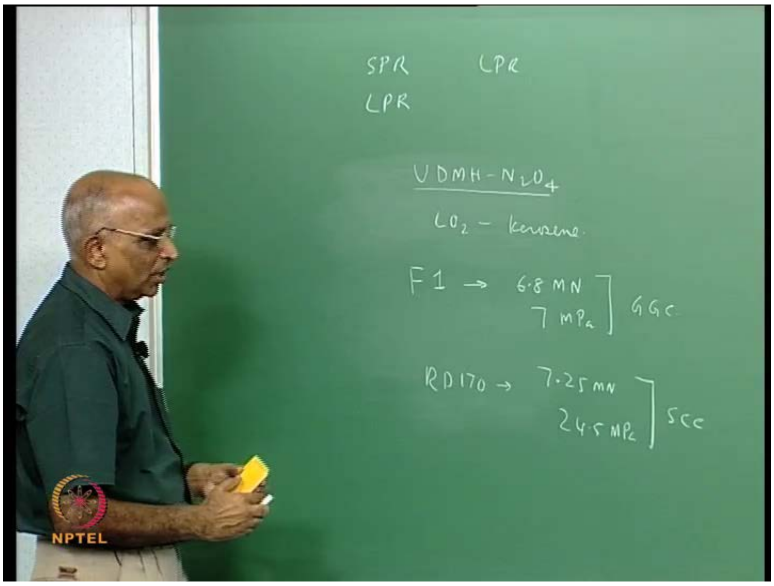

These are somewhat denser and therefore, we find maybe liquid oxygen kerosene has been traditionally used for the booster stages, and examples which we saw where the F 1 engine which was used for the Apollo rocket, and mind you this is something like 30, 40 years old, and this has a huge thrust of something like 6.8 mega Newton; that means, 6.8 into 10 to the power 6 Newton or you are talking of several thousand or million tons of thrust is what we are talking. The chamber pressure of this which uses liquid oxygen and kerosene is something like 7 M P a that is 70 atmospheres, pressure is low thrust is large, and the cycle of operation is the gas generator cycle.

Another rocket which is also uses a booster is the Russian rocket known as R D 170, the beauty is, it is even it has a higher thrust than this of the order of something like 7.25 mega Newton maybe same class, but the chamber pressure is extremely high of the order of two 4.5 mega Pascal, that is something like 240 bar as it is. And since this is a high pressure with a large thrust we use the stage combustion cycle engine. Therefore, these are the two examples of very large rockets which use liquid oxygen and kerosene, one uses the stage combustion cycle, and when you go to lower chamber you use the gas generator cycle, maybe some other examples, well lox kerosene this has a two typical examples.

You know in India we started with UDMH N 2 O 4, and this is what the French used earlier in their area and launch vehicles for boosters, but ever since we told that UDMH is cancer causing it is also costly.

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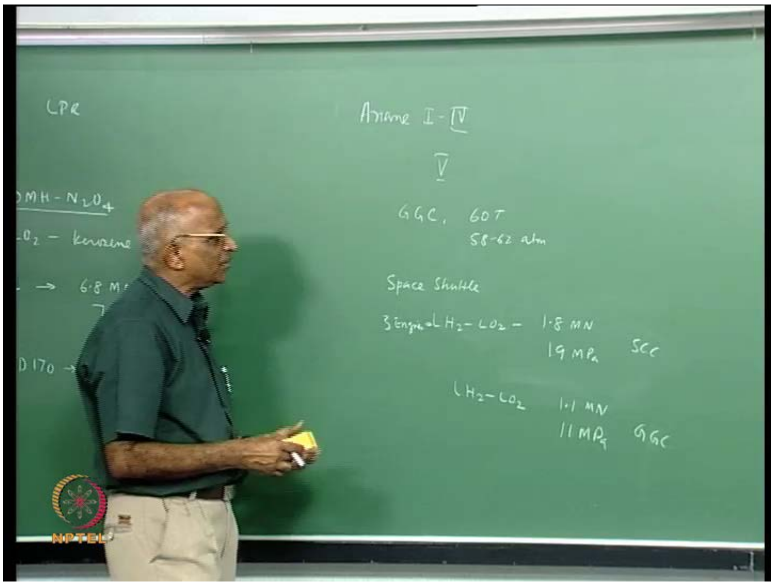

The trend is not to use UDMH and therefore, presently the Arianne rocket like let say Arianne rockets 1 to 4, they make use of UDMH N 2 O 4. But the more recent one Arianne 5 does not make use of UDMH N 2 O 4, but what we use is a derivative of what was used in Arianne, it also uses a gas generator cycle and the typical thrust is around let say 60 ton or let say 60 ton thrust, and the chamber pressure is of the order of the same value around 58 to 62 atmosphere pressure; that means, 5 to 6 M P a.

Well, these are some of the booster engines with let say the heavy propellants lox kerosene and UDMH N 2 O 4, but what was done more recently is if you look at the space shuttle. Mind you space shuttle has not performed its job, it is no longer operational, the last space shuttle is over. What was done in space shuttle is you had liquid hydrogen and liquid oxygen engines, these generator thrust of around 1.8 mega Newton, the chamber pressure is again quite large something like almost like 19 M P a; that means, 190 atmosphere pressure and this use the stage combustion cycle. See, even though the density of the propellant is small, they have a huge booster and we have seen pictures on the back of it you have a liquid hydrogen tank, they carry the liquid hydrogen and you operate a liquid hydrogen liquid oxygen, you have 3 such engines which are used and this is used in the space shuttle.

Whereas, if you use the French type of things, they use again as I said the Arianne 5 went off from using UDMH N 2 O 4 to using L H 2 L O 2, they have a thrust of around 1.1 mega Newton; that means, 1.1 into 10 to the power 6 Newton, the chamber pressure is around eleven M P a, and since the chamber pressure is less they use the less complicated gas generator cycle GGC.

Therefore, you find different types of propellants are used in different stages, and when we want maybe much less powerful engines, we can even go for gas pressurization and use it as the four stage, maybe you can use M M H and N 2 O 4 and maybe the other propellants like what is used in missiles.

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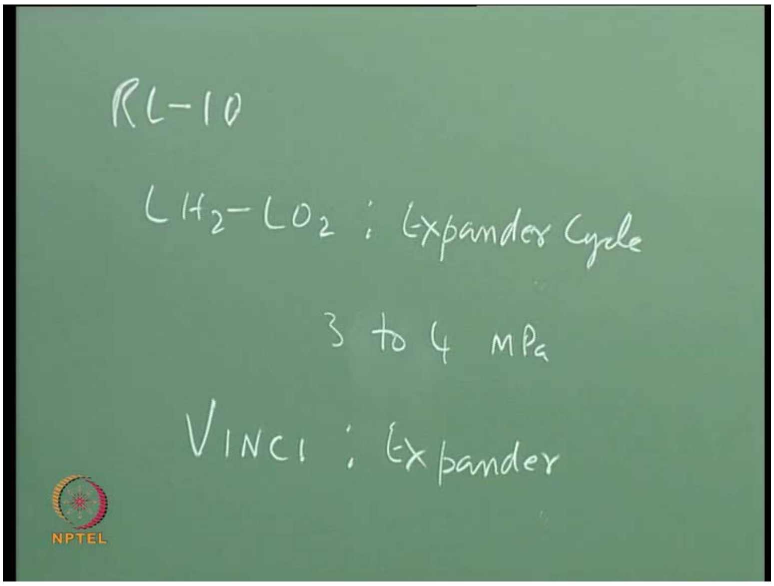

These are the typically the different type of engines used, we see sometimes gas generator cycle being used, sometimes stage combustion cycle is used, stage combustion cycle is used only when the chamber pressure is very high, and this give very extremely high performance. Something which we must remember and I told you of an engine known as a R L 10 engine, which we said uses liquid hydrogen liquid oxygen, but uses the liquid hydrogen in an expander cycle.

What was an expander cycle? One in which the hydrogen gets evaporated while cooling the chamber, and that vapor of hydrogen is used in running a turbine. This is very powerful, the chamber pressure is low of the order of 3 to 4 Pascal that is 30 to 40 atmosphere, and this has been extensively used in many missions for the upper stages. Of late French people are working, and that is challenging in a particular rocket known as a Vinci rocket, I give up homework problem on Vinci rocket, this again uses the expander cycle. In fact, I ask you to calculate, what must be the heat transfer from the chamber to the coolant in order to have an expander cycle? This Vinci rocket has a turbine which rotates I told you around 100000 rpm

Therefore, these are some of the developments, maybe we should keep some of these things in mind as we study the liquid propellant rockets. And do you know, it is quite challenging we find Vinci being develop we find other rockets being develop.

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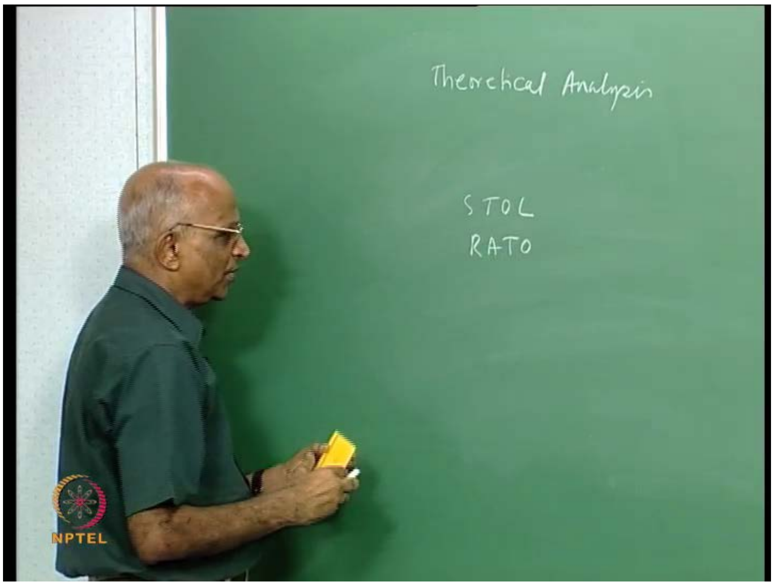

But, something else with respect to liquid propellant rockets compared to solid propellant rockets is, it is easily amenable to a theoretical analysis. Not that I am telling that it is superior in anyway, see a solid propellant rocket has distinct advantages. Supposing, I want a short take of landing for an aircraft, I can just have unrestricted burning attach one or two rockets beneath my wings, and then just burn it will give me thrust immediately for a few seconds or a second, and I can take a I can take off my aircraft in a very short runaway, as is necessary in the forward areas or in some military aircrafts. So, we also call it as rocket assisted takeoff, the short takeoff in landing which uses rockets is also known as rocket assisted takeoff, this is possible with solid.

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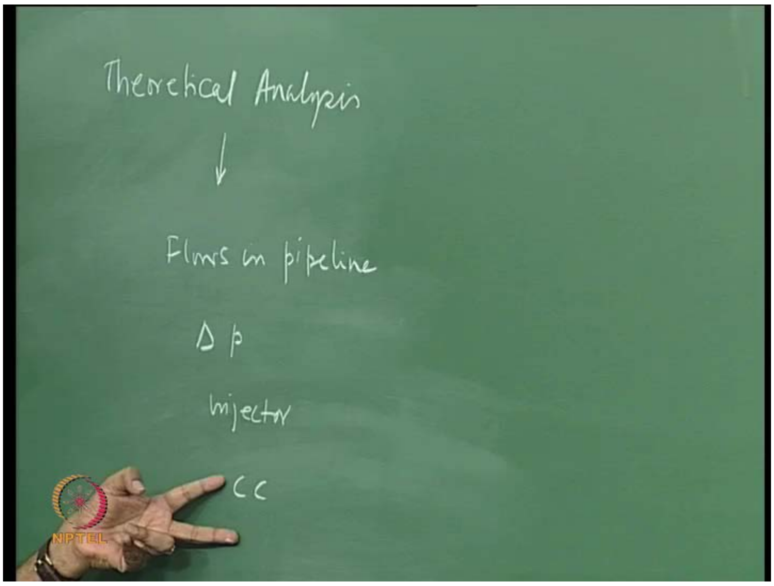

But what I wanted to say was, let us not say everything is liquid, but when we studied about liquid rockets we never really studied about recoil rocket, a description of rocket is like this. All what we studied is, we have a tank propellant flows in pipe pipelines, if it is a pump I know pressure is increased in a pump, I supply it to the injector, what does the injector do? It sprays it into the combustion chamber, the thing evaporates and burns. Well, everything we have studied in other subjects, fluid flow maybe thermodynamics of generation.

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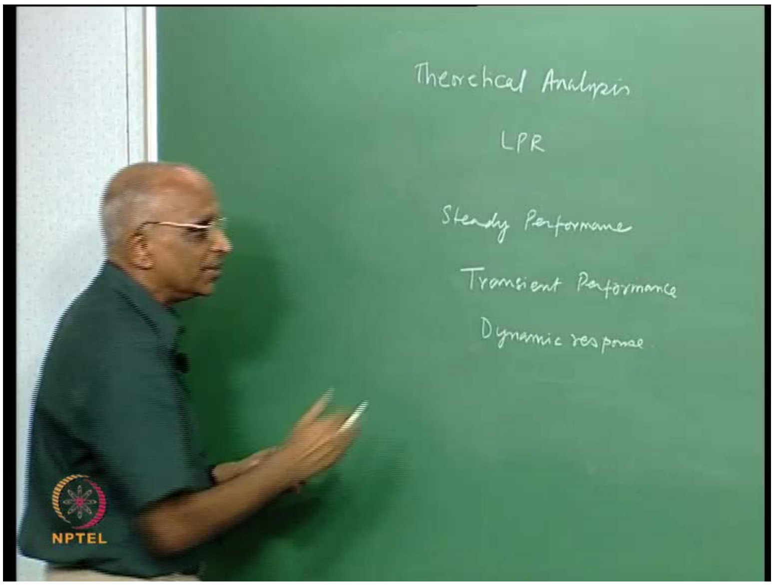

Therefore, we can say well a theoretical analysis of a liquid propellant rocket, for let say steady performance prediction, or let say transient performance, or if we say performance or even if we say I want to look at the dynamics of it, maybe if I were to put some shock into one of the systems, how is the rocket going to respond? Something like dynamic response is all possible, and this is where some attention is required and there are several people working in these areas at present. Lets quickly go through what I mean by this and how do we do it? Supposing, we have a liquid propellant rocket, what did we have? We have the tank ages, and from the tank ages what have happened?

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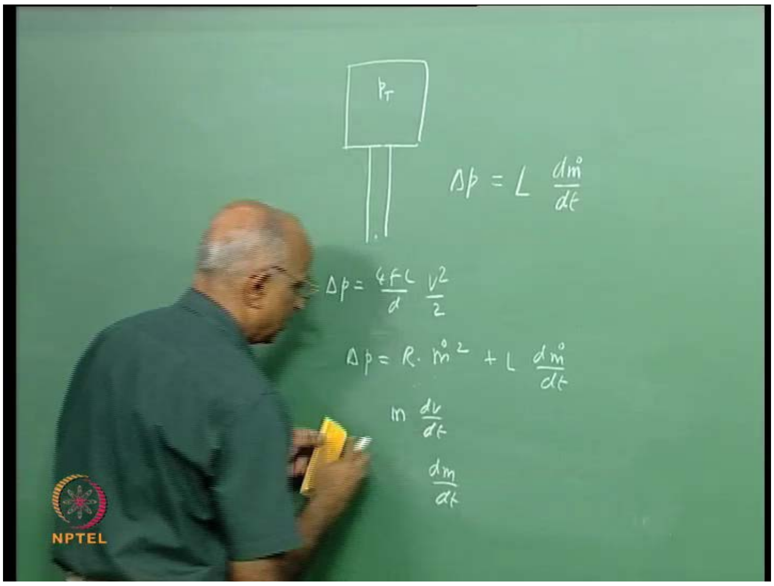

I just draw a single tank age, from the tank age through the plumb lines maybe curve and all that through this lines propellant flows, and do you establish the pressure if the tank pressure is let say p T, how do I get the pressure here? I get a drop in pressure and I say that the drop in pressure goes as maybe 4 F L over d into V squared by 2, maybe under some condition but I need this. Therefore, I can write this equation as pressure drop in a pipeline goes as something like a resistance into velocity, goes as the mass flow rate let say m dot square of the propellants. But under dynamical conditions I have the mass of propellant which accelerates; that means, I have mass into acceleration or rather I have mass into dv by dt, and what is the mass? rho a V.

Therefore, I am talking in terms of something like dm by dt and therefore, because of this acceleration, I have acceleration taking place, I have a pressure drop taking place, I have a force due to acceleration which is the Newton's second law and therefore, I can say the delta p due to acceleration, I can write as something like an inductance or let say some value of inductance, like we have current changing into dm by dt over here, dm dot by dt. Because what is it I have dv by dt and therefore, I can write the net pressure drop under dynamical conditions, I can write it as something like L into dm dot by dt is the pressure drop in a line, this is under static conditions, this is under dynamical conditions therefore, this is the total pressure drop.

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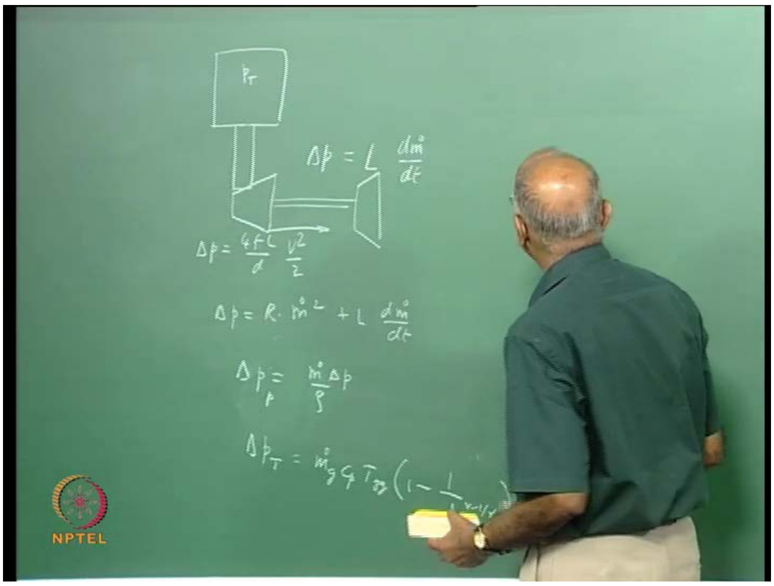

How do I get the pressure rise in a pump? Let us say this feds into a pump let say, and what does the pump do? It increases the pressure from a small value to a larger value, and here you get the outlet. And how do you get the pressure in a pump? We had said pressure in a pump delta p across a pump, let say is equal to the flow rate, which is equal to q, or is equal to m dot into something like delta p, but let us be very clear from unit point of view it should be q dot or rather it should be m dot by p divided by density is the rate of work done in a pump, and similarly the pressure drop in a turbine which drives this pump is given by the work done in the turbine which is… After all, I am taking from gas generator a gas and driving the turbine as it were here, what was it equal to? We said mass of the gas generator into C p into T g g into 1 minus 1 over the expansion ratio in the turbine into gamma minus 1 by gamma. This was under steady conditions.

Well, I can also figure out therefore, I know the pressure here, I can find out the pressure here, I go all these line get into the injector, I can find out the mass flow rate through the injector. Therefore, everything is possible to be calculated from simple equations. Let us go one step further, we also tell well I know the pressure drop across a pump, pressure rise across a pump ,the pressure drop across a turbine.

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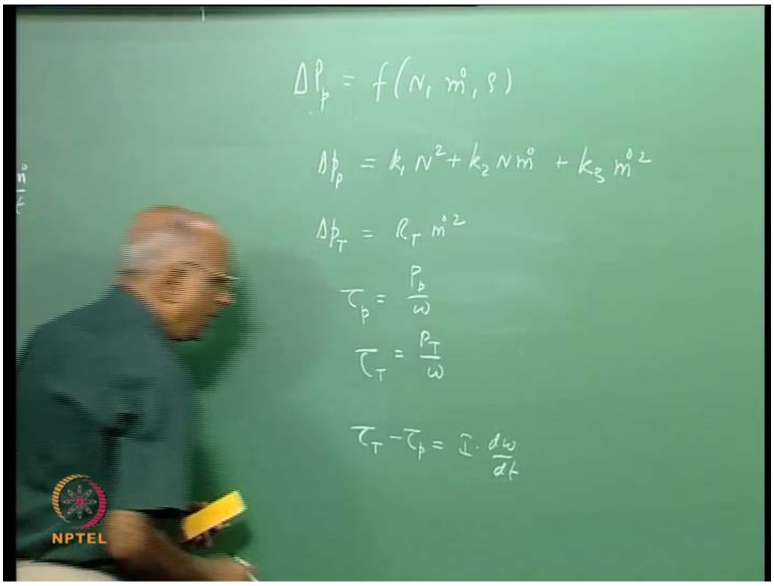

And supposing, I want the delta p across a pump, it depends we saw on non dimensionalization, depends on the speed, depends on the mass flow rate, depends on the density or q and rho, or rather I can write this as equal to, I can write this as let say some constant k into N square plus k 2 into N into mass flow rate plus k 3 into m dot square, and this can be proven considering the blade geometry and all that, that the pressure raise across a pump is given by this particular expression. And we also told ourselves that across a turbine and all turbines were impulse turbines, and this could be written as the resistance into m dot square. Therefore, I know the pressure raise across a pump could be written in terms of the speed of the pump and some constants over here. Similarly, the pressure drop across a turbine can be written like this, we already had the expressions for power of a pump and power of a turbine over here. And how do I use the power of pump and power of a turbine?

Let me put it in terms of capital P. I can translate the power into a torque; torque of a pump is equal to power of a pump divided by the angular rotation. This is tau of p, tau of a turbine is equal to power of turbine divided by omega, and what is happening is the turbine drives might several pumps, may be the fuel pump, may be the oxidizer pump. And therefore, I can say that torque from a turbine minus torque from a pump should be equal to the moment of inertia of the moving parts, which can always be calculated into d omega by dt. And therefore, I know all the things, I can now use all the sets of equations put together to be able to find out the pressure at each of the points, to be able to find the speed of the turbine and not only the speed of the turbine.

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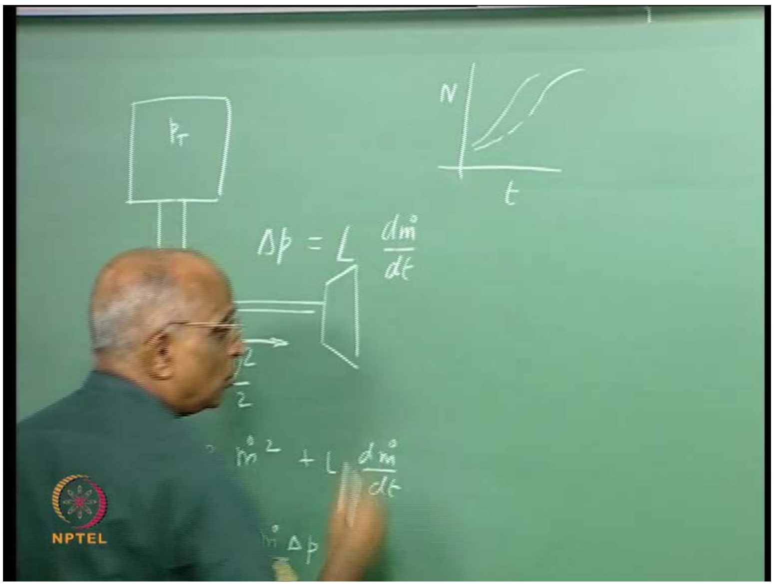

But I will be able to find out, as a function of time how the speed of the pump should develop? How the pressure should develop? And what do I use to get the pressure? I have a gas generator, and what is the equation to the gas generator, which we wrote earlier?

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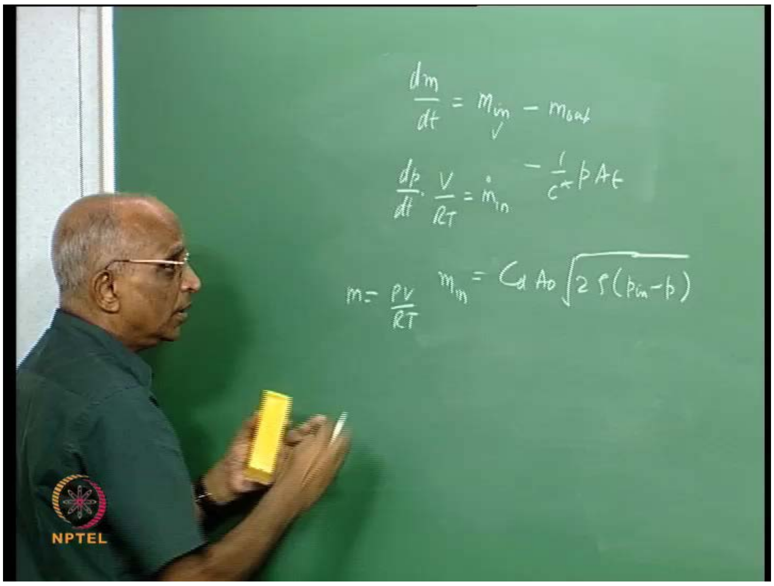

We said dm dt is equal to mass which flows in minus mass which flows out, mass which flows in was equal to we know what is the mass which is flowing, you know the mixture ratio, you know what is flowing. Mass which flows out is equal to 1 over C star into p into A T. And what is dm by dt? dm by dt was equal to d p by dt into PV by R T is equal to m therefore, we have m is equal to PV by R T, V is a constant therefore, V by R T is equal to m dot N. And how do you get m dot N? We said from the injector you have C d into area of orifices into something like 2 rho into the injection pressure minus the pressure in the chamber therefore, I know what is the thing which is flowing. Therefore, I am able to get all what I want through a set of equations which describe my system, and it'll be indeed challenging to be able to put together all these things with dynamics, and this is what all of us like to do with liquid propellant rockets. This we can say is something like a dynamical simulation or a theoretical simulation of a liquid propellant rocket.

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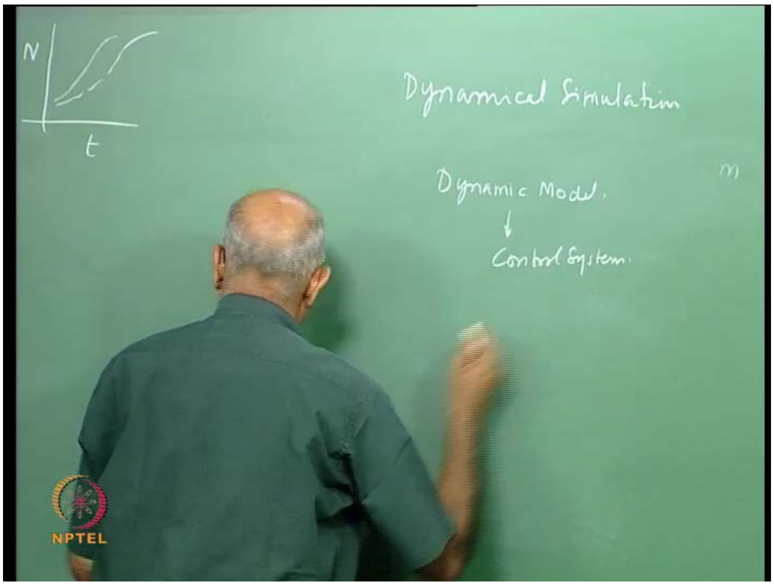

And you will see people always talking in terms of, do you have a dynamical model of your system, or do you have a static model of the system? All what this meant is this equations have to be put together maybe, I went through it hurriedly, because we have covered individual components together and does not much point in again repeating the whole thing, but I think we should keep this in mind. And in a dynamical model not only you solve for the parameters at the different places, but also you put your control system. And what is the control system? You would like the mixture ratio to be fixed, and in the chamber for the mixture ratio to be fixed you need have some control system which controls this as it is moving. I think this is all about the liquid propellant rockets, and you see even a simulation is possible.

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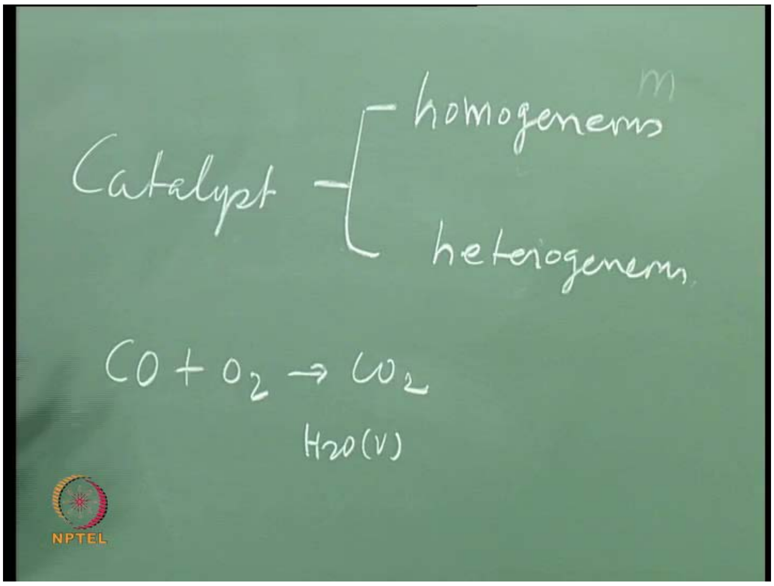

Having said that we continue with our exercise in to may be monopropellant rockets and what are monopropellant rockets? We use a single propellant, when I use a single propellant how does it brake, how does it generate hot gases? See when we were in our high school, we talked in terms of certain substances known as catalyst. A catalyst is a substance which improves the rate of a reaction without itself taking part in the reaction; that means, it does not get change during the reaction, and a typical reaction is if I have C O plus O 2 I want to form C O 2, dry C O and O 2 will not form this, but water vapor will catalyze the reaction and help you to get it. You have catalyst, which could be either be homogeneous or it could be heterogeneous. Let us take an example, by heterogeneous means it is in a different phase from what is the substance, which it is catalyzing.

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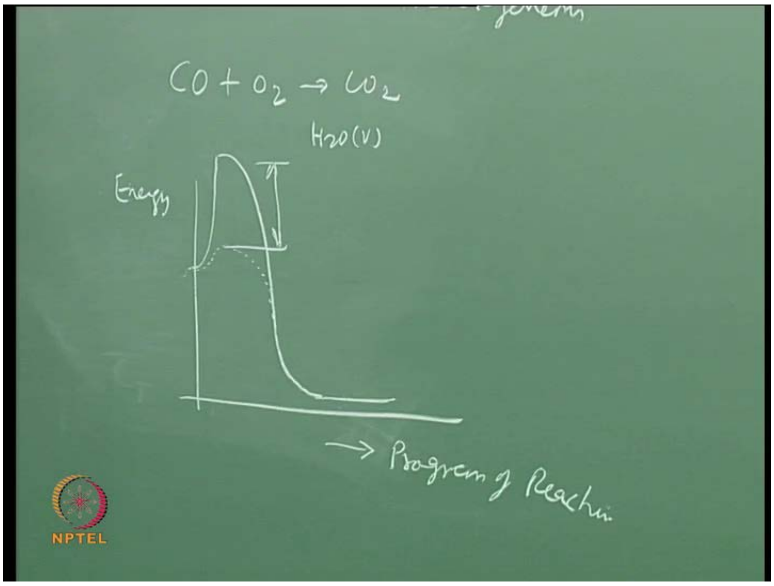

And why does it have to happen? May be this is your reaction, reactant may be some substance like let say a single propellant over here, combustion products have much lower energy level, this is the heat of formation or the energy here, this is the of the products over here. I have to give some energy for it to start reacting and once it comes here it goes this therefore, axis becomes the progress of the reaction and this becomes let say the energy involved. Well, this is the ignition energy required to start a reaction, and once a reaction starts the reactants go to products. When I use a catalyst, I sort of reduce the type of energy which is required; that means, a catalyst reduces the activation energy to start a reaction that is the basic function of a catalyst. And we have certain substances like let us say silver.

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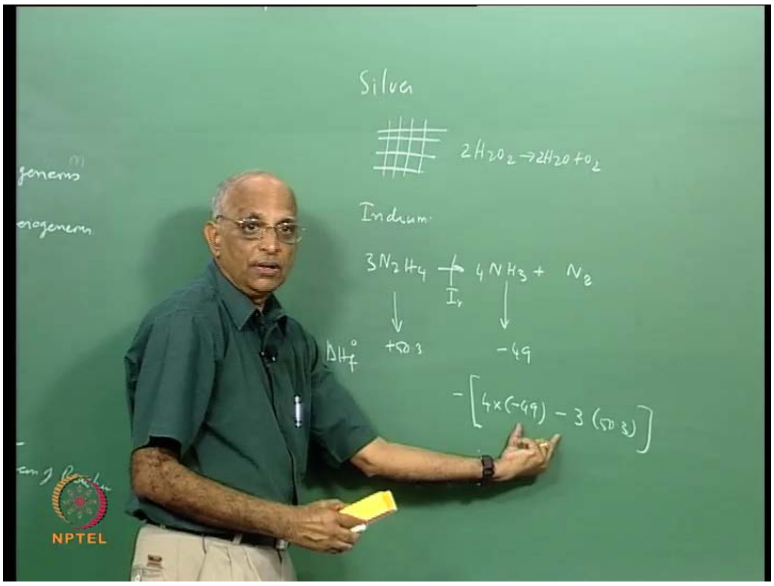

Silver, when I have a silver wire make it into a mesh, and I pour hydrogen peroxide over it, the hydrogen peroxide dissociates into H 2 O plus O 2, may be 2 H 2 O 2 H 2 O plus O 2. And similarly, the silver is heterogeneous because it is solid; it catalyzes a liquid hydrogen peroxide into two gases steam and oxygen. Similarly, if I have a catalyst like iridium, may be iridium ion. What it does is when iridium ion is in contact with the hydrogen into H 4, it immediately or when it is the iridium catalyzes the decomposition of hydrogen into ammonia plus, whatever is left let us say you have 3 N 2 H 4, let us just say is equal to you have 4 N H 3 plus N 2 over here, 12 here 6 4 plus 2 6 here, this is the decomposition reaction, and in presence of iridium ion the hydrogen is decomposed to ammonia and nitrogen.

If you look at the heat of formation of hydrogen which we studied when we were studying propellants, we said it is around plus 50.3, ammonia if you look at the heat of formation delta H f star at standard condition, this was something like minus 40 9 or so and therefore, you say minus of 4 into minus 49 minus of 50.3, that is 3 into 50.3 and this is positive and therefore, the net one contributes to the heat over here, we had minus of heat liberated in the reaction is equal to 4 into minus 49 plus 0 here minus of 3 into 50.3 kilo joule per mole, I had 3 moles of this, I had 4 moles of this. Therefore, this and this get added over here plus and plus here, and I get heat of decomposition over here, and this is how a monopropellant rocket works. And therefore, a monopropellant will be different from the rockets which we studied so far.

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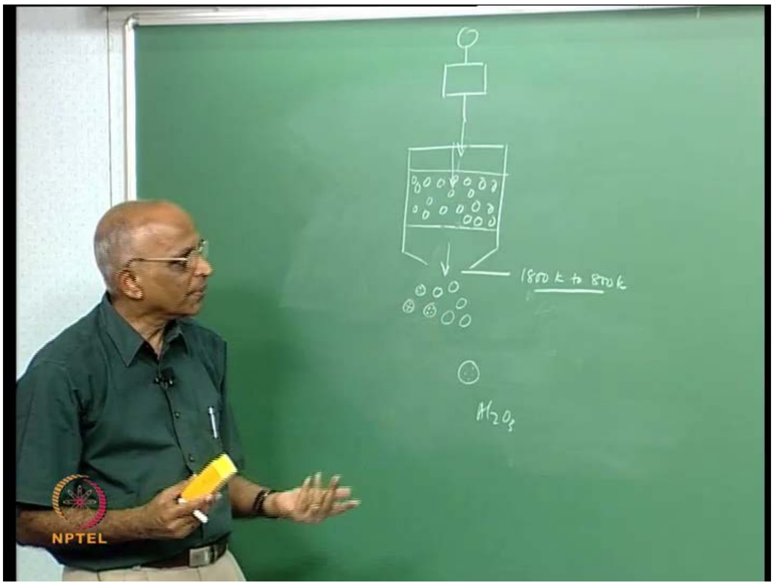

In that I just have a chamber, all what I need to do is put catalyst over here. And how do we put this catalyst like iridium? I have balls, I need iridium to be quoted and I take may be alumina which is something like a porous refractory, I make balls of aluminum may be 1 mm or 2, 3 mm thick or 3 mm in diameter spherical ones, and into this I coat iridium ions on it therefore, in depth also it is porous therefore, iridium ions will be there, I put all these things over here and into this I pass hydrogen, hydrogen when it is flowing will come in contact with iridium, because these are all porous things, and into the alumina I have iridium, it will flow into, it will react with iridium, and decompose and out of the thing I will get the dissociated product which are at a high temperature.

The typical temperature could be between 1800 Kelvin to a lower temperature of 800 Kelvin, I will come back why this temperature changes. Therefore, this is the function therefore, all what I now need is; I have gas bottle, I have a hydrogen tank, from through hydrogen tank I inject the hydrogen into, it gets into the catalyst bed, reacts with the iridium in the particles of alumina which is in which is impregnated into it, like what we do is we take this alumina A l 2 3 it is with porous, I put something like a hexachloroiridic acid or something and make sure that when I treat it, I get iridium which is available on these crystals and inside the pores, and when the hydrogen follows it decomposes, this is the function of a monopropellant system. But what happens when propellant keeps flowing, the ammonia which is formed begins to again decompose.

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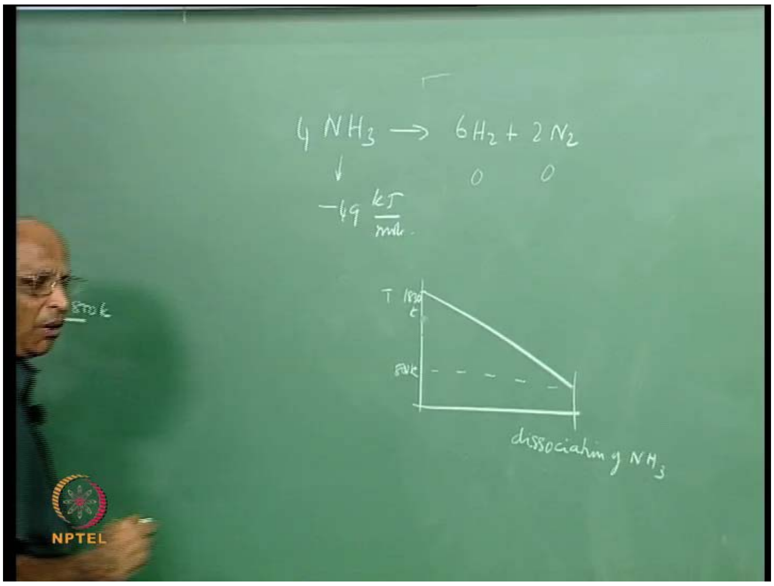

And what happens is N H 3, mind you I formed 4 N H 3 here, the 4 N H 3 which is being formed here could again decompose into something like 6 H 2 plus 2 N 2. In other words, as it begins to react immediately I get ammonia and whatever nitrogen there, and this ammonia further decomposes because of the high temperature whatever is available here into hydrogen and nitrogen. You find that the heat of formation of hydrogen is 0, nitrogen is 0, ammonia as a heat of formation we said something like minus 49 or something minus 49 kilojoules per mole.

Therefore, you find that this particular reaction minus of minus which becomes, again we have 2 minuses here therefore, this reaction becomes endothermic and therefore, it absorbs the heat from the reaction and therefore, this decomposition will rob heat from this particular reaction and therefore, more the dissociation less will be the temperature, or rather as the dissociation increases, ammonia increases the temperature will keep on falling. If there is no dissociation the temperature is around 1820 or 1830 Kelvin, and if the dissociation is complete I get something like 800 Kelvin. How do I write both these reactions together?

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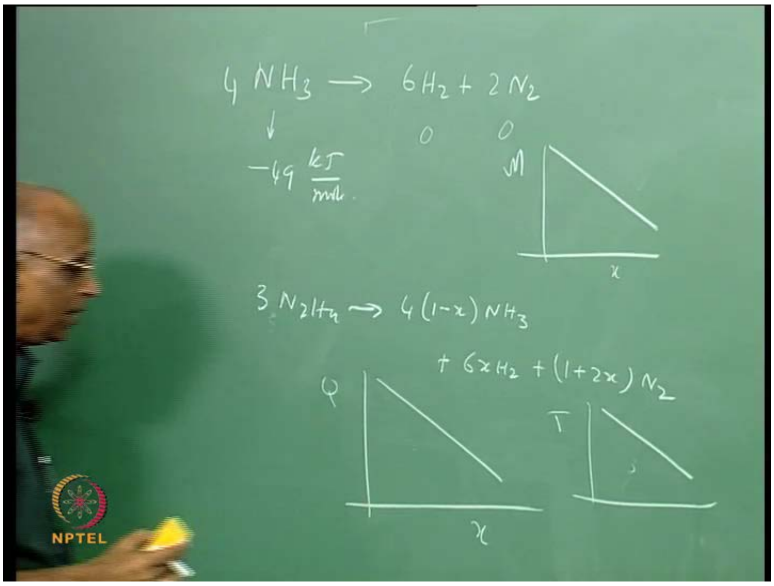

If I now say x of the 4 N H 3 which is formed dissociates, I can combine this equation and this equation, and then write it as 3 N N 2 H 4 is equal to, now I get 4 N 4 1 minus x has dissociated, x has dissociated therefore, I am left with N H 3, and now what has happened? I get for each which has dissociated now I get 6 x H 2, and now I get 2 ; that means, 1 plus 2 x because I had originally N 2 of N 2 over here. Therefore, this becomes my equation when part of the ammonia which is formed dissociates into hydrogen and nitrogen.

And now, if I find out the heat of formation as x increases, I find as x increases the heat liberated comes down therefore, the temperature come down, and this is where I said temperature decreases from something like 1800 to 800, but I find I am getting more and more of hydrogen therefore, my molecular mass of the products x also decreases, this decreases from a value like 19 to something like 10 you can work it out, I give a homework problem on that and therefore, since molecular mass comes down and temperature comes down, if I were to put both of them together in terms of either C star or in terms of specific impulse.

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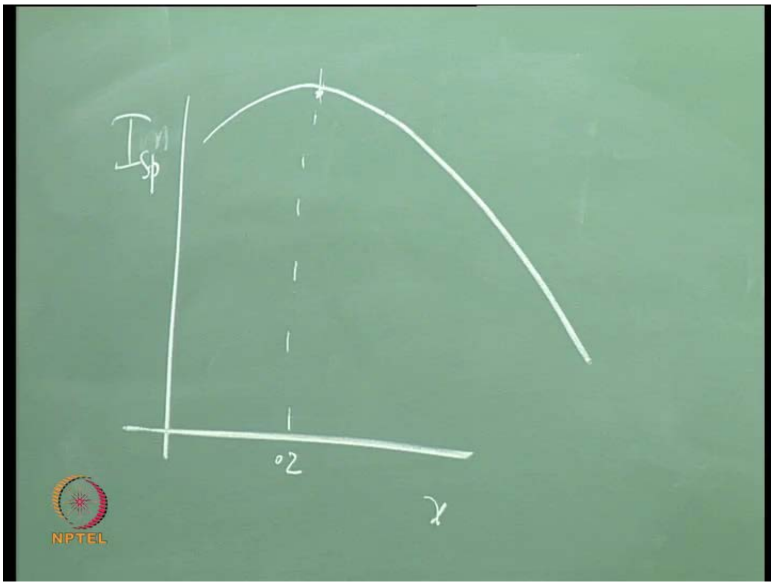

I find my specific impulse with respect to x is maximum for a value around 0.2 dissociation and therefore, my I s p goes like this and keeps decreasing; I get a maximum value around this. The change in specific impulse between 0 dissociation to 0.2 dissociation is does not change much, but thereafter it begins to come down. Therefore, you would like to configure your catalyst bed such that you have degree of dissociation as 0.2, and that is when you get maximum performance. This is the background for monopropellant rockets, let us try to put things together now and ask ourselves what is required for a monopropellant rocket.

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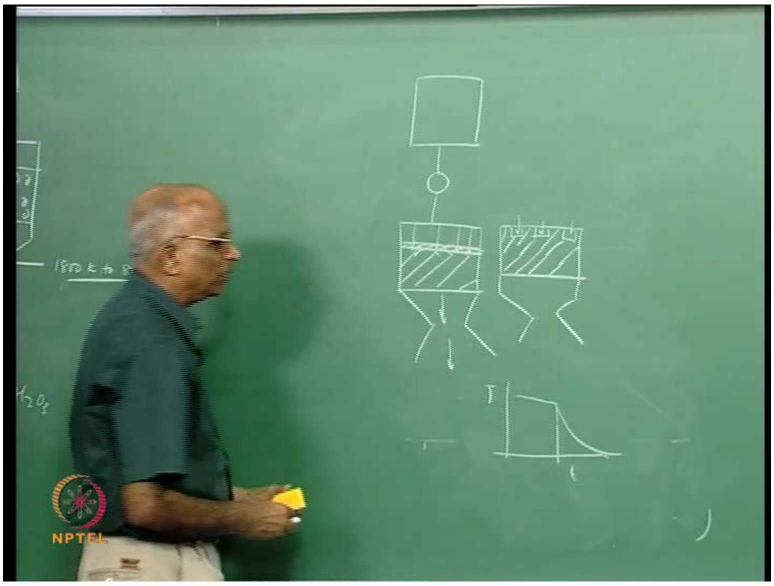

Well, it is very extremely simple, I have a tank, I have a pressure regulator, the pressure regulator supplies propellants to a catalyst bed, and this catalyst bed decomposes it and out goes the products through the nozzle. This becomes my catalyst bed, I need an injector may be an ordinary shower head injector which forces the liquid on this is okay, but you know if I force it like this on the thing it does not uniformly get distributed therefore, maybe I could put some screens here, metal screen over here impinge on the screen and distribute it uniformly that is one solution, or else I could allow the bed to be very much near I put metal screens over here, I inject it as a shower head here, impregnate the catalyst bed right at the injector, and this one other configuration of doing it.

It is of course, necessary to make sure that whenever you have put such injectors could be some screens, could be shower head could be this metal meshes over here. Whatever, we put it is also important that the dribble volume, mind you we talked in terms of manifold must be small, if the dribble volume is large it keeps on dribbling and you will have thrust generation with respective time, instead of giving like this it may keep on going for a longtime, this is the dribble volume well these are the only things in monopropellant rockets we find it quite simple.

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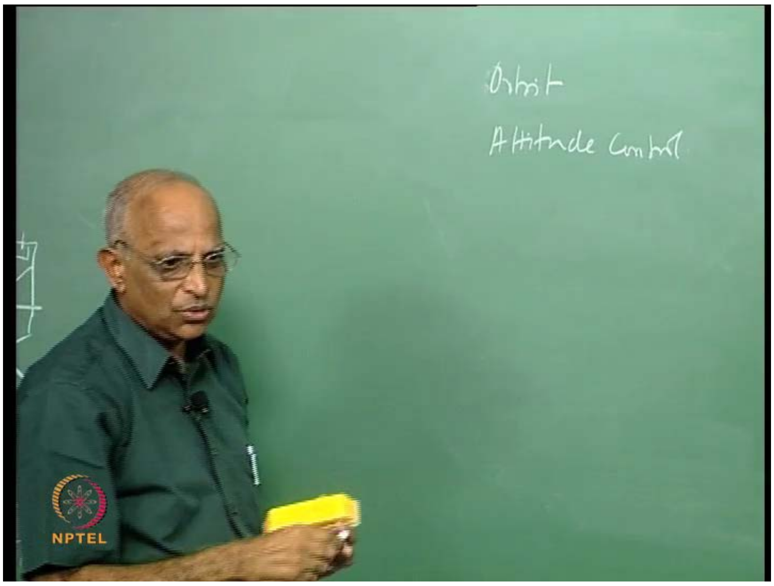

And in fact, it is widely used for in satellites for controlling the trajectory or let us say orbit control, and for altitude of the satellite this is where we use it. Having said that let me quickly run through what I have been telling so far in monopropellant rockets.

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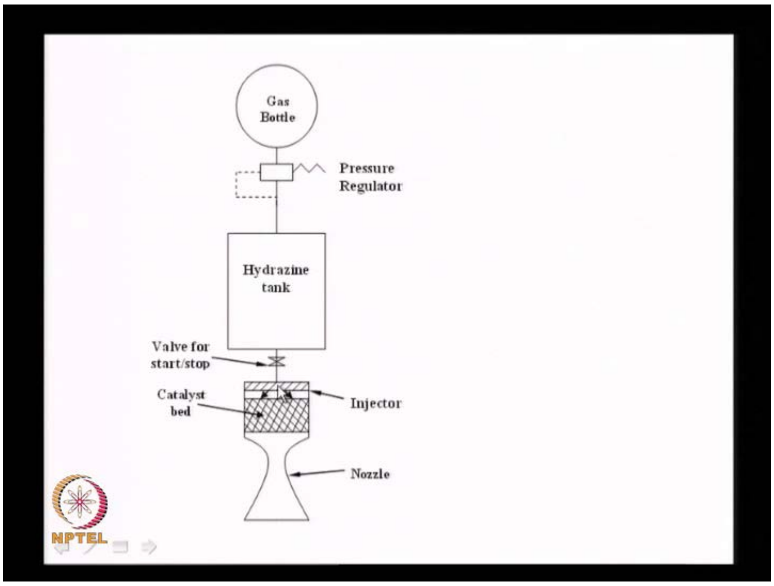

We talk in terms of a gas bottle, pressure regulator, hydrogen tank pushes it in to the catalyst bed over here, you have a valve you can stop and close you can do it in pulses, but if you do in pulses the catalyst bed gets hot, heat gets transfer back here and it may heat up the injector, if the injector becomes hot hydrogen may decompose and even cause an explosion.

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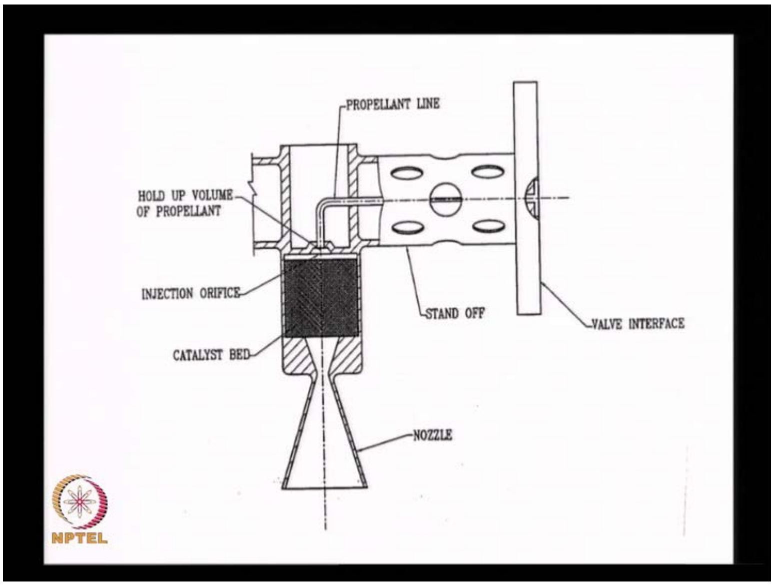

Therefore, what is it you do you? Go back and tell myself well this is my catalyst bed; this is how I expand it. In order to cool it, I am forcing the hydrogen through it, I put some metal here just like I use fins in the case of motorbike, I use fins here such that this part get heated and heat gets radiated out. This is something like we say between the thing here and the monopropellant rocket here I have something like a standoff.

As I told you, I would like my manifold volume which we called as hold up volume of the propellant to be as small as possible, I have the injector here which could be shower head or some of the screens I am talking of, and this is the catalyst bed. How do you specify a catalyst bed? Let us just spend a couple of minutes on the catalyst bed.

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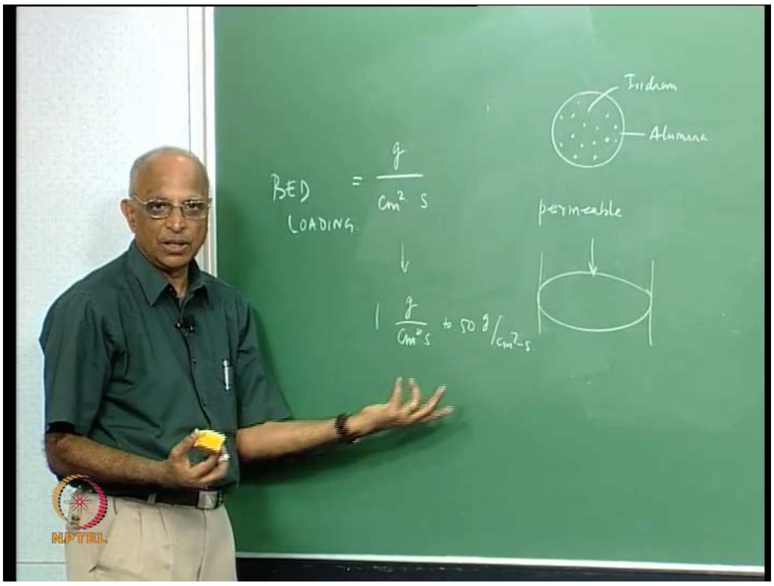

We told ourselves, well catalyst bed consist of alumina, in the alumina I have lot of pores or holes, and when I impregnated I make sure the iridium is available at all the places and therefore, when hydrogen flows it wets this; that means, the alumina is substance which is permeable to hydrogen permeable therefore, permeability is an important parameter, this is iridium in alumina and therefore, it must be permeable and therefore, how do you design a catalyst bed?

After all you have a bed of certain size and hydrogen flows into it therefore, it is specified in terms of mass flow of hydrogen in grams divided by the surface area; that means, so much centimeter square, and you are flowing per second and this is known as bed loading. In other words what we have to necessarily ensure is, that if I have the surface area of this bed to be so much, let say a meter square or a centimeter square, and if I flow hydrogen at so much grams per second, mass flow rate of hydrogen in grams per second divided by the surface area tells me the bed loading, and this bed loading tells me bed loading and the length of the bed will what tells me whether what amount of dissociation I get of the ammonia.

Therefore this bed loading typically where is between 1 gram per centimeter square second to 50 grams per centimeter square second. For large rockets might be whenever we use monopropellant, we do not go high thrust, maybe the maximum thrust which we can go is something like 500 Newton to 1000 Newton, the smallest could be anything small maybe milli Newton or something like that, for very small one we use a small bed loading, for larger once we use a larger bed loading, this is all about the monopropellant rockets.

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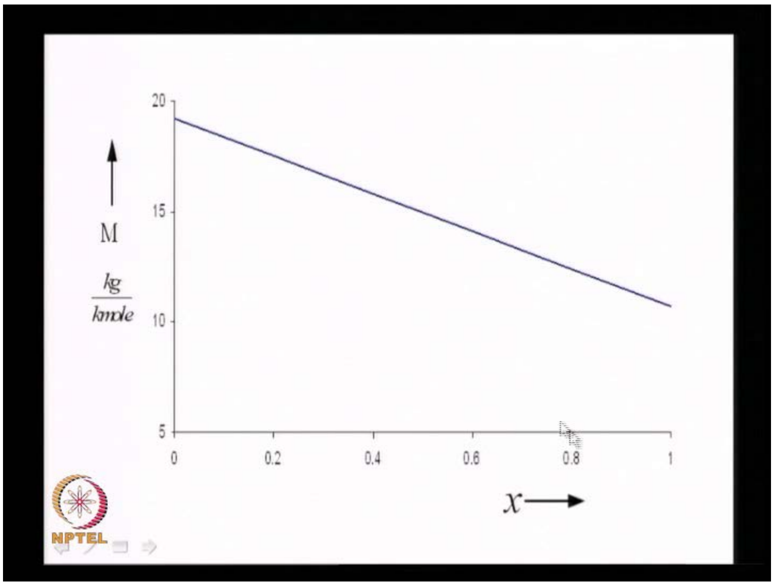

Therefore I think, I should stop here but or rather let us just finish of, we say the temperature with the degree of dissociation keeps coming down; the molecular mass also comes down from something like 18 to value around 12 or so.

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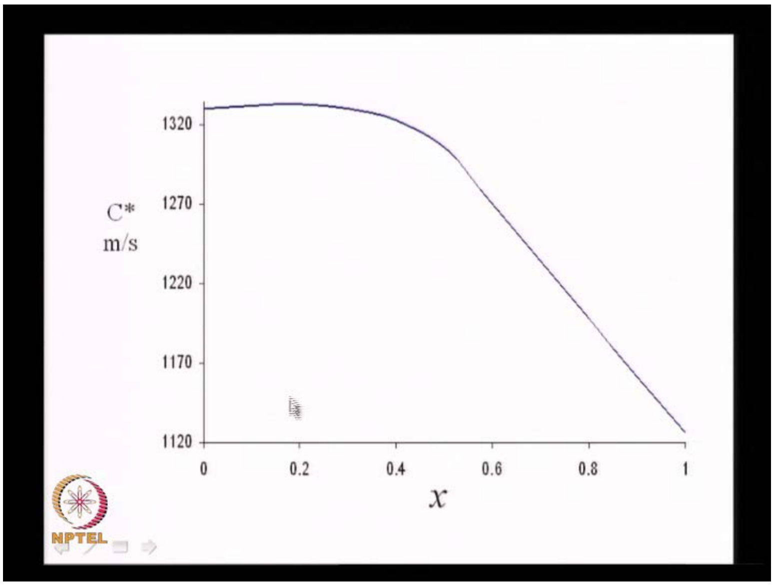

And when I put both the things together the C star as a maximum value around 0.2 over here.

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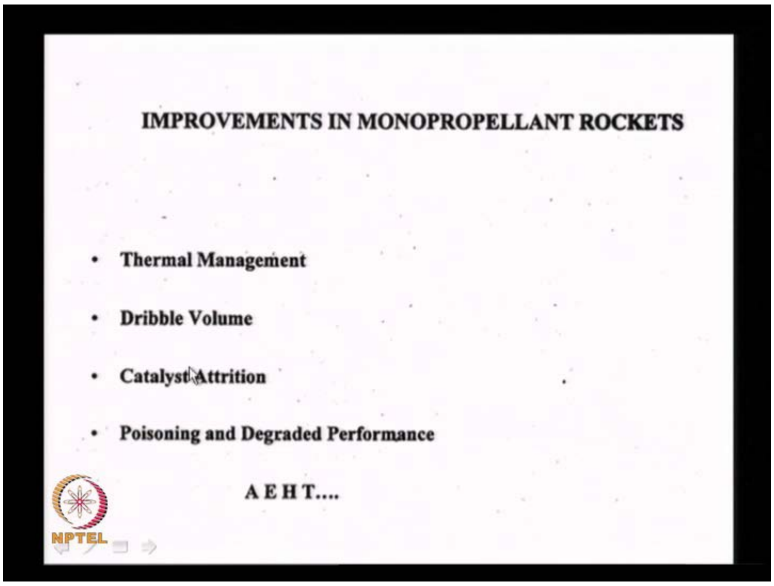

Well, what are the problem areas in monopropellant thrusters? Well the catalyst bed runs hot therefore, the injector runs hot, hydrogen could dissociate, and if hydrogen being a monopropellant it could as well explode and therefore, we must ensure we have thermal management. And how do we do the thermal management? We told ourselves well I have something like a fin, which will dissipate the heat whenever the thing gets hot and remove the heat from here.

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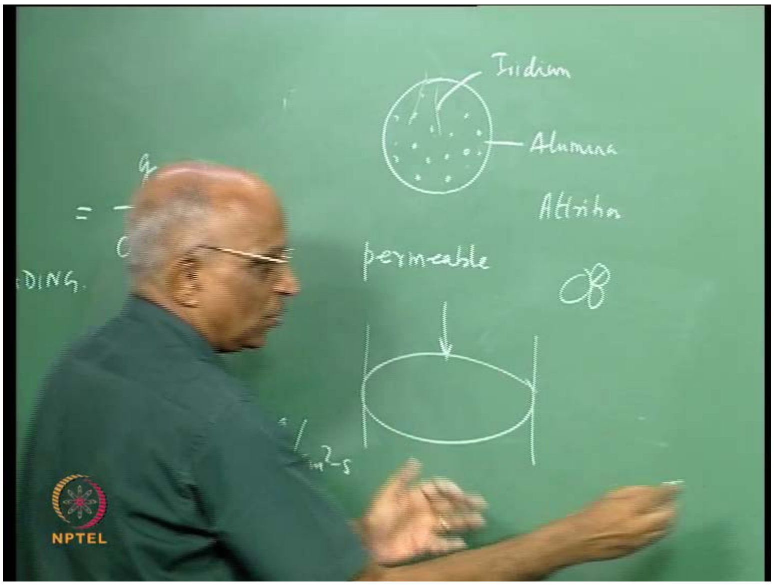

Well, dribble volume must be small, you know we have some problems whenever we have catalyst like for instance, whenever I have these alumina things over here, and we said the thing goes wet set it could sometimes break which we call as attrition. What is attrition? You have all these one with other and all that, it create some pressure and leads to breakage of the catalyst, and some of the catalyst gets out through the nozzle that is known as loss of catalyst.

And again, we told ourselves when I use in spacecrafts, I need to have something like a positive explosions system, maybe the bladder material might get into the hydrogen and might poison the catalyst; that means, the activity of the catalyst can come down.

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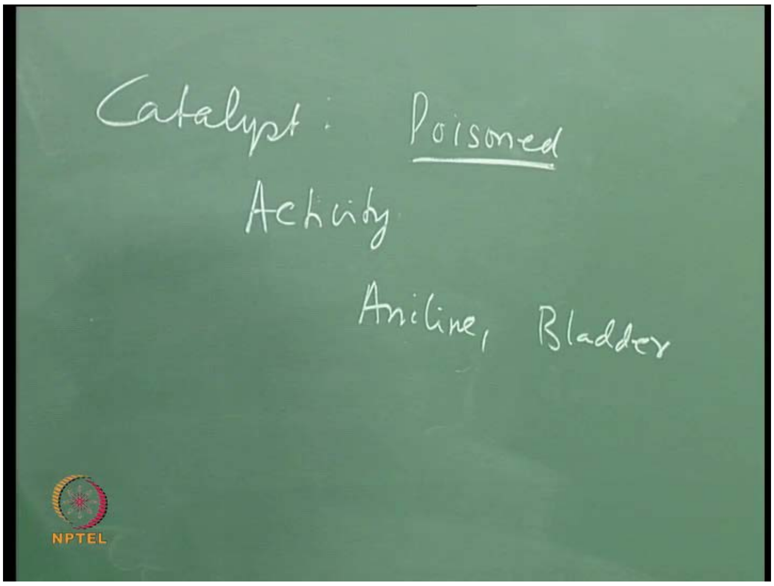

Therefore, the two things which we have to keep in mind is, whenever we have catalyst the activity of the catalyst must not get disturbed, because you have hydrogen might contain some aniline, it might contain some material from the bladder which can go and block the iridium and make sure that it does not function as require. Therefore, we must ensure that the… when the activity of the catalyst is decreased, we say we call it as catalyst gets poison it is no longer effective, we must prevent the poisoning of catalyst.

And of course, whenever something gets poison it is not able to do its performance well. But the main drawback with using the monopropellant thruster is, it has low performance compared to bipropellant rockets the performance is very much lower.

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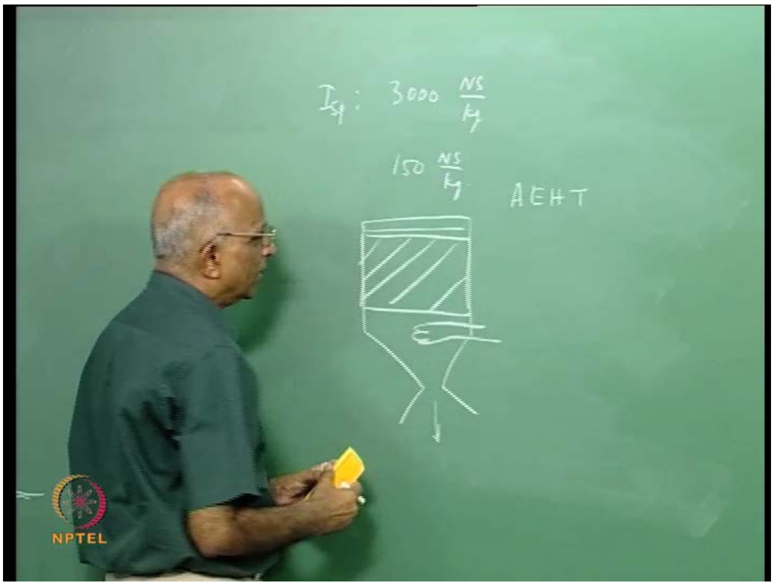

Maybe something like 3000 Newton second by kilogram is the I s p of let us say low performing propellant, we called it as propellants which have relatively low energy propellant, compared to that this might be around 1500 Newton second by kilogram. And therefore, there has also been an interest to say, supposing I have a monopropellant thruster; that means, I have a catalyst bed, I have an injector over here, I have the thruster over here.

Can I put some electrical heating and improve the temperature? We said that the maximum temperature is around 1800 Kelvin, I increase the temperature using electrical heating, and the such type of thrusters in which I have monopropellant d composition to an intermediate temperature, and still increase the temperature further to improve my I s p is known as augmented electron hydrogen thruster.

I will revisit this problem, maybe in the after some 5 or 6 classes when we talk of electrical proportion; that means, since the performance of monopropellant thruster is on the low side, I can always improve it by electrically heating the gases from the higher temperature of the 1800 to something like let say 2500 or so, and still get my high value of specific impulse.

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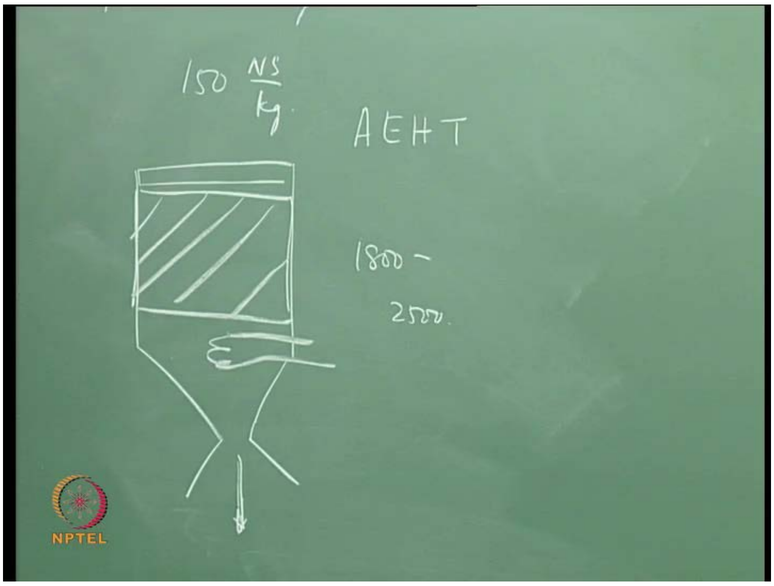

Well, this is all about the monopropellant thrusters, but there are some things which we have to keep in mind. See monopropellant rockets are very versatile.

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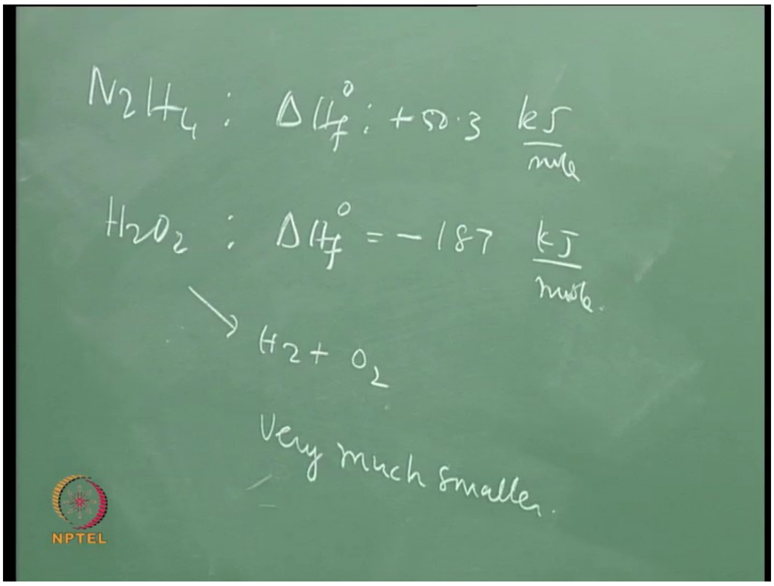

In fact, I think I should tell you this example, H 2 O 2 I did not consider, I always kept in terms of hydrogen. Why is it, can somebody tell me? All I will tell you give a clue is, N 2 H 4 hydrogen as a standard heat of formation of we said something like plus 50.3, when I talk of hydrogen peroxide the heat standard heat formation, I have to put standard here is equal to something like minus something like 187 or something kilojoules per mole kilo joule per mole.

Therefore, now somebody can tell me why is it that hydrogen peroxide is not used much as a monopropellant? The standard heat of formation is terribly negative, it again form something like H 2 of plus O 2 and these are 0; that means, the amount of heat which I can generate is the heat liberated is going to be very much smaller, because here I have positive and therefore, I can get this coming out and giving me heat therefore, the temperature what I can get by H 2 O 2 decomposition will be very much smaller. And therefore, universally if we see other than maybe in early part of the program, maybe in 1940s and 50s we used hydrogen peroxide as monopropellant, nowadays it is not being used at all.

The reason being, I get extremely poor performance, and why do I get performance because this heat of formation is much more negative and these things we have covered earlier.

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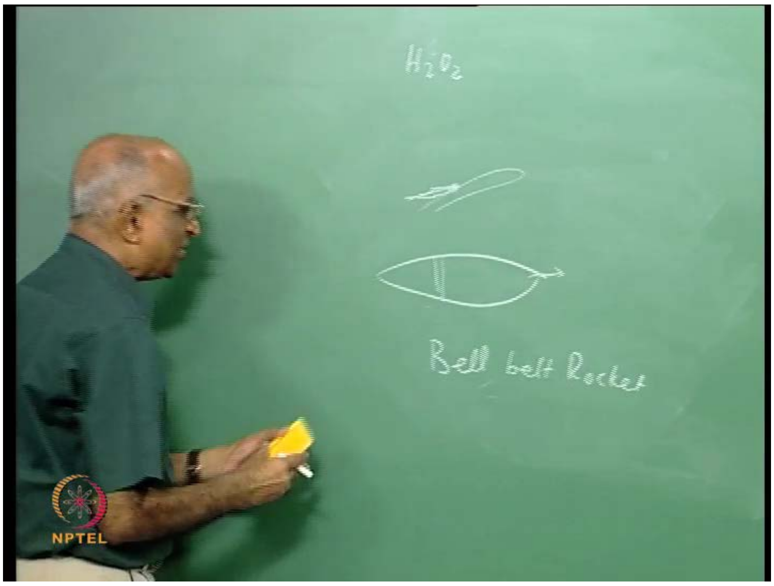

But there is one application in fact, you know whenever this Olympic games occur, you would have seen some people having in their belt something like a rocket, and they go across like in los Angeles Olympics you find human beings been propelled in the sky using rockets, and what is it? For human beings to fly is very difficult, because we are all aerodynamically terribly unstable, for something to fly you need a good configuration, you need an aerodynamic configuration which can fly. We have hands and legs and, it is not possible. But I can always have a belt, and the hydrogen peroxide which is used is known as a bell belt rocket.

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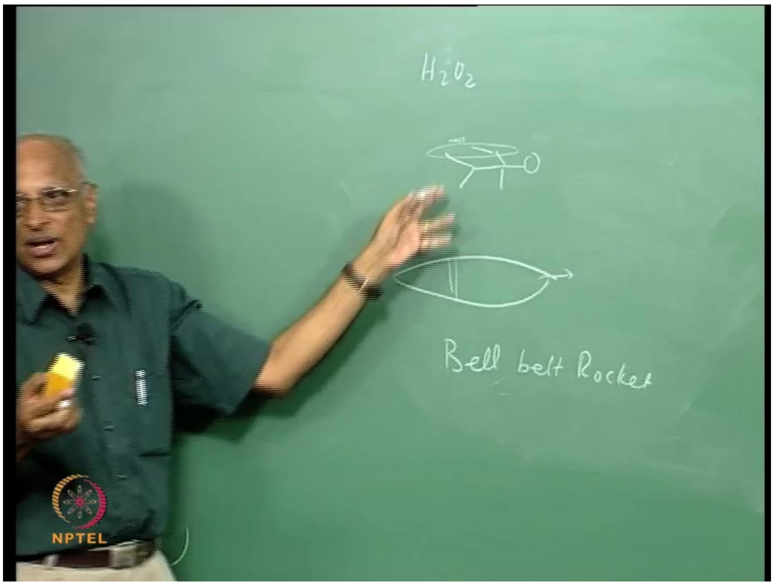

All what is done is you have a stabilizing device, like let us say a human being I plot like this hands legs is like this, you put a stabilizing device on him, maybe make him little more aerodynamics, and maybe put a small monopropellant rocket over here, and whenever he want he switches on a rocket and he can go in different directions, and such type of sky driving or acrobatics is done during some of these carnivals like Olympics and all that, and I give a problem on this bell belt rocket. Now, something which I think I must tell something, since we are talking of propulsion in the master's degree program.

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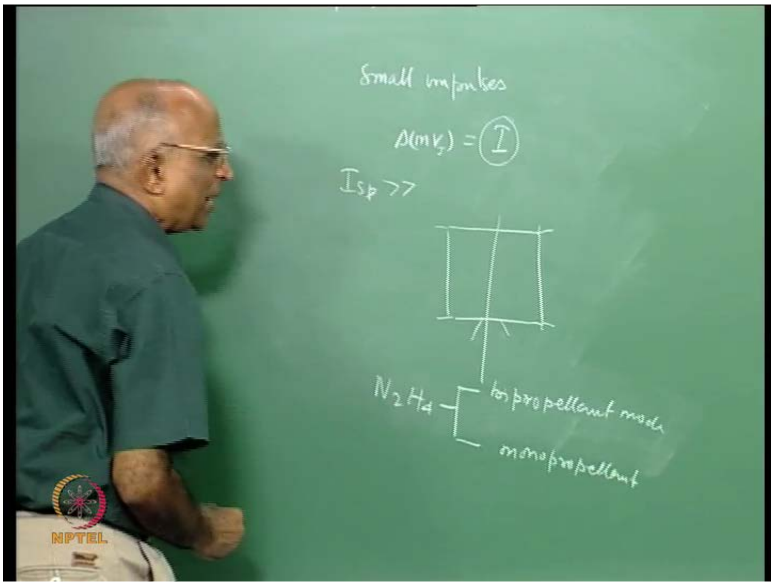

See, monopropellant rockets can give extremely small impulses. What do you mean by small impulses? Maybe, if I say the change of momentum is impulse delta m V is equal to impulse I, I can just pass a small amount of hydrogen and it gives me a small value of V J, the V J is much smaller than a bipropellant and therefore, I can get very small amounts of impulses. Why are impulses important? Supposing, I have let us say I used a, I showed you the case of inside spacecraft, I have something like 16 rockets at the edges of it which are there, and which we say I generate small amount of thrust such that if its accesses is not in proper shape to be able to correct it and all that, which means I have to supply a small impulse. How do I supply? I need a very small amount of propellant to go and maybe make a change in momentum.

Now, it is very useful for small corrections, but I also know that I would like to have higher value of specific impulse, when if I have want to power it, if I want to take a satellite from one orbit to the other, I need to supply study value, I need a larger value of I s p. Therefore, the question is, can I use hydrogen N 2 H O 4 for both in the bipropellant mode as well as in a monopropellant mode?

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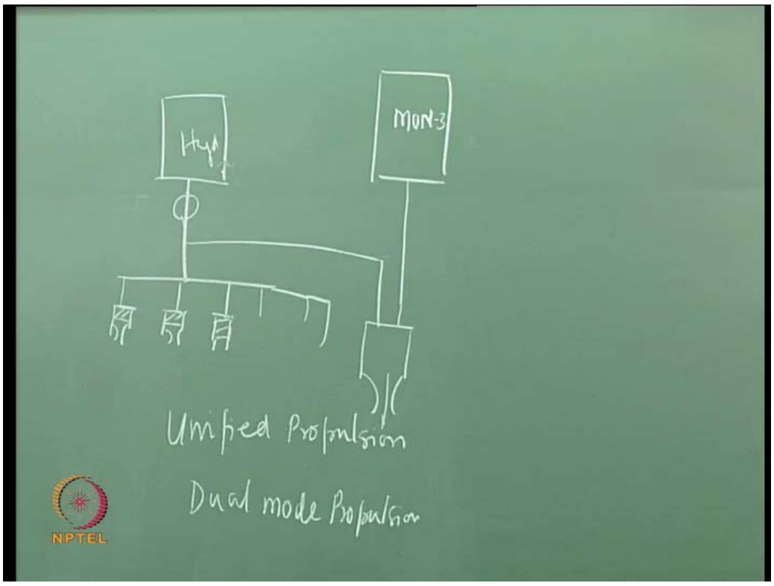

What is it I am telling, let us again think in terms of a configuration, well I have the hydrogen tank as it well, tank of hydrogen, I allow it to come to through up maybe a pressure regulator over here to a series of small rockets, which are all monopropellant rockets all have catalyst in them which can be used for small maneuvers.

And I also carry let us say MON 3, you all will remember MON 3 is something like N 2 O 4 in which I add some amount of N O such that it is it has a lower freezing point, and I also take little bit of this here, I take this here, I also give this to a slightly bigger in engine or rocket engine, and when I want to change the trajectory I operate it with hydrogen, and MON 3 let us say or mix oxides of nitrogen generator thrust, then I want small corrections I use this and this is known as a unified propulsion. Of late, I do not see the word unified being used, they say it is a dual mode propulsion. What dual mode propulsion means? Hydrogen is used as a bipropellant in part of it and part of the system it is used as a series of monopropellant rockets. Well, this is the dual mode propulsion, but something even solids can give small impulses and this they are doing at this they have reported at J P L.

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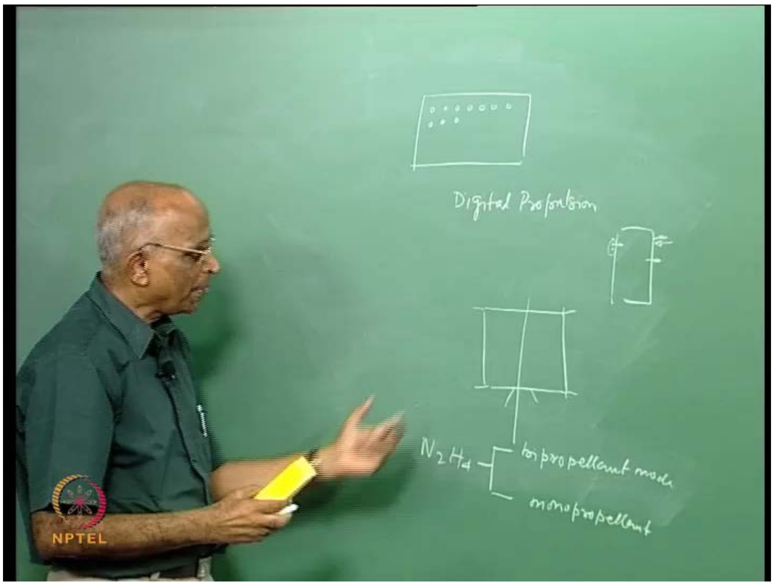

Wherein, you have maybe on a silicon wafer vapor or something, you have small pellets, micrograms of solid pellets, and you have resistor wire in incorporated in them. Whenever you want thrust, you want this thrust in this direction, you press a pellet in this direction, you have a small force going and this is known as digital propulsion. As you see the subject of propulsion especially, rocket propulsion is something in which lot of developments can take place.

All what I want is, I want a spacecraft to be given some small force like this it is in vacuum therefore, I have a pellet here which I fire and it gives me this, if I want a pressure in this direction maybe I put some string over here, some pellets here I fire it in this direction therefore, this is known as you have something like digits which you fire it is known as digital propulsion. But what is conventionally used is maybe something like a combination of these things, but hydrogen with MON 3 creates combustion problems which I think I will address when I study when I get into combustion instability problems.

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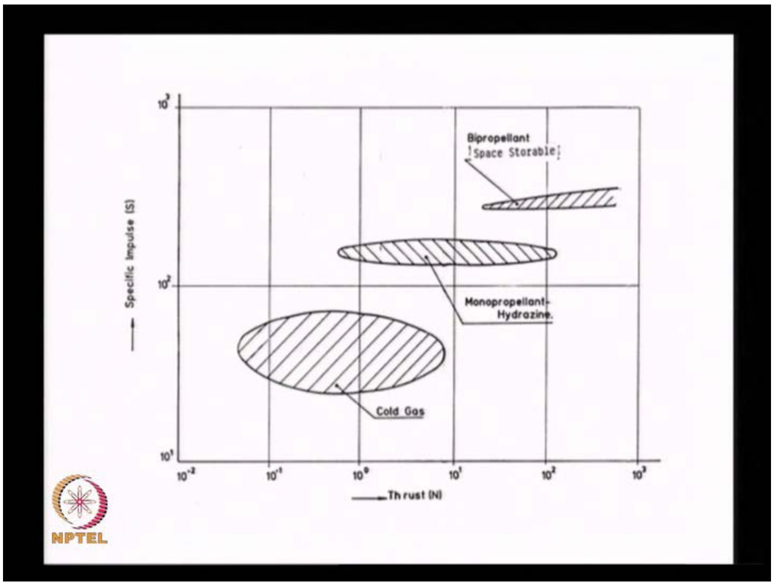

Well, this is all about monopropellant rockets, just to summarize we have cold gas which gives extremely low performance, monopropellant, which is still low which is somewhat higher by propellant which is quite high.

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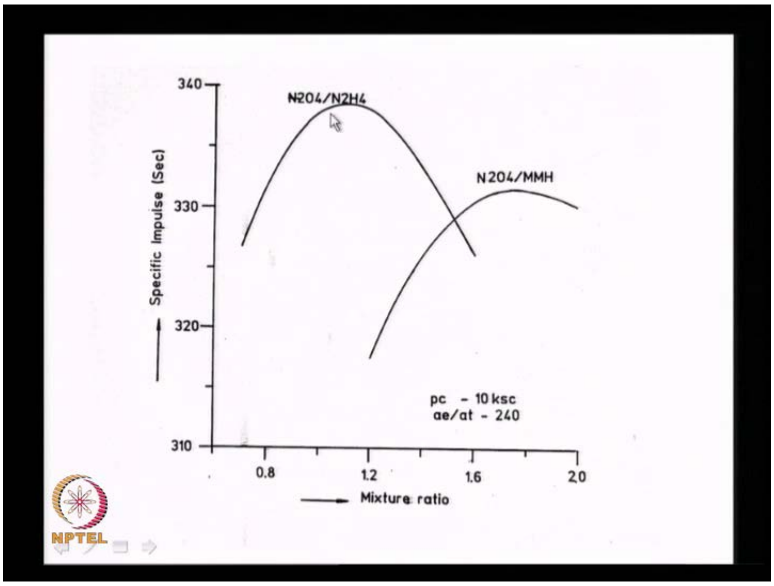

And as I told you in a bipropellant mode it gives a hydrogen with N 2 O 4 gives much higher performance than with MMH and therefore, it is desirable. Japanese people make use of these things, but I think we still have to understand little more about it.

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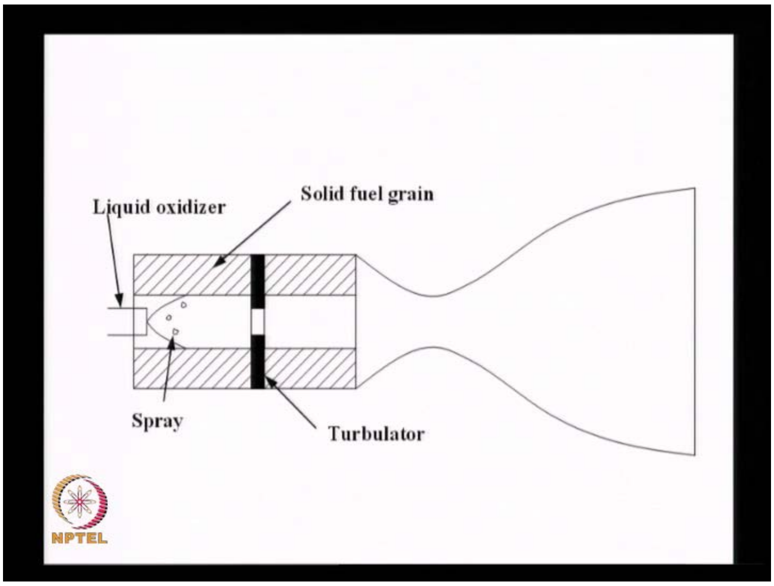

I think this is all about monopropellant rockets, but just to complete the subject of rockets we can also have instead of monopropellant bipropellant, we could have three propellants Tripropellant rockets.

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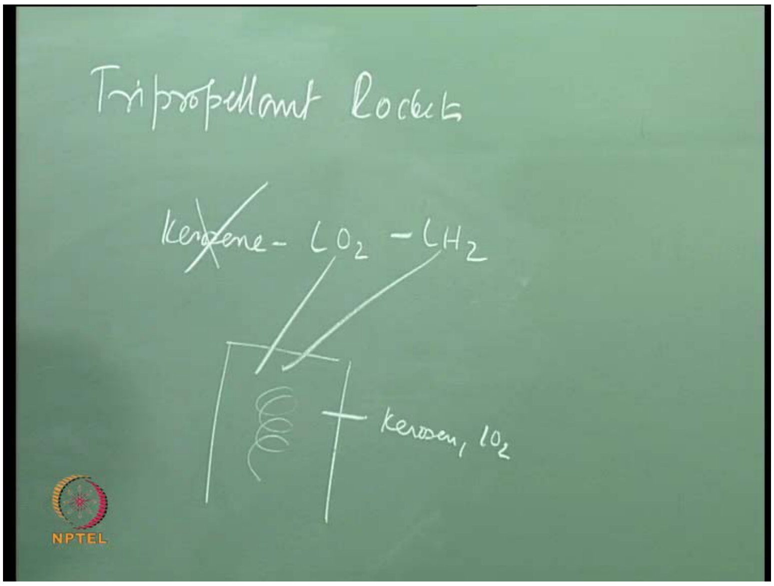

What are Tripropellant rockets? Maybe, I have something like kerosene, I have liquid oxygen which can use as boosters, I also carry maybe liquid hydrogen. And what happens when initially when I burn the system? I start burning kerosene and liquid oxygen together, and into this I can also add little bit of liquid hydrogen which stabilizes the combustion, and when the boosters stage is over into the same chamber, now I cut of the kerosene and use these two propellants and this becomes a Tripropellant rockets. The advantage of a Tripropellant rocket is a single rocket can be made to go to space, well it has still not been used but there is some interest in having the Tripropellant rockets.

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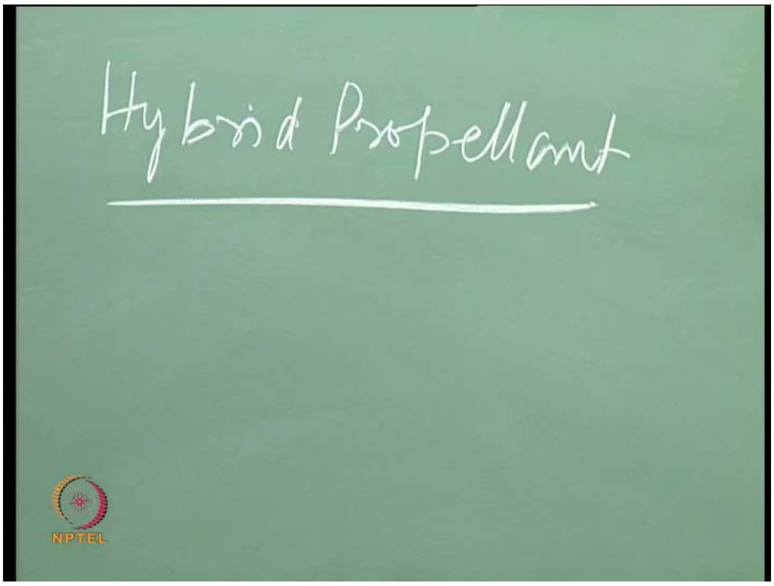

I think I should stop here, but before stopping as usual, I think we have not done anything about hybrid propellant. Before I start the next lecture on combustion instability, maybe I will spend a couple of minutes on hybrid rockets, because I find it has not been very promising earlier. But off late, some private people like you know the millionaire by name Burt rutan, he formed a company known a scale composite, and he used hybrid rockets for fairing people to space, maybe he says space can be used for enthusiasm, who are interested in looking; therefore, he says it is something like a voyager or something like a place, where you can go and view the earth from top.

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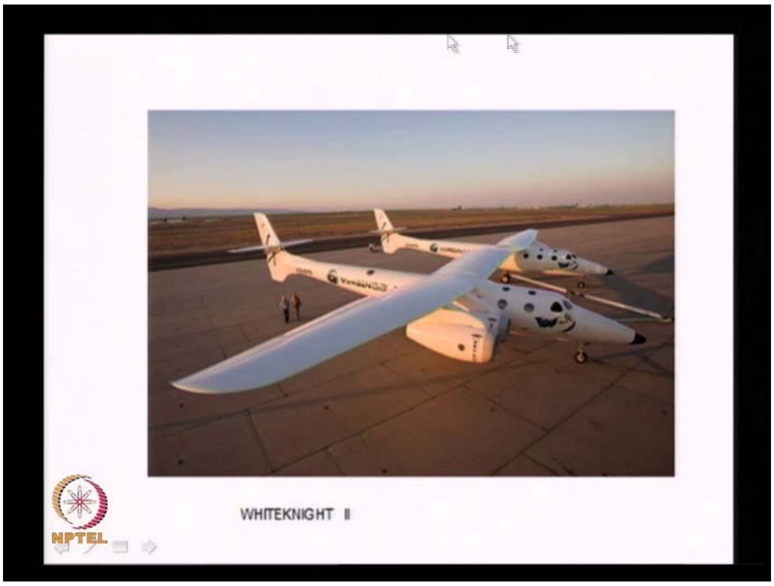

And therefore, he used that an aircraft known as white knight, he has some hybrid rockets and the space capsule in this. This aircraft takes him to a height of 14 kilometers, from there he takes the tourist into space and into a suborbital flight and makes them and come back over here; maybe, we will spend some five minutes on hybrid rockets in the next class and then get into the question of combustion instability. Well, thank you then and this all.