Rocket Propulsion

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Lecture No. # 32

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

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 let us quickly review what are the things we learnt in solid propellant rockets and the liquid propellant rockets.

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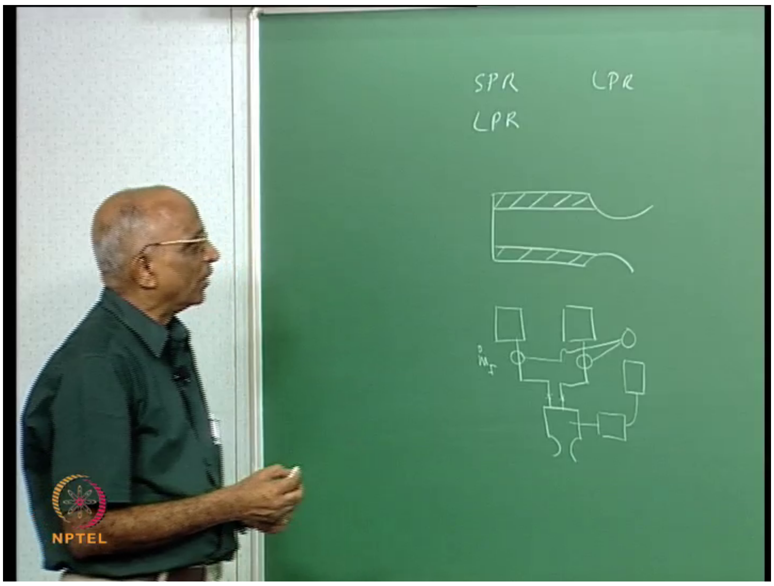

We have gone through solid propellant rockets into detail, but we said controllability is a problem in solid propellant rockets. What do we mean by that? Once a solid propellant rocket gets ignited, like you have a star grain or a cylindrical grain is ignited, it is just not possible to stop the combustion.

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 control the flow and hence the thrust, 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 something reference. I can control the chamber pressure; I have a reference pressure, I make sure that the reference pressure and the chamber pressure 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°f which it measures, I can measure the m°o, I can instantaneously record the value of m°o by m°f through a particular circuit. Let us fed this signal over here. If I find that the mixture ratio is exceeding the amount specified, I can give a command to adopt to these valves or to a valve upstream to increase or decrease the flow of the concerned propellant. 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 it 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 we choose hydrogen and oxygen, the performance or rather the specific impulse is quite large. Therefore, we can say in general the liquid propellant rocket is more versatile and has better performance than solid propellant rockets. But then we note that it becomes a little more complex; I have plumb lines, I have tanks, I have pumps and therefore, it is little more complicated, and I will come back to this. Can we simulate this through theory is something which is seems possible? 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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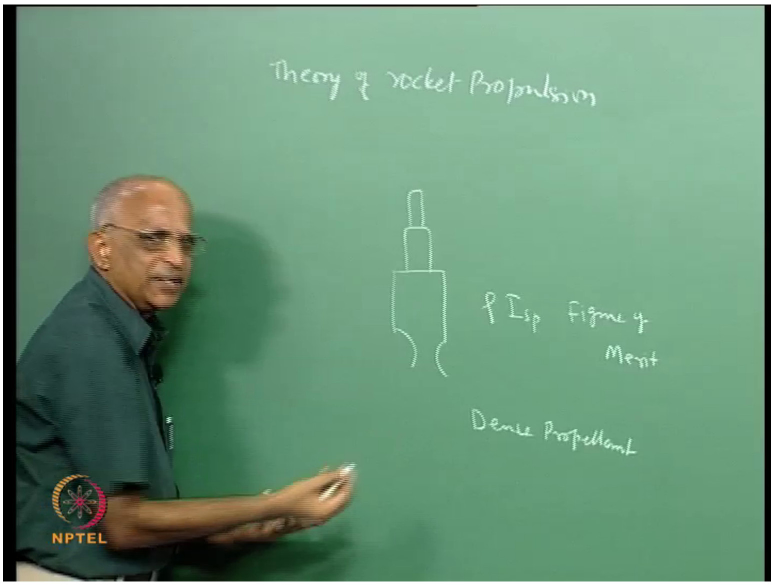

Like for instance, when we studied the theory of rocket propulsion, we will recall we said boosters are those rockets which are used during takeoff, and the upper rockets are are known as sustainers or upper stage rockets. For booster rockets we found that in addition to Isp, the term like density specific impulse rho Isp becomes important. You will recall and why did we say that? The mass of the cases, mass of the upper stages above the booster cause its mass to be more, and under those conditions we derived an expression that rather than Isp the product of the density of the propellant multiplied by Isp 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 we talked in terms of dense propellants what immediately comes to my mind is, can I use propellants which are like let say UDMH which has a good density, maybe N_2O_4 as a oxidizer, or use liquid oxygen with kerosene.

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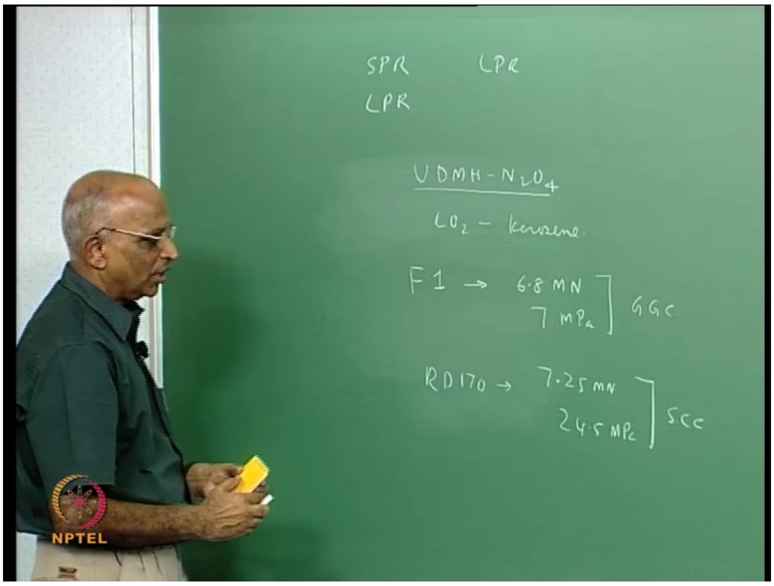

These are somewhat denser and therefore, we find maybe liquid oxygen kerosene has been traditionally used for the booster stages. In the example ,which we saw of F1 engine which was used for the Apollo rocket, and mind you this is something like 30 to 40 years old. It has a huge thrust of about 6.8 mega Newton; that means, 6.8 into 10 to the power 6 Newton or you are talking of several thousand tons of thrust. The chamber pressure of this which uses liquid oxygen and kerosene is something like 7 MPa 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 used as a booster is the Russian rocket known as RD 170, the beauty is, it has even a higher thrust than the F1 engine of the order of something like 7.25 mega Newton maybe same class, but the chamber pressure is extremely high of the order of 24.5 mega Pascal, that is something like 240 bar. 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 pressure you use the gas generator cycle. There are other examples but for lox kerosene these are two typical examples.

You know in India we started with UDMH - N_2O_4 as propellants, and this is what the French used earlier in their launch vehicles for boosters. We told that UDMH is cancer causing and it is also costly.

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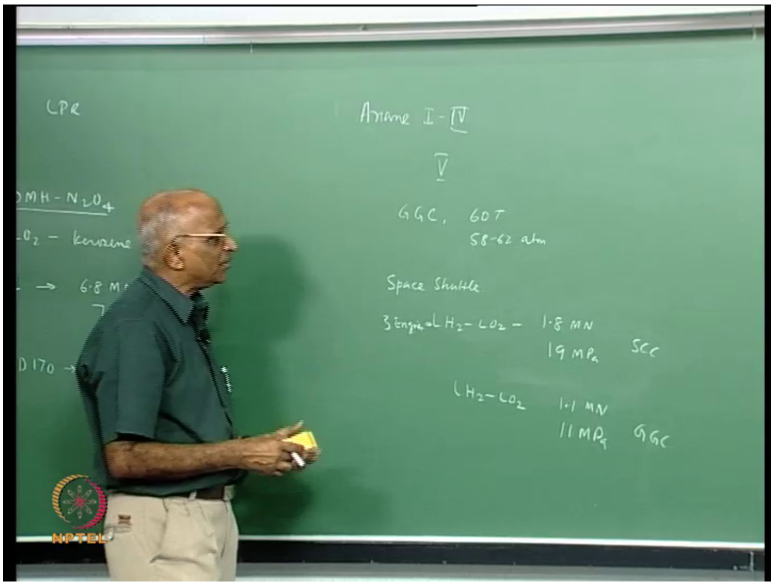

The present trend is not to use UDMH and therefore, presently the Arianne rocket of France does not make use of UDMH- N_2O_4. Arianne rockets models 1 to 4 made use of UDMH - N_2O_4. But in the more recent one Arianne 5, we use a 100 T thrust cryogenic engine. It is a derivative of what was used in Arianne upper stage, it also uses a gas generator cycle and the typical thrust is around let say 100 ton and the chamber pressure of the order of the same value around 10 MPa.

Well, these are some of the booster engines with let say the heavy propellants Lox kerosene and UDMH N_2O_4, but what was done more recently is if you look at the space shuttle. Mind you space shuttle has performed its job, it is no longer operational, the last space shuttle flight is over. What was done in space shuttle is you had liquid hydrogen and liquid oxygen engines, these generate a thrust of around 1.8 mega Newton, the chamber pressure is again quite large something like almost like 19 MPa; that means, 190 atmosphere pressure and this uses 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 with liquid hydrogen and liquid oxygen. You have 3 such engines which are used and this is used in the space shuttle.

Whereas, if you use the French philosophy of rockets, they switched from UDMH N_2O_4 to using LH_2 LO_2, they have a thrust of around 1.1 mega Newton; that means, 1.1×10^6

Newton, the chamber pressure is around eleven MPa, and since the chamber pressure is less they use the less complicated gas generator cycle.

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 MMH and N_2O_4 and maybe the other propellants like what is used in missiles.

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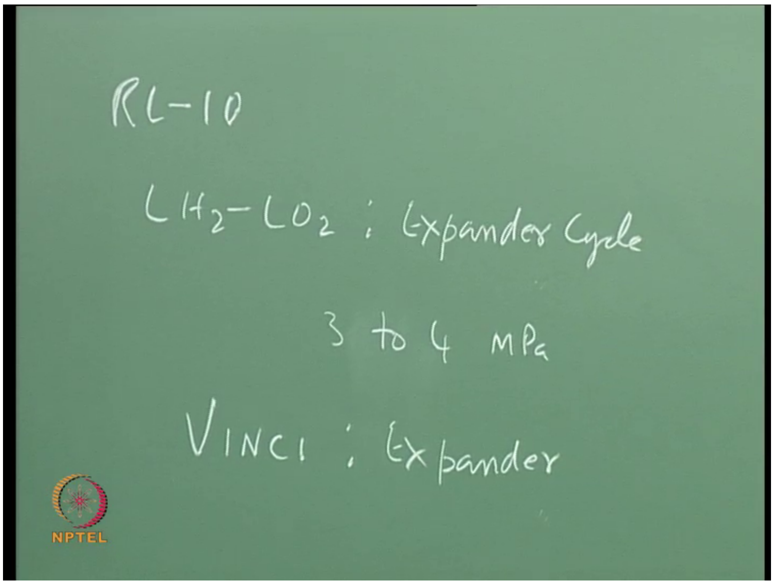

These are the typically the different type of liquid propellant engines used. We see sometimes gas generator cycle being used, sometimes stage combustion cycle is used. Stage combustion cycle is used only when the chamber pressure is very high, and this give very extremely high performance. Something which we must remember and I told you of an engine known as a RL 10 engine, which we said uses liquid hydrogen liquid oxygen, but uses 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 not very powerful, the chamber pressure is low of the order of 3 to 4 mega 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 you a homework problem based 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 100,000 rpm

Therefore, these are some of the developments. We should keep some of these things in mind as we study the liquid propellant rockets.

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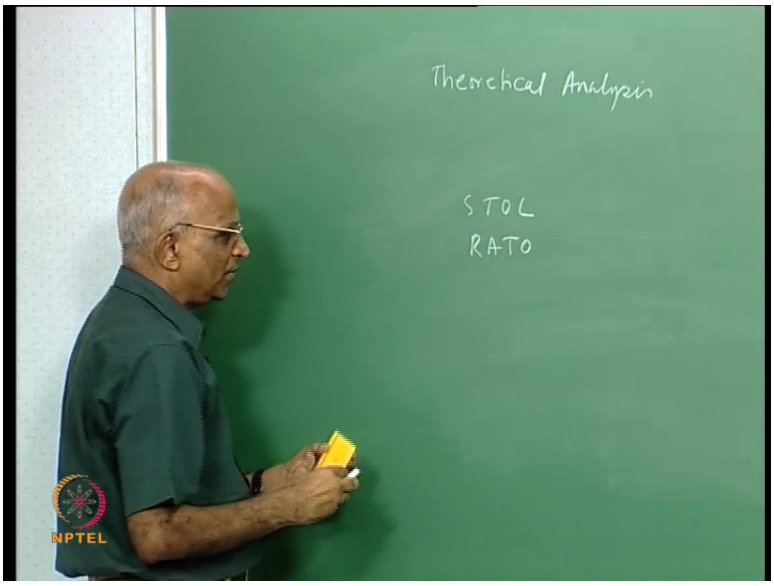

But, something else with respect to liquid propellant rockets compared to solid propellant rockets that we must note. It is easily amenable to a theoretical analysis. Not that I am telling that it is superior in anyway; see a solid propellant rocket has distinct advantages. Supposing, I want a short take off and landing for an aircraft, I can just have unrestricted burning of the grain with the solid propellant rockets beneath the wings. It will provide thrust immediately for a few seconds or a second, and we can take off the aircraft in a very short runaway, as is necessary in the forward areas or in some military aircrafts. We call it as rocket assisted take off (RATO), the short take off and landing (STOL).

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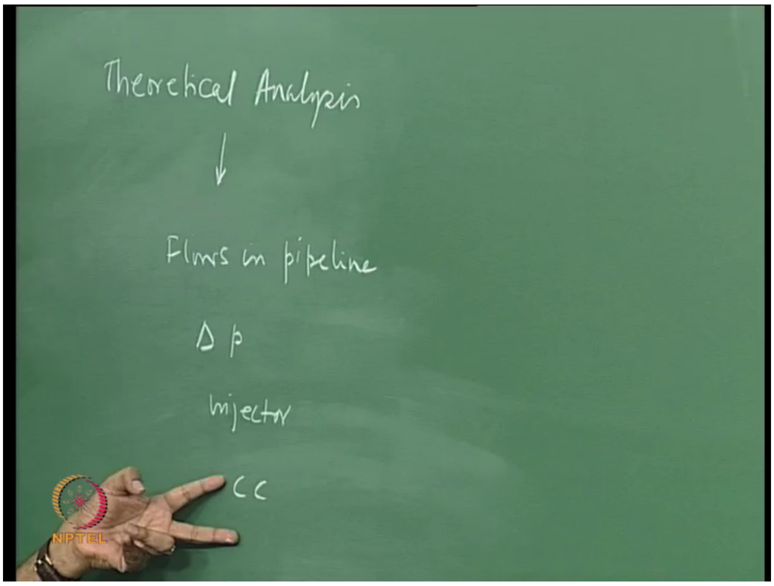

But what I wanted to say was, let us not say that liquid rockets are superior. But when we studied about liquid rockets we never really studied about a description of rocket. All what we studied is, we have a tank, propellant flows in pipe pipelines, if it is a pump I know pressure is increased in a 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 mechanics, thermodynamics, combustion, etc.

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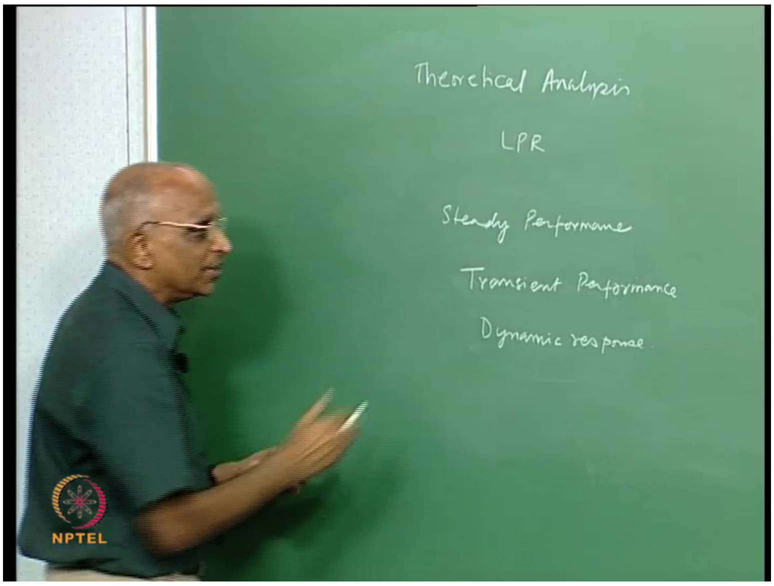

Therefore, we can as well make a theoretical analysis of a liquid propellant rocket, for let say steady performance prediction, or let say transient performance, or even if we want to look at the dynamics of its operation; a dynamic analysis. I could introduce some shock into it and examine how the rocket going to respond? Something like dynamic response is also 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. We have the tankages containing propellants, and from the tankages what subsequently happened?

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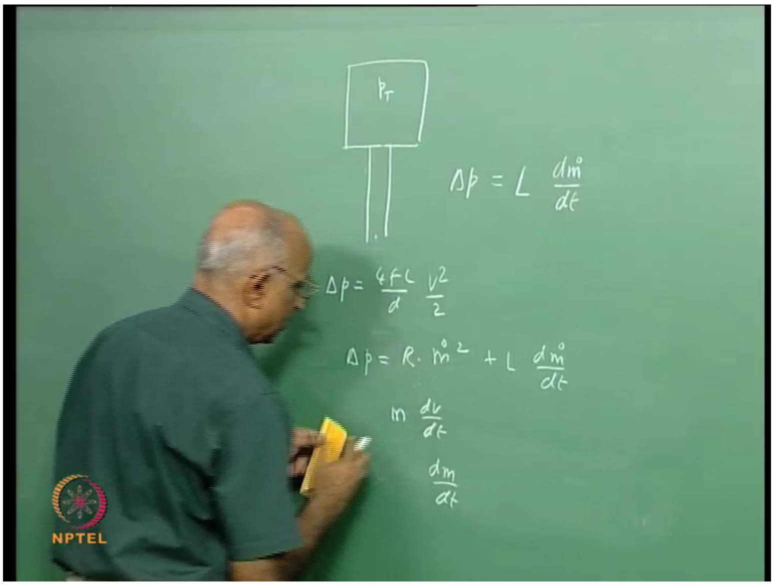

We draw a single tank and from it through the plumb lines maybe straight or curved the propellant flows. How do you establish the pressure if the tank pressure is let say p_T? How do I get the pressure here? I get a drop in pressure and the propellant flows in the line. I say that the drop in pressure goes as maybe $4fL/d \times V^2/2$, maybe under some condition. 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 $m^{\circ 2}$ square of the propellant flow. But under dynamical conditions I have the mass of propellant, which accelerates. That means, I have mass into acceleration or rather I have mass × dv/dt, and what is the mass? ρAV.

Therefore, I am talking in terms of something like dm/dt and therefore, because of this acceleration, I have acceleration taking place and a pressure drop taking place. I have a force due to acceleration which is the Newton's second law and therefore, I can write the Δp due to acceleration as something like an inductance such as with electric current changes × dm°/dt. We can write the net pressure drop under dynamical conditions as L ×dm°/dt while under steady conditions it is resistance into m dot squared. Therefore the total pressure drop is the sum of the two.

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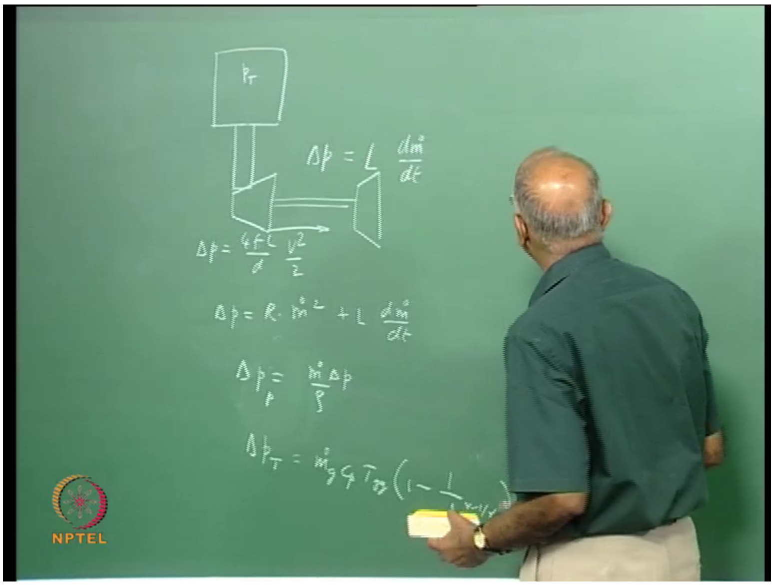

How do I get the pressure rise in a pump? Let us say the line above feeds into a pump. What does the pump do? It increases the pressure from a small value at inlet to a larger value at the outlet. And how do you get the pressure rise in a pump? We had said pressure increase in a pump Δp across a pump; let say the work done is equal to the flow rate Q° × delta p, but let us be very clear from units point of view. The turbine supplies this work. The expansion process in the turbine or the pressure drop in a turbine supplies the rate of work for pumping. After all, we are taking from gas generator the hot gas and driving the turbine as it were here. We said mass of the gas generator into Cp into T_{gg} into 1 minus 1 over the expansion ratio in the turbine to the power gamma minus 1 by gamma. This was under steady conditions.

We are able to get the pressures at the different points in this way. We go through all these lines and get into the injector. We 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 know the pressure rise across a pump ,the pressure drop across a turbine, etc.

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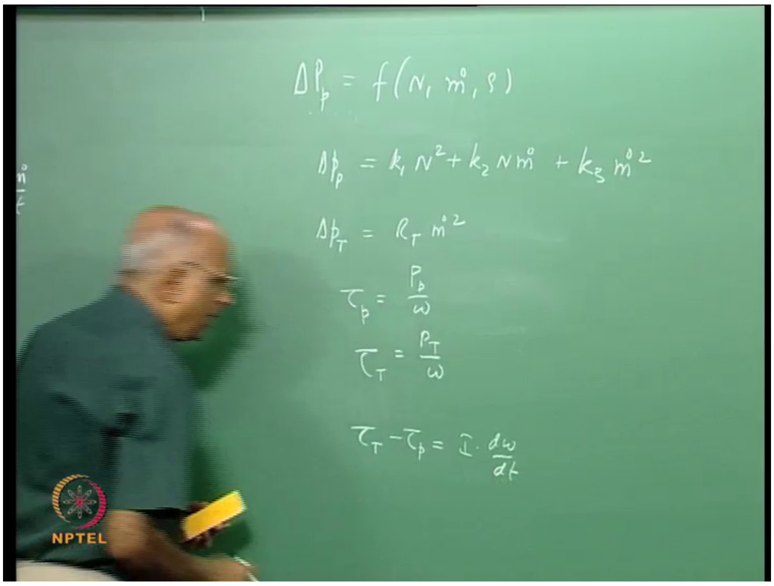

And supposing, we want the Δp across a pump; it depends we saw on non dimensionalization, depends on the speed, depends on the mass flow rate, depends on the density, Q° and density. We can write this as let say some constant $k_1 \times N^2 + k_2$ N × mass flow rate + a constant k_3 into $m^{\circ 2}$, and this can be proven considering the work of the pump and in rotation. The constants can be determined in cold flow tests and verified in hot tests. The constants can also be theoretically determined. The pressure raise across a pump is given by this particular expression. And we also told that across a turbine and all turbines are generally impulse turbines, the pressure drop could be written as the resistance into $m^{\circ 2}$. Therefore, we 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; we already had the expressions for power of a pump and power of a turbine. And how do we use the power of pump and power of a turbine especially during the transients when it is picking up speed?

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 τ_P, torque of a turbine is equal to power of turbine divided by ω, and what is happening is that turbine drives 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 dω/dt. And therefore, we know all these parameters. We assemble a set of equations to be able to find out the pressure at the different locations, to be able to find the speed of the turbine and not only the speed of the turbopump, but we will also be able to find out, as a function of time how the speed of the pump should develop?

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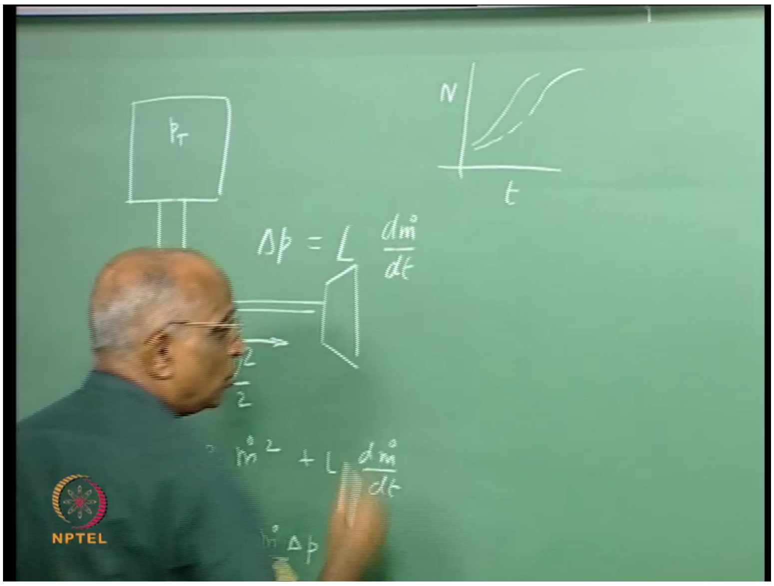

How the pressure should develop in the combustion chamber? And what do we use to get the pressure? we have a gas generator, and what is the equation to the gas generator?

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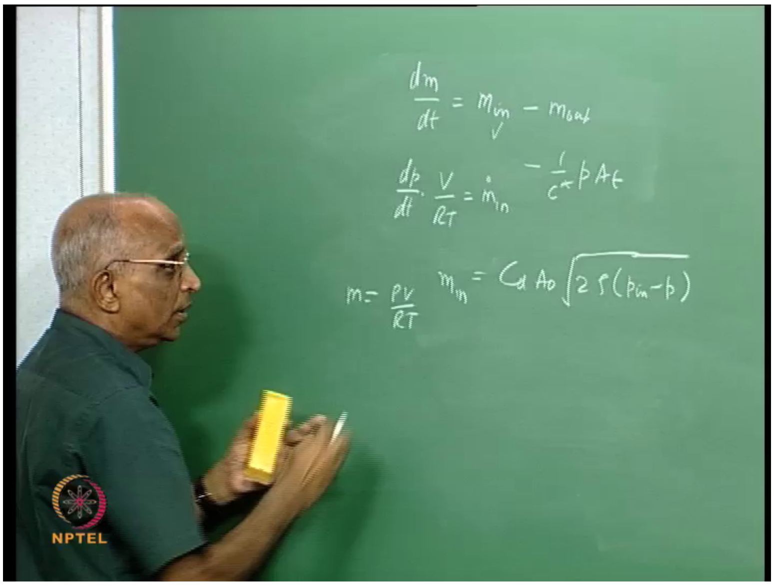

We said dm/dt = mass which flows in − mass which flows out. The mass which flows in is the mass which is flowing from the injector. You also know the mixture ratio. Mass which flows out is equal to 1/C* × p × A_T. And what is dm/dt? dm/dt was equal to dp/dt ×V/RT, since PV/RT is m. V is a constant therefore, V/RT × dp/dt = is equal to m° inj − m n. T is reasonably constant. And how do you get m dot inj? We said from the injector you have Cd ×into area of orifices × $\sqrt{2}$ ρ × the injection pressure minus the pressure in the chamber. Therefore, we are able to get all what we 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 in the analysis of 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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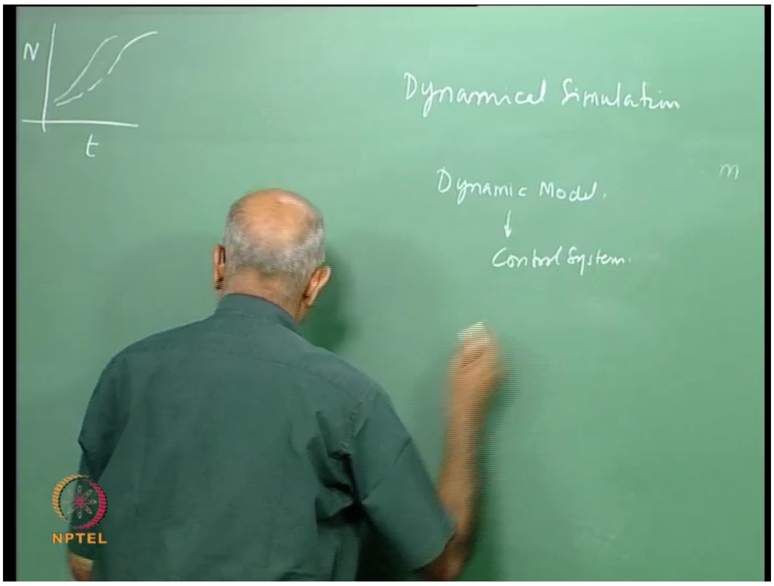

And you will see people always talking of a dynamical model of the system, or do you have a static model of the system? All what this meant is this equations have to be put together maybe, I went through it hurriedly, because we have covered individual components together and there is not much point in again repeating the whole thing. 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 it. I think this is all about the liquid propellant rockets, and you see even a theoretical simulation is possible.

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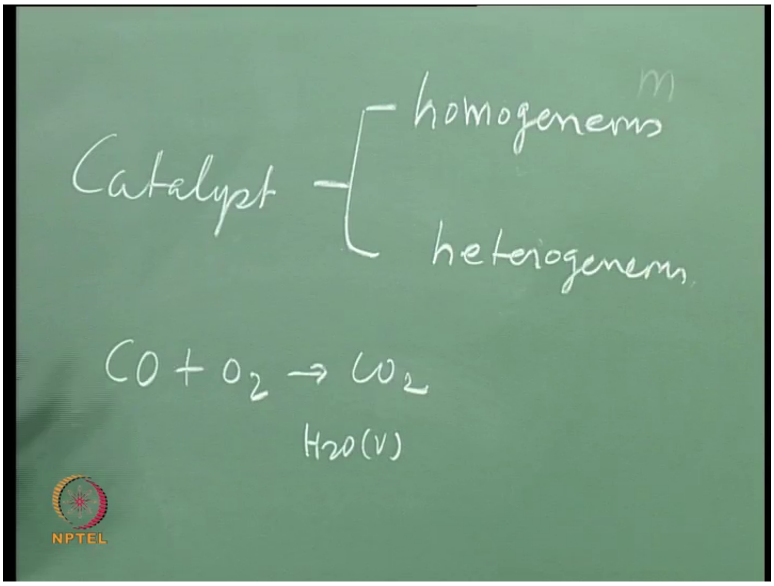

We now get started with monopropellant rockets and what are monopropellant rockets? We use a single propellant in a rocket; when we use a single propellant how does it burn and generate hot gases? When we were in our high school, we talked in terms of certain substances known as catalysts. A catalyst is a substance which improves the rate of a reaction without itself taking part in the reaction; that means, it does not get changed during the reaction, and a typical reaction is if we have CO plus O_2 and I want to form CO_2, dry CO and O_2 will not form this, but water vapor will catalyze the reaction and help in progressing the reaction. 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 the reacting substances.

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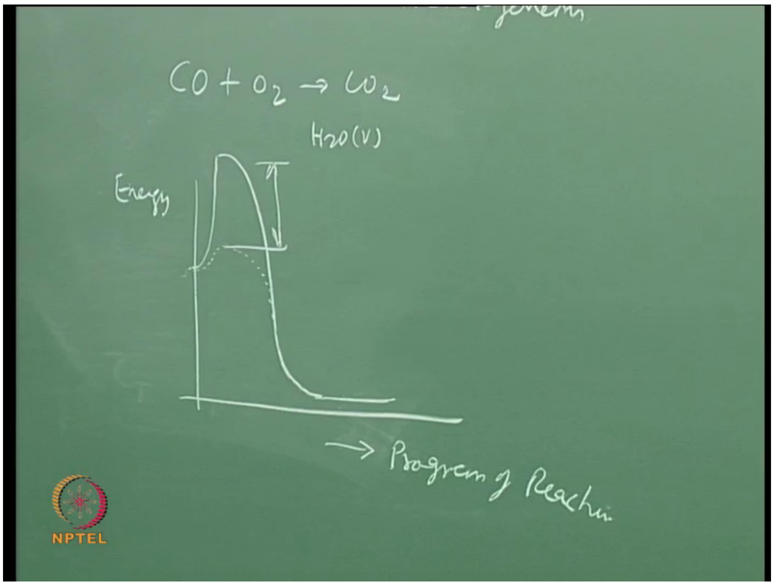

And why does it have to happen? May be this represents the progress of a reaction, reactant may be some substance like let say a single propellant over here on the left, combustion products have much lower energy level, this is the heat of formation or the energy here, this is the of the products over here. I have to give some energy for it to start reacting and once it overcomes the energy barrier the reaction rapidly goes to completion. The x axis becomes the progress of the reaction and this becomes let say the energy involved. Well, this is the 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 this activation 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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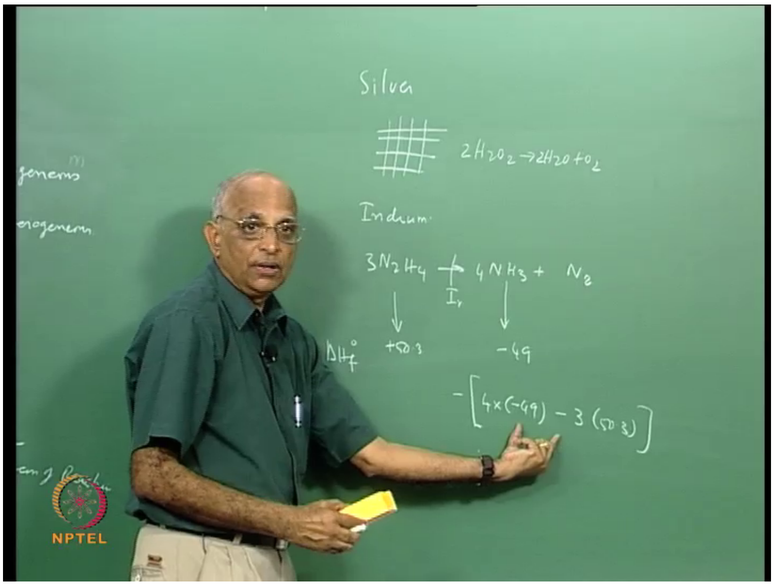

I have a silver wire and make it into a mesh and slightly heat it. I pour hydrogen peroxide over it. The hydrogen peroxide dissociates into H_2O plus O_2, may be 2 H_2O_2 = 2 H_2O + O_2. And similarly, the silver is heterogeneous because it is solid; it catalyzes a liquid hydrogen peroxide into two gases steam and oxygen. Similarly, if I have a catalyst like iridium, may be iridium ions; iridium ion is in contact with hydrazine N_2H_4 causes it to decompose. Iridium catalyzes the decomposition of hydrazine into ammonia plus nitrogen. You have the reaction 3 N_2H_4 = 4 NH_3 + N_2. 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 hydrazine, which we studied when we were studying propellants, we said it is around + 50.3 kJ per mole. Ammonia if you look at the heat of formation ΔH_f^o at standard condition, this was something like − 49 kJ/mole. Therefore, the heat released in the decomposition is – [4 × (− 49) − 3 × 50.3]. We had 3 moles of hydrazine and got 4 moles of ammonia. And therefore, a monopropellant will be different from the rockets which we studied so far in that we just have a chamber, all what we need to do is put catalyst over here and pass hydrazine through it.

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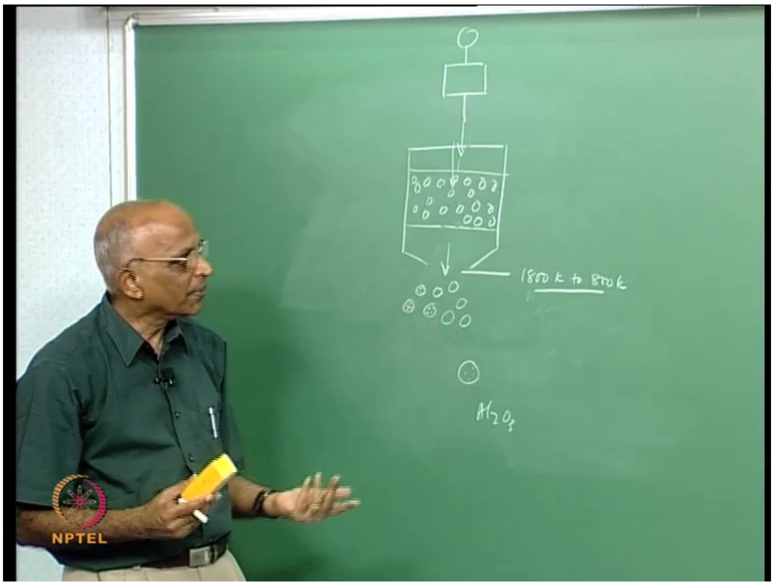

And how do we put this catalyst like iridium? we need iridium to be coated and I take alumina spheres of fine diameter and alumina is a porous refractory. We make spheres of aluminum may be 1 mm or 2, or 3 mm in diameter, and on this we coat iridium ions. The iridium ions will also be available in depth as it is porous. We pack these alumina impregnated with iridium in a catalyst chamber and into this we pass hydrazine. Hydrazine when it is flowing will come in contact with iridium, because these are all porous, and iridium will catalyze the decomposition of hydrazine. We will therefore get the dissociated products, 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, in a hydrazine monopropellant thruster we have gas bottle. We have a hydrazine tank. We inject the hydrazine into the catalyst bed where the iridium in the particles of alumina catalyzes and causes its decomposition. And how do we impregnate iridium ions in the porous alumina? We take the alumina Al_2O_3 spheres, which are porous and treat it with hexachloro iridic acid to get iridium ions in it. When the hydrazine flows it decomposes and this is how a monopropellant rocket functions.

But what happens when propellant keeps flowing, the ammonia, which is formed begins to again decompose.

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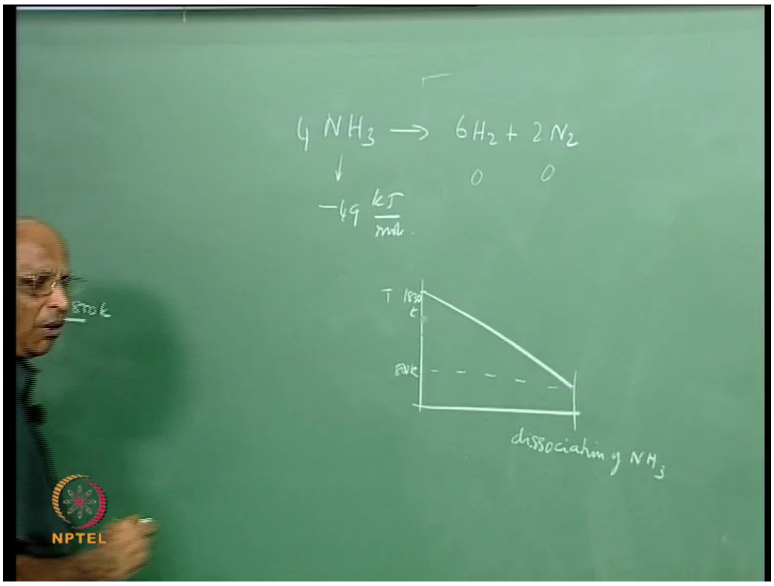

Ammonia NH_3 that formed 4 NH_3 from 3 N_2H_4 could again decompose into something like 6 H_2 + 3 N_2. In other words, as it begins to react we get ammonia and nitrogen left in the reaction. This ammonia further decomposes because of the high temperature into hydrogen and nitrogen. You find that the heat of formation of hydrogen is 0, nitrogen is 0, ammonia the heat of formation was − 49 kJ/ per mole and the heat of the reaction is something minus − 49 kJ per mole of ammonia.

Therefore, you find that this particular dissociation reaction is endothermic and therefore, it absorbs the heat and therefore, this decomposition will rob heat from this particular reaction of hydrazine and with more the dissociation of ammonia less will be the temperature. Rather as the dissociation of ammonia increases, the temperature will keep on falling. If there is no dissociation the temperature is around 1820 or 1830 K, and if the dissociation is complete we get something like 800 K. We would like to combine both these reactions together to understand further.

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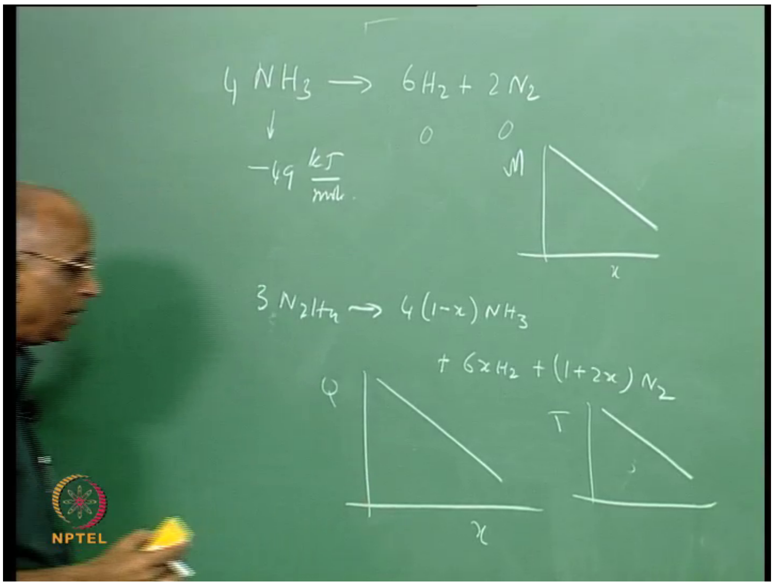

Let us assume that a fraction x of the NH_3 formed from the decomposition of 3 N_2H_4 dissociates into hydrogen and nitrogen. Please recall that 4 NH_3 was formed from the decomposition of hydrazine. I can combine this equation and the earlier equation 3 N_2H_4 = 4 NH_3 + N_2, and then write it as 3 N_2H_4 = 4 (1 – x) NH_3 i.e., a fraction x dissociates. Therefore 4(1 – x) of 4 NH_3 is left. The 4 × x of NH_3 dissociates to form 6x of H_2, plus 2 x of N_2. But we originally had N_2 and therefore we get (1 + 2x) of N_2. This becomes the equation when x part of the ammonia which is formed dissociates into hydrogen and nitrogen viz., 3 N_2H_4 = 4 (1 – x) NH_3 + 6x H_2 + (1+2x) N_2.

And now, if I find out the heat of reaction from the standard 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 we said temperature decreases from something from 1800 to 800 Kelvin. As the dissociation increases, we find we are getting more and more of hydrogen therefore the molecular mass of the products decreases as x increases. This decreases from a value like 19 g/mole to something like 10 g/mole. You can work it out. I give a homework problem on it. Since molecular mass comes down and temperature comes down, if we were to put both of them together in terms of either C* or in terms of specific impulse we find the specific impulse with respect to x is maximum for a value x around 0.2 dissociation. Therefore, Isp initially increases before it starts coming down as the decomposition of ammonia increases.

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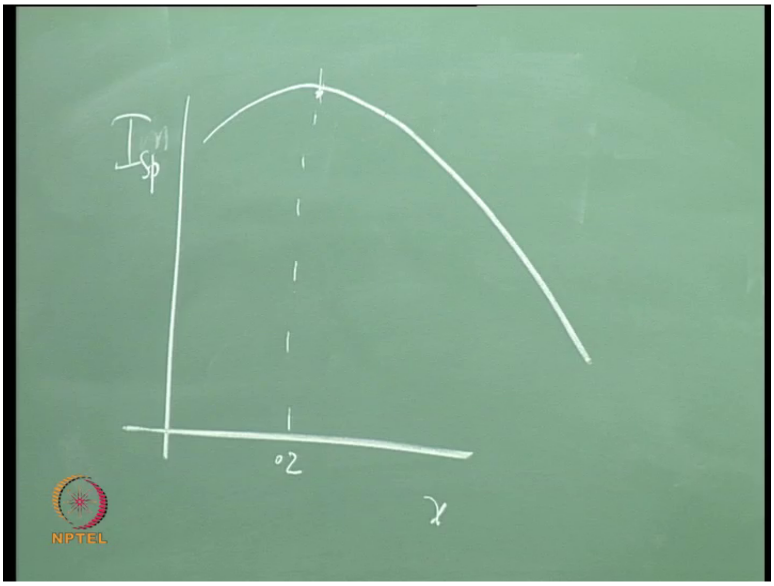

The change in specific impulse between 0 dissociation to 0.2 dissociation is due to the decrease in the molecular mass of the products. But beyond a dissociation of 0.2 it begins to come down. Therefore, you would like to configure the catalyst bed such that we have degree of dissociation as 0.2, and that is when you get maximum performance. This is the background for monopropellant rockets using hydrazine. Let us try to put things together now and see what is required for a monopropellant rocket.

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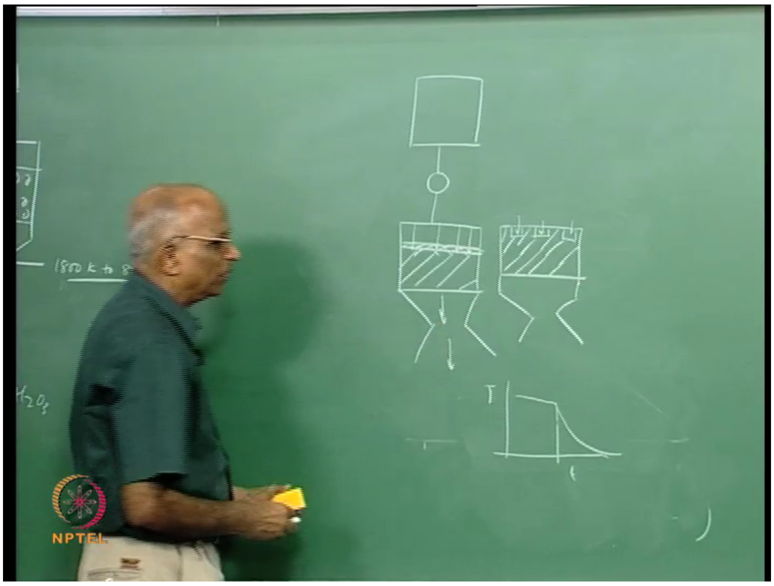

Well, it is very extremely simple. We have a tank, a pressure regulator; the pressure regulator supplies propellants at constant pressure to a catalyst bed, and this catalyst bed decomposes it and out goes the products through the nozzle. This becomes the catalyst bed. We need an injector: may be an ordinary shower head injector which forces the liquid on the catalyst bed. But you know if we force the hydrazine jets straight on like this it does not uniformly get distributed in the catalyst bed. Therefore we put some screens here, metal screen to distribute it uniformly like in a manifold. That is one solution. Or else we could allow the bed to be very much near to the injector; we put metal screens over here and inject the shower.

It is of course necessary to make sure that whenever you have such injectors, screens are required for even distribution. We have shower head and metal meshes over here. It is also important that the dribble volume must be small. Mind you we talked in terms of manifold volume must be small, if the dribble volume is large the propellant keeps on dribbling and you will have slow rate of thrust decay with respective time, instead of giving fairly sharp cut off of the thrust.

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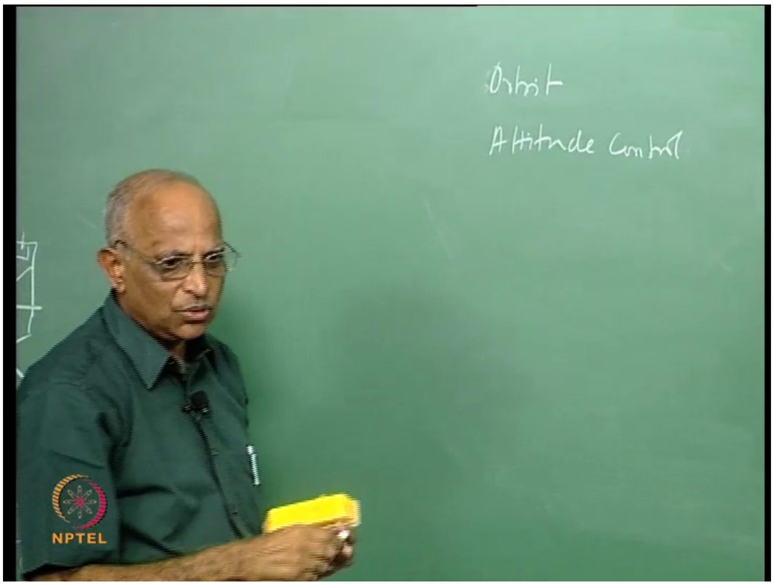

And in fact the monopropellant hydrazine thruster was quite widely used in satellites for controlling the trajectory or let us say orbit control and for attitude and altitude corrections of the satellites. Having said thus, let me quickly run through to summarize what I have been telling so far regarding monopropellant rockets.

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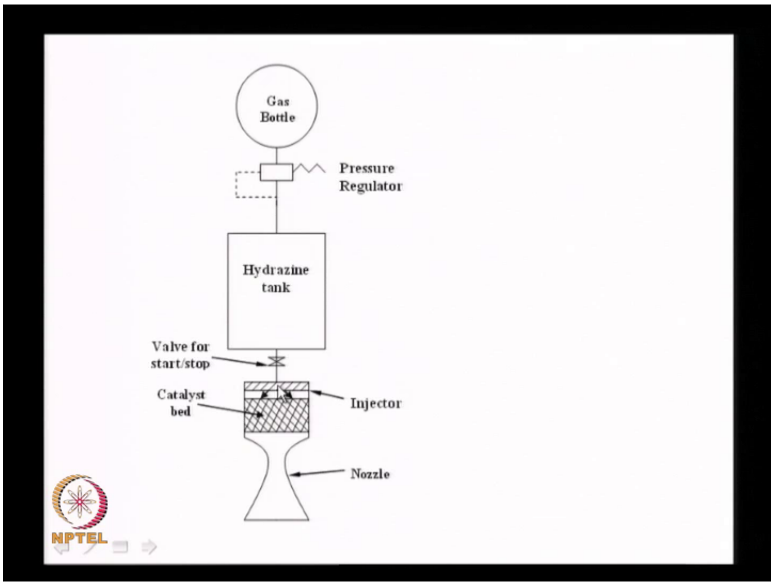

We talk in terms of a gas bottle, pressure regulator, hydrazine tank, hydrazine being supplied to the catalyst bed. You have a valve; you can open and close it in pulses if we require small pulses of thrust. But when operated in pulses, during the dwell period i.e., the idle period, the hot catalyst bed transfers heat back to the injector. This may heat up the hydrazine contained in the injector manifold and if the injector becomes hot the hydrazine in it may decompose and even cause an explosion.

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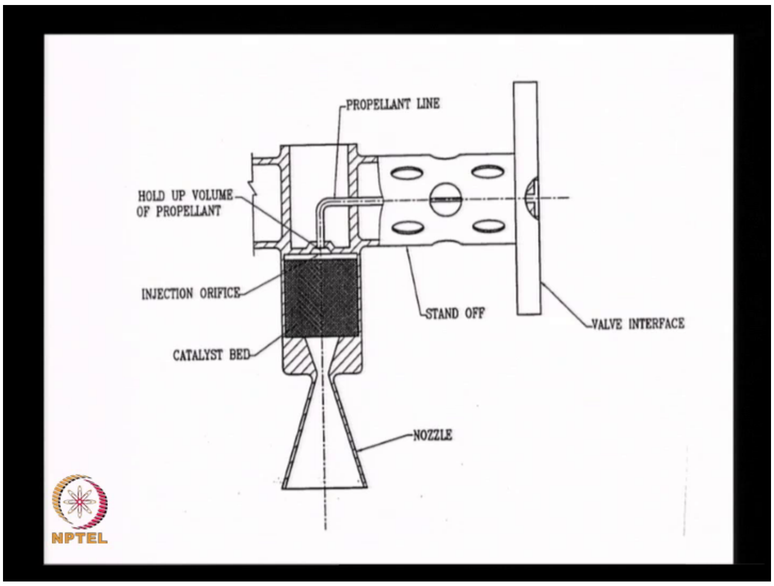

Therefore, what is it that we do? This is the catalyst bed; this is how I expand the decomposed hot gases. In order to cool the injector, I am forcing the hydrazine through it but if the hydrazine is not actively cooling it, we put some metal here just like we use fins in the case of motorbike engine. We use fins here such that this part get heated and heat gets radiated out. Between the chamber and the propellant supply and the monopropellant chamber, we have something like a standoff.

As I told you, we would like the manifold volume, which we called as hold up volume of the propellant to be as small as possible. We have the injector here which could be shower head and some of the screens 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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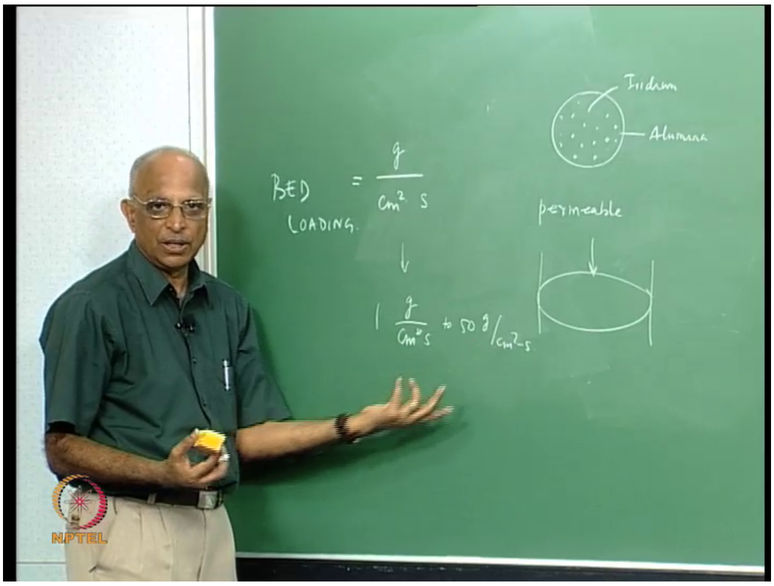

The catalyst bed consists of alumina spheres. In the alumina we have lot of pores or fine holes, and when impregnated with the iridium, the iridium ions are available at the surface of these pores. When hydrazine flows in the catalyst chamber, it wets the alumina pellets. The alumina is permeable to hydrazine and permeability is an important parameter. The iridium in alumina catalyzes the decomposition of hydrazine at the surface and in the pores. How do we therefore, design a catalyst bed?

After all you have a bed of certain size and hydrazine flows into it therefore, it is specified in terms of mass flow of hydrazine in grams divided by the surface area; that means, so much centimeter square. And you are passing or flowing hydrazine in so many grams per second. This parameter in g/cm^2 is known as bed loading. In other words we have to necessarily ensure a certain surface area of this bed so many meter^2 or centimeter^2 is available for passing certain number of grams per second or mass flow rate of hydrazine through it. The hydrazine flow in grams per second divided by the surface area of the catalyst bed is the bed loading. The length of the bed is decided on the amount of dissociation of ammonia.

The bed loading is typically between 1 g/ (cm^2 second) for smaller thrust rockets and 50 g/(cm^2 second) for larger rockets. Whenever we use monopropellants, we do not go high thrust, maybe the maximum thrust is something like 500 Newton to 1000 Newton, while the smallest could be anything small maybe a milli Newton. For a very small mono propellant rocket, we use a small bed loading. But for larger once we use a larger bed loading.

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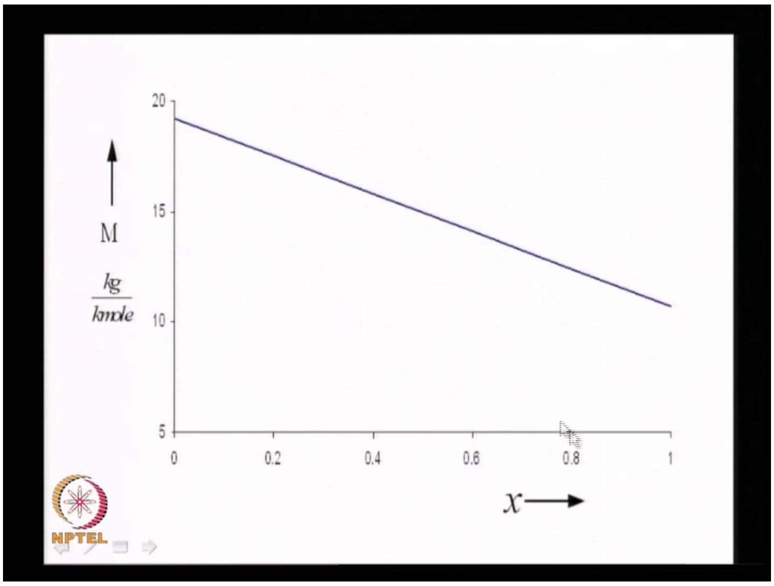

We stop here. To summarize, we say the temperature of the dissociated species keeps coming down with increase of the dissociation of ammonia.; the molecular mass also comes down from something from 18 g per mole to value around 12g per mole.

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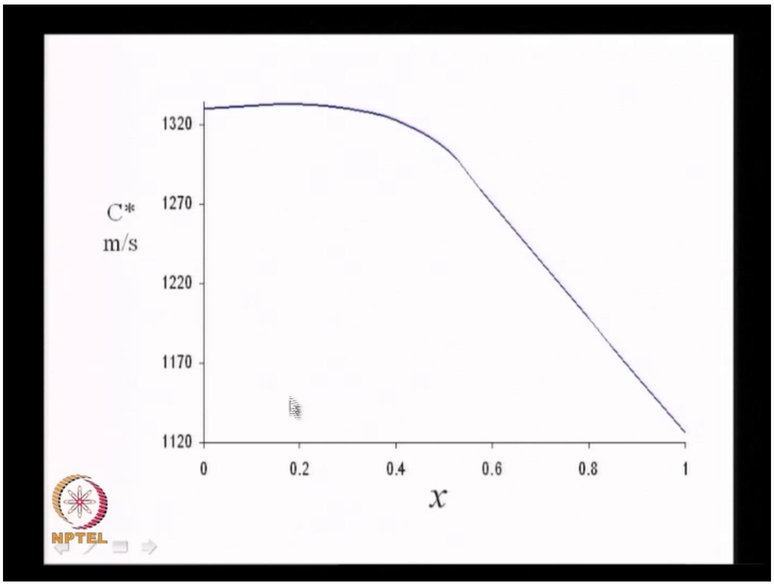

And when I put both the temperature and molecular mass together the C* has a maximum value for a fraction of ammonia dissociation of about 0.2 .

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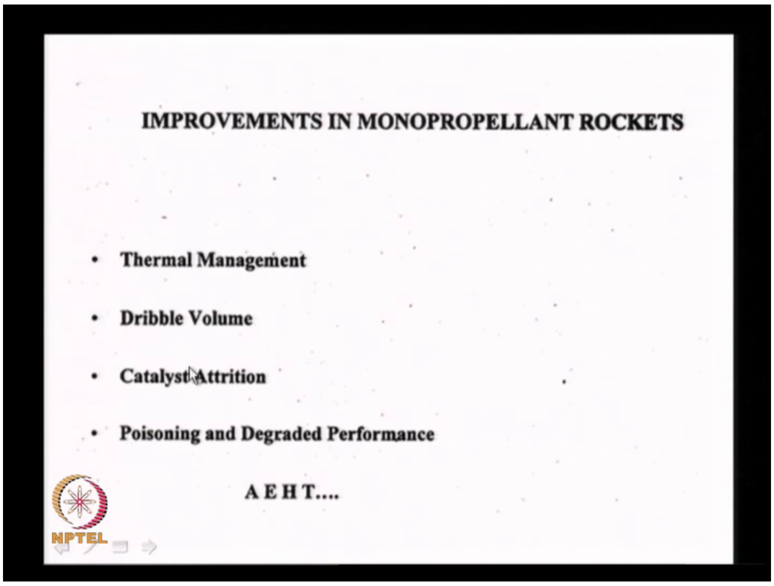

What are the problem areas in monopropellant thrusters? Well the catalyst bed runs hot therefore, the injector gets heated especially during the period when the thruster has stopped firing. Hydrazine could therefore dissociate, and since hydrazine is a monopropellant it could as well explode and therefore, we must ensure that we have adequate thermal management. And how do we do the thermal management? We told that we could dissipate the heat using a stand off using fins. The dribble volume must also be small.

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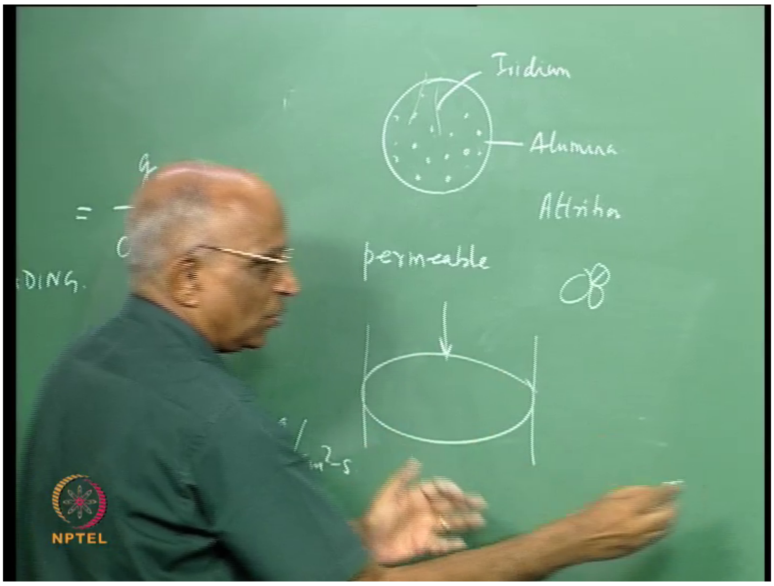

We have some problems with catalysts. The alumina pellets in which iridium ions are adsorbed sometimes break and we call as attrition. What is attrition? You have chemical reactions of decomposition in the pores of the catalyst. Pressure is created in the pores and this leads to breakage of the catalyst, and some of the disintegrated and powdered catalyst gets ejected out through the nozzle. Therefore there is a loss of catalysts and the performance of the monopropellant rocket diminishes with time.

We had noted that with liquids propellants used in spacecrafts, we need to have something like a positive expulsion system, and the bladder or diaphragm material might get into the hydrazine and might poison the catalyst; that means, the activity of the catalyst can come down.

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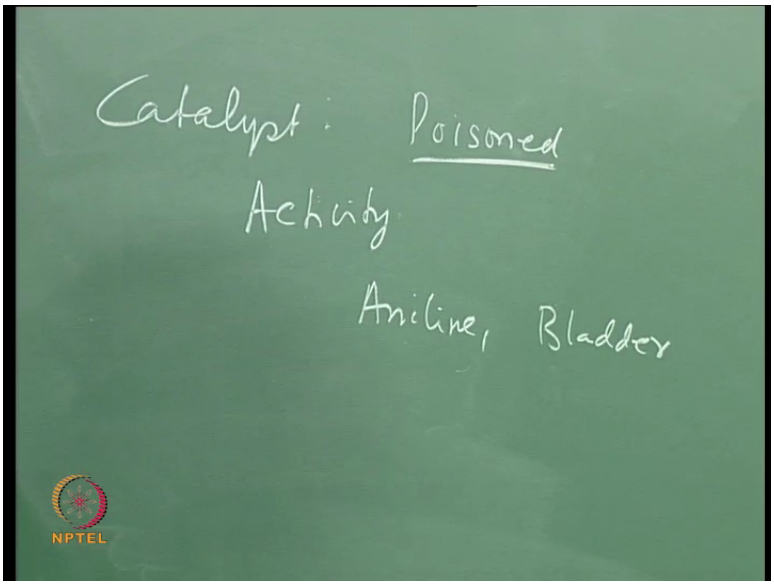

We have to keep these aspects in mind. Whenever we have catalyst, the activity of the catalyst must not decay. We have hydrazine and it might contain some aniline, it might contain some material from the bladder, which can go and block or inhibit the activity iridium. Therefore, we must ensure that the activity of the catalyst is not decreased. We say a catalyst gets poisoned by aniline or by the bladder material in hydrazine and we must prevent the poisoning of catalyst.

And of course, whenever something gets poisoned it is not able to achieve its performance. But the main drawback with using the monopropellant thruster is, it has vey much low performance compared to bipropellant rockets.

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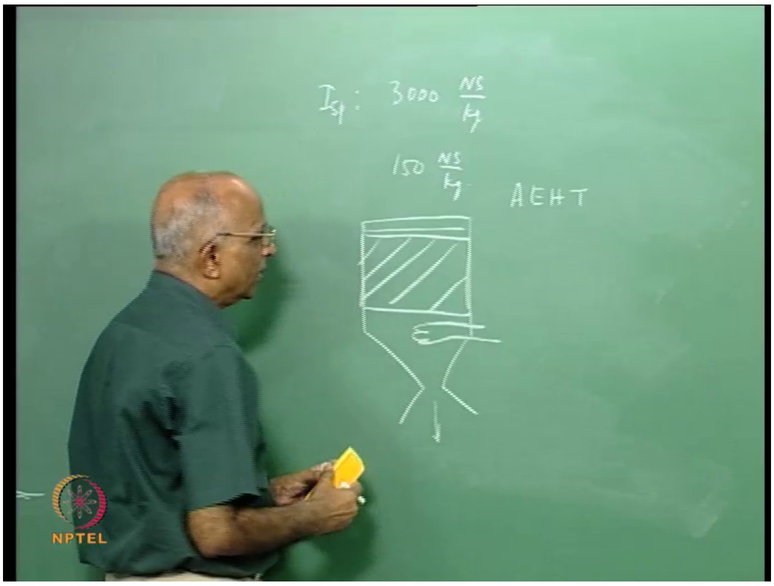

Compared to an Isp of something like 3000 N s / kg for a low performing bi propellant, that we called as low energy propellant, the Isp for the monopropellant rocket is around 1500 N s / kg. And therefore, there has also been an interest to improve the performance of a monopropellant thruster; that means, we have a catalyst bed, we have an injector and we slightly modify it to enhance the temperature or decrease the molecular mass.

Can we put some electrical heating after the decomposition and increase the temperature of the gases? We said that the maximum temperature is around 1800 Kelvin. We increase the temperature using electrical heating, and the such type of thrusters in which we have monopropellant decomposition to an intermediate temperature, and increase the temperature further to improve the Isp is known by electrical heating are known as augmented electro thermal hydrazine thruster (AEHT).

We will revisit this AEHT later on when we talk of electrical propulsion; that means, since the performance of monopropellant thruster is on the low side, we can always improve it by electrically heating the gases to a higher value of about 2500 Kelvin or so, and increase the value of specific impulse.

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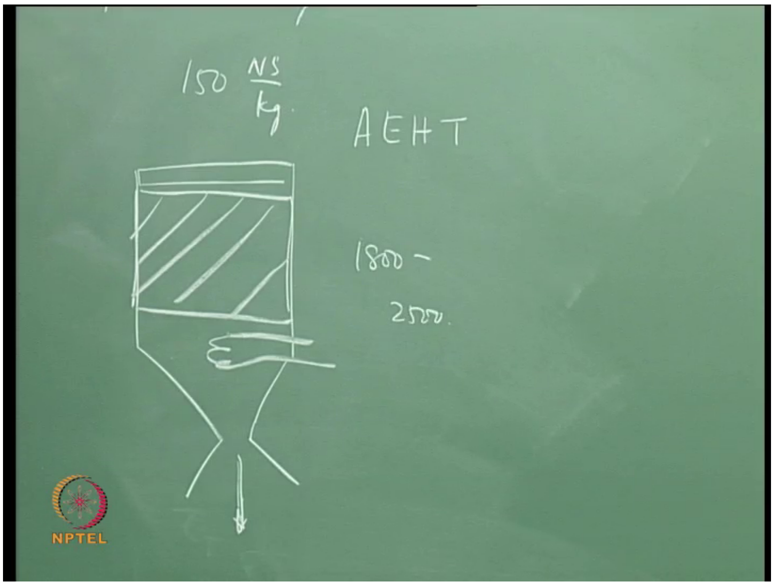

Well, this is all about the monopropellant thrusters, but there are some things which we have to keep in mind. See monopropellant rockets are very simple and easy to use.

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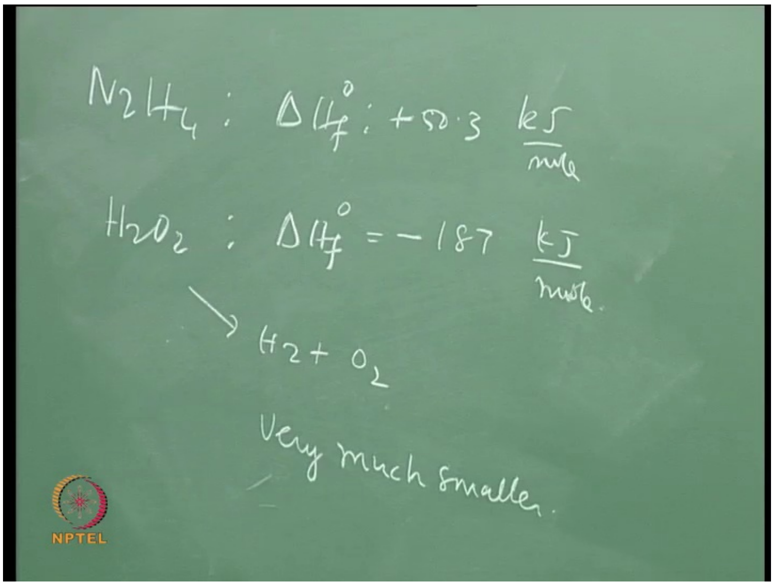

So far we did not consider the monopropellant H_2O_2. We were always centered around hydrazine. Why is it, can somebody tell me? I give you give a clue. N_2H_4 hydrazine has a standard heat of formation of + 50.3 kJ per mole, while hydrogen peroxide the standard heat formation is − 187 kJ/mole.

The standard heat of formation is terribly negative and the amount of heat which we can generate is going to be very much smaller. The temperature what we can get by H_2O_2 decomposition will be very much smaller. And universally if we see other than maybe in early part of the rocket program, maybe in 1940s and 50s, when hydrogen peroxide as monopropellant was used, nowadays it is not being used.

The reason being, we get poor performance, and why do we get performance; because this heat of formation is much more negative and these aspects are clear to us.

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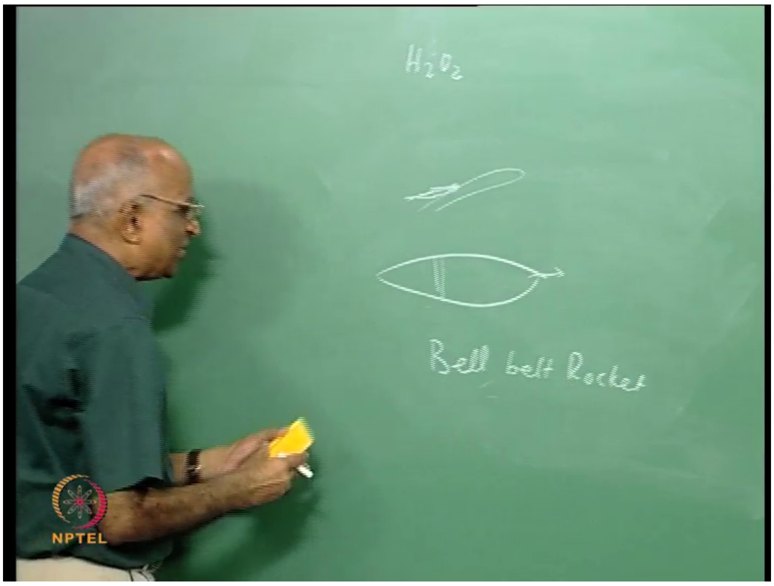

But there is one application of the low performing hydrogen peroxide mono propellant rocket. During a carnival such as the opening games of say Olympic games, you may have seen some people having in their belt something like a rocket, and they fly above the stadium. This was seen in the Los Angeles Olympics. 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 we can always in my belt contain a rocket, and the hydrogen peroxide has been used. This is known as a bell belt rocket.

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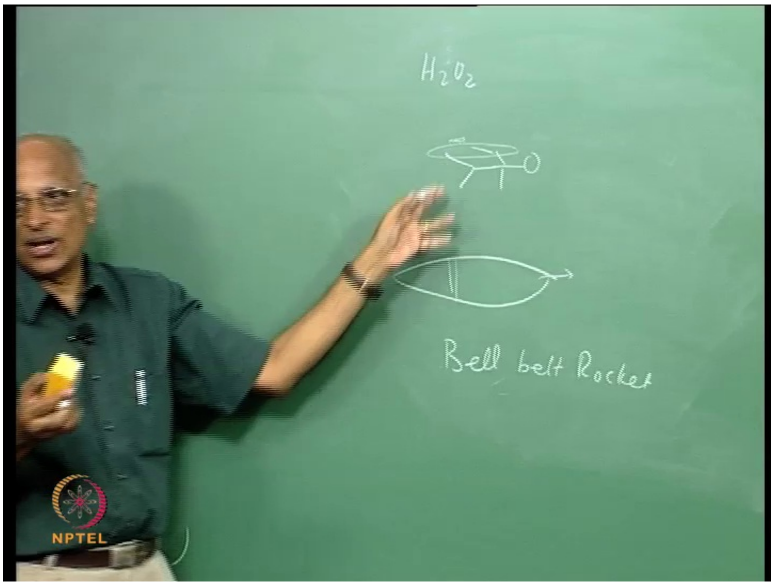

All what is done is you have a stabilizing device, like let us say a human being I show like this hands legs is like this, you put a stabilizing device on him, maybe make him little more streamlined, and maybe put a small monopropellant rocket over here, and whenever he want he switches on a rocket and he can go in different directions, and such type of sky diving or acrobatics is done during some of these carnivals like Olympics. I give a problem on this bell belt rocket.

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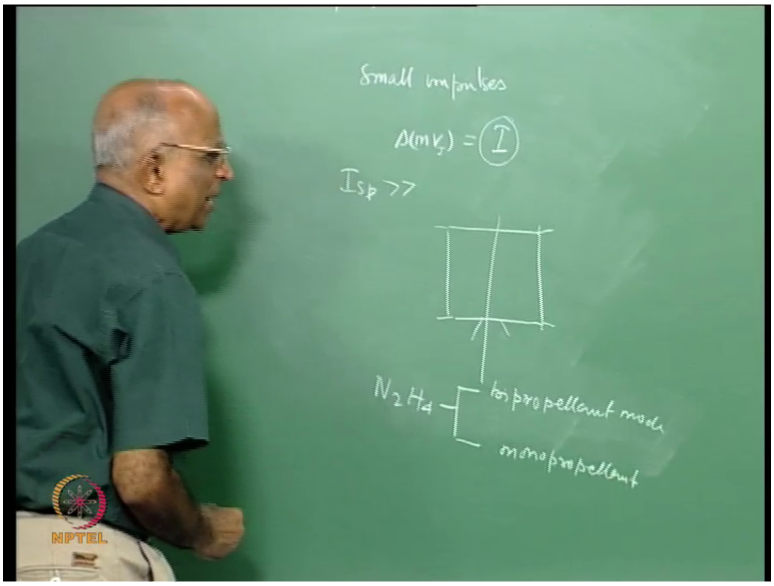

Monopropellant rockets can give small values of thrusts and impulses. What do you mean by small impulses? Maybe, change of momentum is impulse: mV_J = impulse. We can just pass a small amount of hydrazine and it gives me a small value of V_J, the V_J is much smaller than a bipropellant rocket. For a small pulse of mass we can get very small amounts of impulses. Why are small impulses important? Let us say we need to correct the perturbations in the position of a spacecraft. We have to supply a small impulse to correct it. We need a very small amount of impulse to effect change in momentum.

Though it is very useful for small corrections, we also would like to have higher value of specific impulse such as when if we want to push the spacecraft. If we want to take a satellite from one orbit to the other, we need to supply a steady value of thrust and need a larger value of Isp. Therefore, the question is, can we use hydrazine N_2H_4 both in the bipropellant mode as well as in a monopropellant mode?

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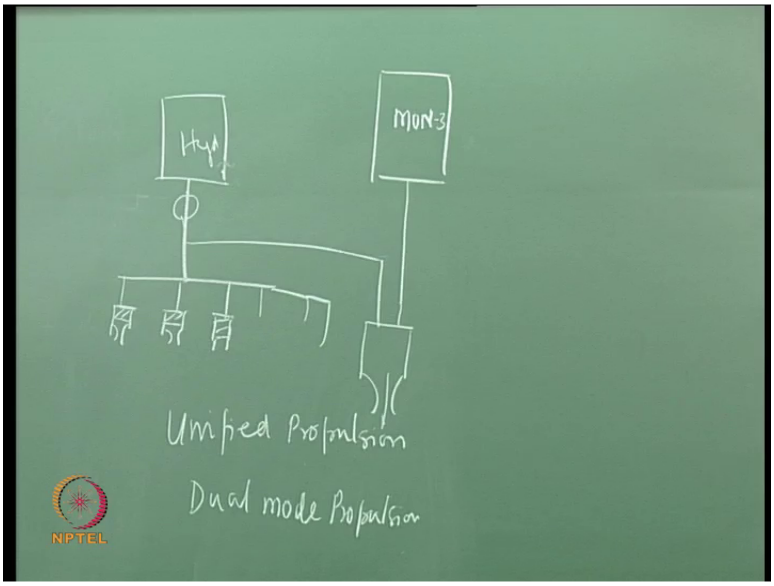

Let us again think in terms of a configuration. We have a hydrazine tank. The pressurized hydrazine is supplied through valves to a series of small rockets, which are all monopropellant rockets. All have catalyst bed in them, which can be used for small maneuvers.

And we also carry the oxidizer MON 3; you will remember MON 3 is something like N_2O_4 in which we add some amount of NO such that it is it has a lower freezing point. We supply this oxidizer along with the hydrazine to a slightly bigger rocket engine whenever larger impulses are required such as when we want to change the orbit. For small corrections we use hydrazine in a monopropellant mode. This is known as a unified propulsion. Of late, we do not see the word unified being used; it is referred to as dual mode propulsion. What does dual mode propulsion mean? Hydrazine is used as a component of a bipropellant in part of the mission and it is used as a series of monopropellant rockets in the other part. Well, this is the dual mode propulsion, but something even solids can give small impulses and this is reported at JPL.

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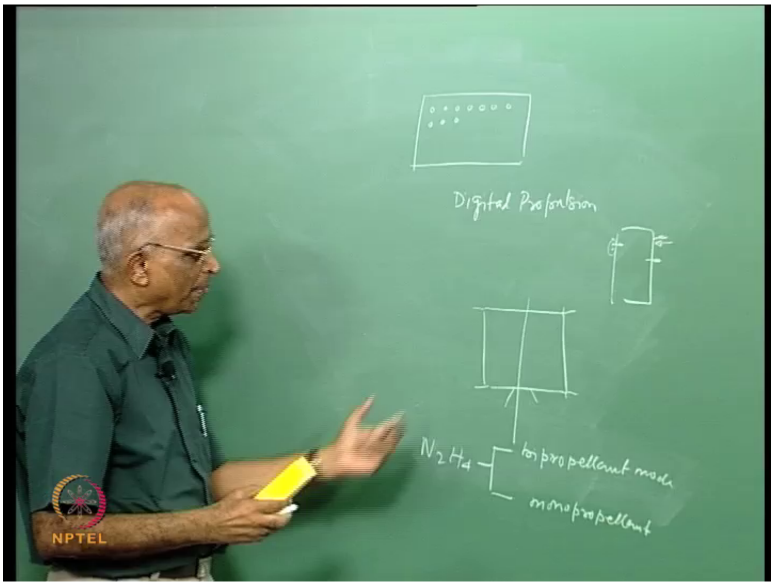

You have maybe on a silicon wafer small pellets containing micrograms of solid propellant, and you have resistor wire in incorporated in them. We have a number of them. Whenever, we want thrust we ignite a pellet and generate a small force and this is known as digital propulsion. We fire a digit that is required out of the large number of them. As you see the subject of propulsion especially, rocket propulsion is something in which lot of developments are possible.

All that we want is the spacecraft to be given some small force in vacuum. Therefore, we have a solid pellet which we fire and it gives the impulse in the required direction. You have something like digits, which you fire; it is known as digital propulsion. But what is conventionally used is the bipropellant rockets. Dual mode propulsion has been used; however, hydrazine with MON 3 creates combustion instability problems.

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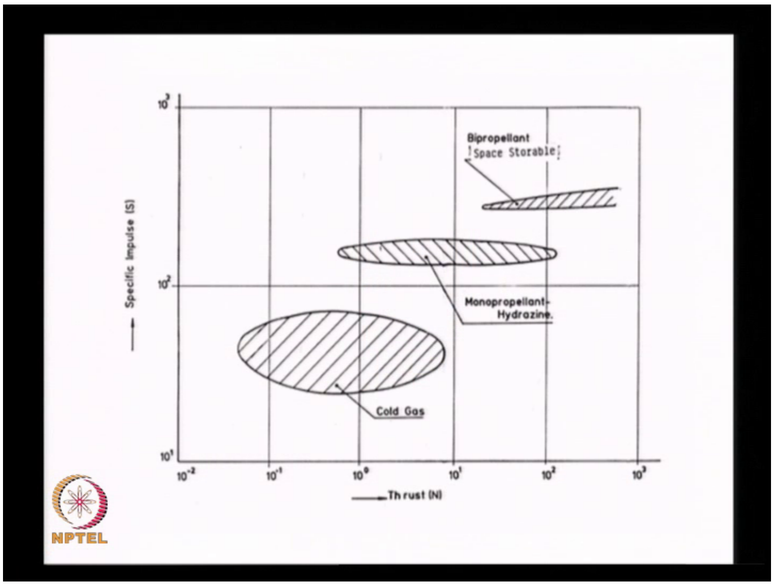

Well, this is all about monopropellant rockets. We have cold gas jets that give extremely low performance, monopropellant, which is still low but higher than cold gas propulsion. Liquid bipropellants have much higher values of Isp.

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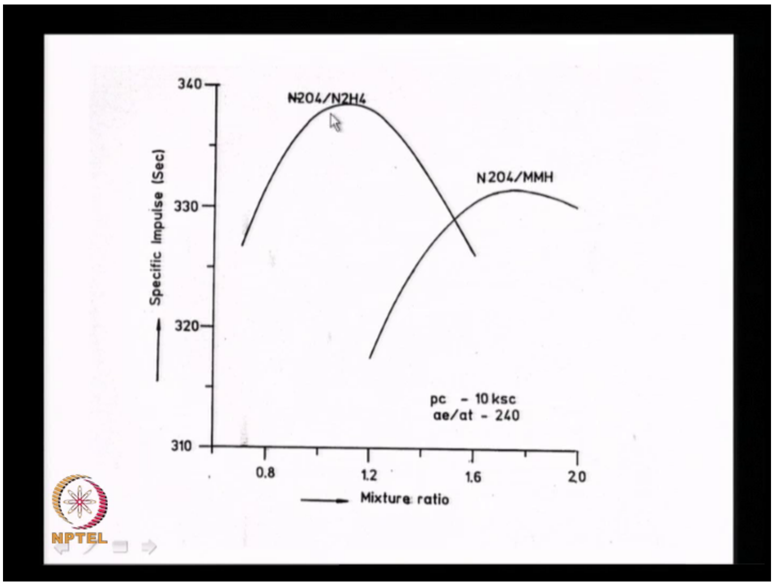

And as we discussed, in a bipropellant mode hydrazine N_2H_4 with N_2O_4 gives much higher performance than of MMH and N_2O_4. Fuel hydrazine is therefore desirable. Japan makes use of hydrazine with N_2O_4 for spacecraft propulsion. But we still have to understand about combustion problems associated with it.

I think this is all about monopropellant rockets. But to complete the subject of liquid propellant rockets we note that instead of monopropellant and bipropellant rockets, tripropellant rockets making use of three propellants are also suggested.

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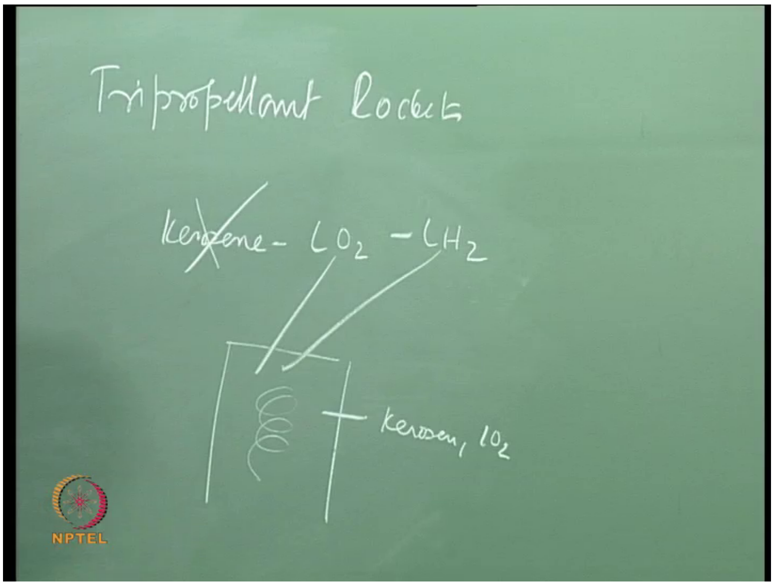

What are tri-propellant rockets? We have three propellants. We have kerosene and liquid oxygen and this propellant combination can be used for boosters; we also carry liquid hydrogen. And what happens is that we initially start burning kerosene and liquid oxygen together, and into this kerosene and oxygen we can also add little bit of liquid hydrogen which stabilizes the combustion. When the boosters stage is over, we cut of the kerosene and use hydrogen and oxygen and this becomes tri-propellant rocket. The advantage of a tri-propellant rocket is a single rocket can be made to go to space. It has still not been used though there is some interest in tri-propellant rockets.

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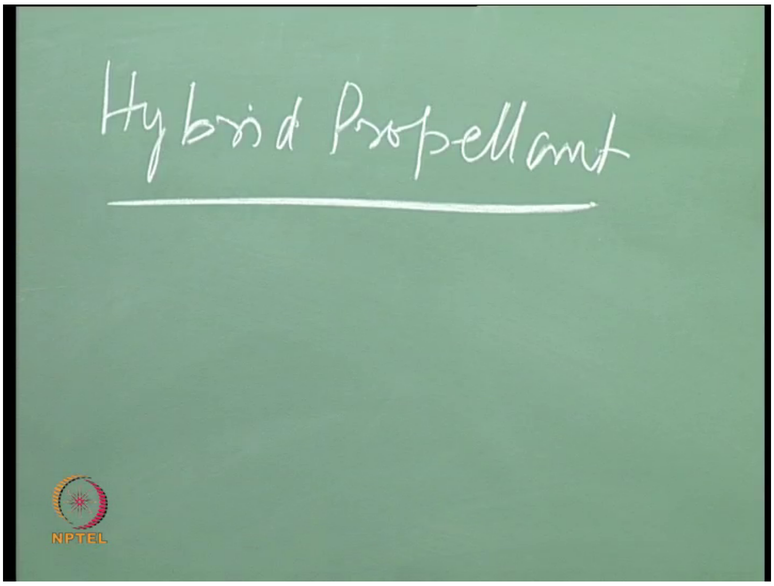

I think I should stop here. We have not done anything about hybrid propellant rockets. Before I start the next lecture on combustion instability, maybe I will spend a couple of minutes on hybrid rockets. It has not been very promising earlier. But of late, some private company known a Scaled Composites is using hybrid rockets for ferrying people to space as part of space tourism.

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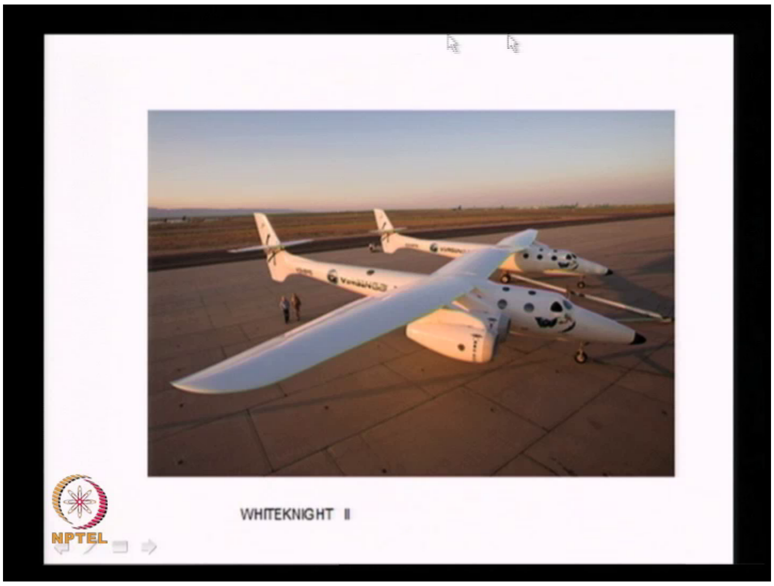

They uses an aircraft known as White Knight to take off from the ground with a space capsule powered by hybrid propellant rockets. This aircraft takes the space capsule to a height of 14 kilometers, from there the hybrid rockets propel the space capsule into a suborbital flight. The capsule comes back to Earth. Maybe, we will spend some five minutes on hybrid rockets in the next class and then get into the topic of combustion instability.