Rocket Propulsion
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Lecture No. # 26
Feed Systems for Liquid Propellant Rockets

We will start this new chapter on liquid propellant rockets.

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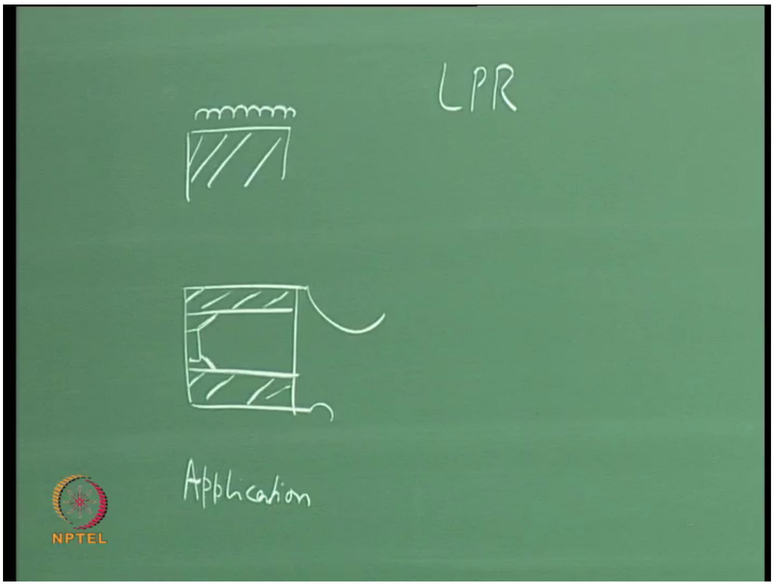

When we discussed solid propellant rockets, we had a solid propellant grain which burns at the surface, you had a flame near to the surface. And once a solid propellant rocket begins to burn, it is almost impossible to extinguish it. Once you ignite the grain, there is no way you can quench it, it continues to burn. Of course, there is some work done to see under what conditions you can stop the burning. And by rapid depressurization you can quench it, but this has not reached a stage of being applied for a rocket. Therefore, we say a solid propellant rocket, once it gets started, you cannot control it, it burns and burns, that is about it. Whereas, when we talk of a liquid propellant rocket, we have considered the different liquid propellants and we inject the liquid propellant into the chamber. We can always control it and therefore, there are certain advantages that liquid propellant rockets have.

But to get started with this liquid propellant rockets, I thought let us look at nature as we did examine it when we considered the theory of rocket propulsion.

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We talked of a small insect known as the bombardier beetle, you will recall. What did we tell at that time? This particular insect beetle is something smallish may be an inch to 2 inches in size. And it is somewhat heavy and we find it all the time at all places, it sort of unwieldy and it cannot fly that rapidly. And it is invariably attacked by insects. But it is harmless, it does not bite, it cannot fly much. We just pick it up on a piece of paper and throw it out whenever it flies in. One particular form of beetle, known as bombardier beetle, has been investigated for the last 10 to 15 years. And an such article came in the proceedings of the U S National Academy of Sciences in 1997. It is in volume 94. It runs over 5 pages from pages 1692 to 1697. It makes very interesting reading.

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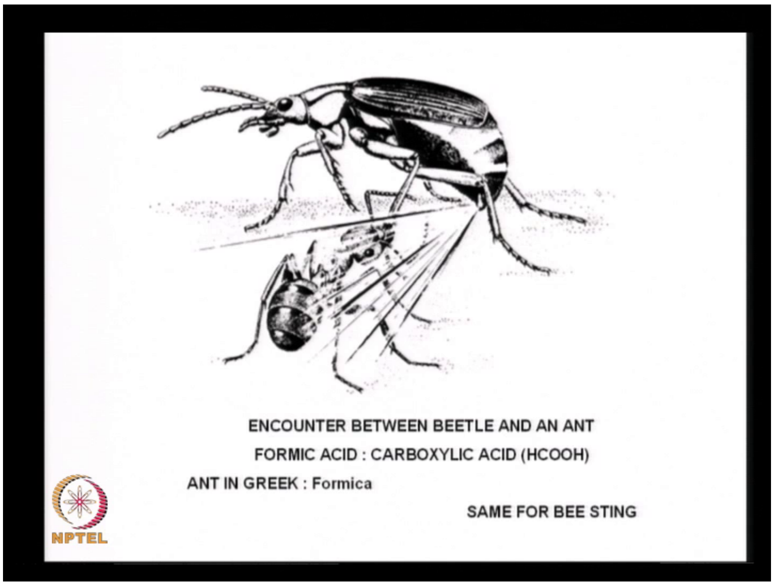

As I was telling you, this particular bombardier beetle is attacked by ants, and what does ant do? It stings. Why do feel a sting? It injects some formic acid into our system. Formic acid is something like carboxylic acid and that is why you feel a sting and that is the same as bee also stings. We feel pain because something is injected into us.

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In fact, the ant in Greek is known as Formica because when it stings us, it injects the formic acid into us. The ant also pesters this beetle by stinging it. And what mechanism does this beetle have to escape from it or to get rid of the ant? What it has is, it has one chamber in its stomach wherein it produces hydrogen peroxide. In the other chamber, it produces a fuel like hydroquinone, which is hydrocarbon. And whenever something attacks it flexes its muscles and pushes the hydrogen peroxide and hydroquinone into a third chamber of its stomach. This third chamber is coated with some enzyme, which is catalyst.

Enzyme is something you know like even when we prepare the batter for making idly you know we put some yeast into it and it foams. We have this enzyme coated third chamber, wherein the hydrogen peroxide and hydroquinone are mixed together. And in the presence of the catalyst, the hydrogen peroxide and the hydroquinone they react and form hot gases and the bombardier beetle squirts it, squirts it on the ant and therefore, the ant gets driven away. And this is nature's way of protecting the bombardier beetle. It is a very unique evolution of species. All the species if you look at Darwin's theory has come through some hierarchy, but it seems this particular insect seems to be different from the other species, but it is very illustrative of something, which I will now tell you.

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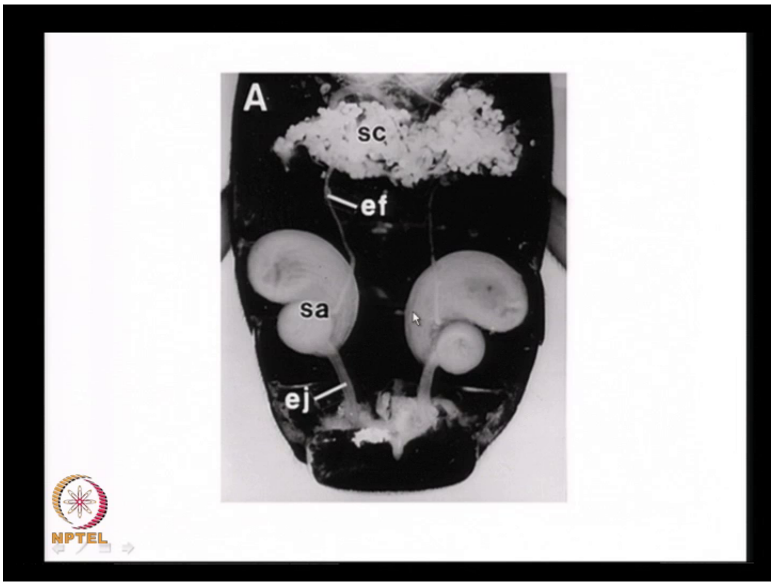

Let us go ahead and see what really happens. In one stomach H_2O_2, hydrogen peroxide. Is formed. In the other chamber, hydroquinone, which is the fuel is formed. When the bombardier beetle wants to squirt hot gases out of it, it pushes this hydroquinone and hydrogen peroxide into the third chamber, which is coated with enzyme, and it chemically reacts, to form hot gases, which is squirted out.

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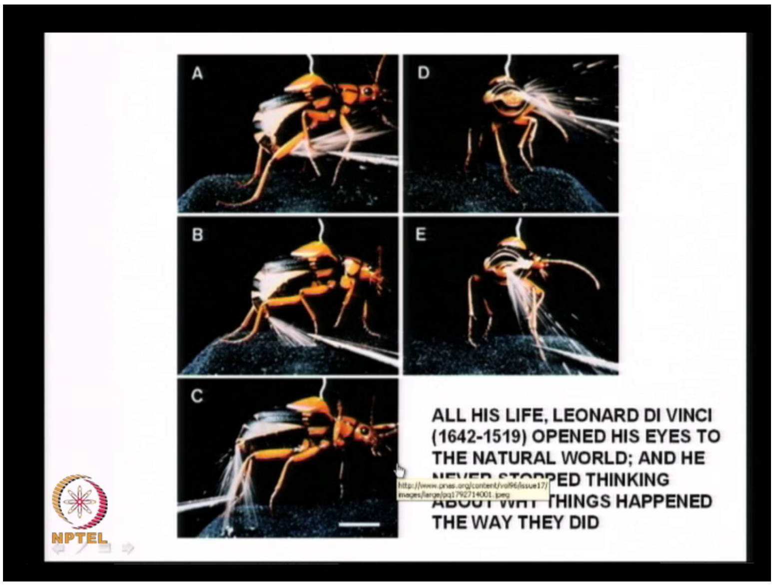

Well, the experiments which I told you of at the National Academy of Science are one of a number of experiments done on a bombardier beetle. They take something like a fork here, and they try to place it mimicking the ant and immediately it squirts out the hot gases. They put this particular intrusive fork over here, mimicking the ant and it pushes the gas. Therefore, it is able to squirt the hot gases in the different directions. You put this fork here and it squirts out the hot gases in this direction and so on.

This feature reminds us of Leonardo Di Vinci. You know he was the painter, who lived in the late sixteen century. And you know he made different sorts of things. He sort of looked at the birds flying, he tried to construct an airplane, he made bridges of course, he was a famous painter, you will remember the Mona Lisa painting. And all throughout his life and we should remember this, he opened his eyes to the natural world and he never stopped thinking about why things happened the way they did. And so also may be if one had seen this insect with interest long back, maybe we would have seen something like an oxidizer and fuel injected into a chamber and a liquid propellant rocket long long ago.

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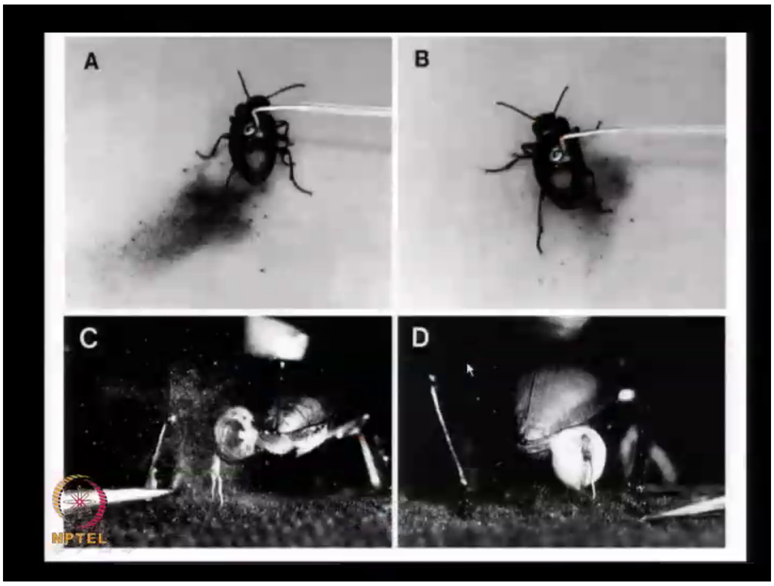

And if you get to see what really happens in the case of the bombardier beetle? This is again about squirting hot gases. And squirting is in different directions.

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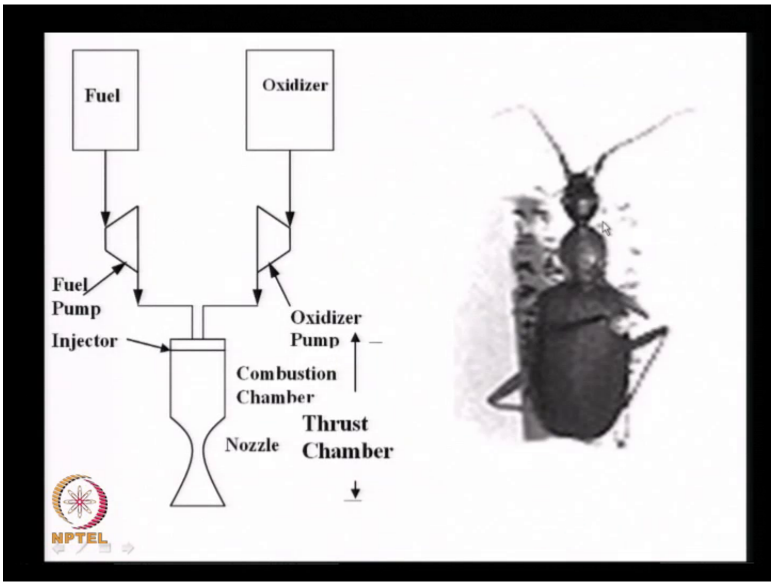

And if we were to apply the principle of what the bombardier beetle does to a device; we have a chamber containing oxidizer, a chamber containing fuel, a third chamber in which it reacts and forms hot gases and squirts it out. Well, a liquid propellant rocket consists of a fuel in a tank, an oxidizer in a tank; you pump the fuel and the oxidizer into a chamber. And how do you pump it? You pump it at high velocities through an injector may be you break it up into fine droplets; you vaporize it which is all happening in the third chamber of the bombardier beetle. And then you have combustion taking place and you expand through the nozzle. We have an injector and a combustion chamber. And the nozzle is what creates a thrust. The combination of injector, chamber and nozzle is also known as thrust chamber. And therefore, a liquid propellant rocket consisting of all these gadgets is nothing very much different from the bombardier beetle, which is there in nature.

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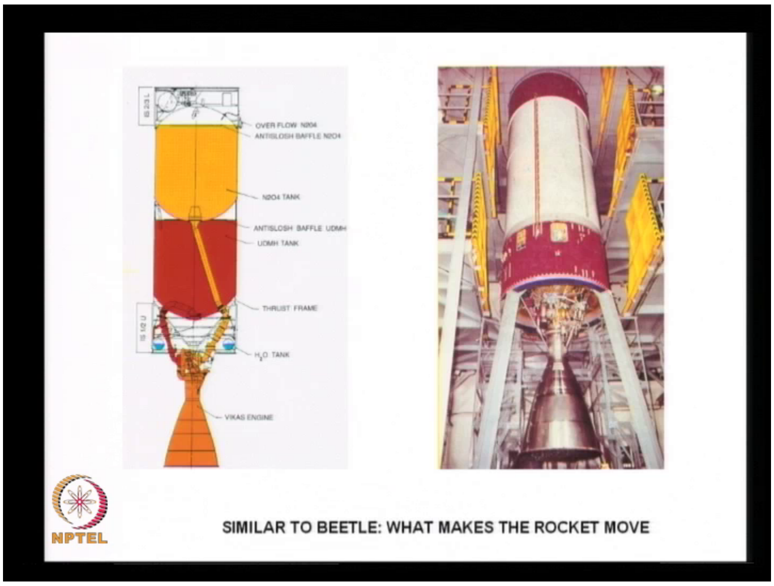

And therefore, I think we should learn to look at nature and understand more about nature. And say now we come to a large rocket, what does the large rocket consists of? This consists of N_2O_4 as the oxidizer and UDMH as a fuel. And what is done is you squirt it out through from the tank by a pump; you force the N_2O_4 into the chamber, you force the UDMH into the chamber make it burn over here, expand the burnt products through the nozzle and this is what a liquid propellant rocket consists of. We see the oxidizer N_2O_4 tank, the UDMH tank at the bottom, you have a series of pumps, which push the propellant into the chamber and you get the thrust. Well, this is the liquid propellant rocket, which is much akin to the mechanism by which the bombardier beetle generates hot gases.

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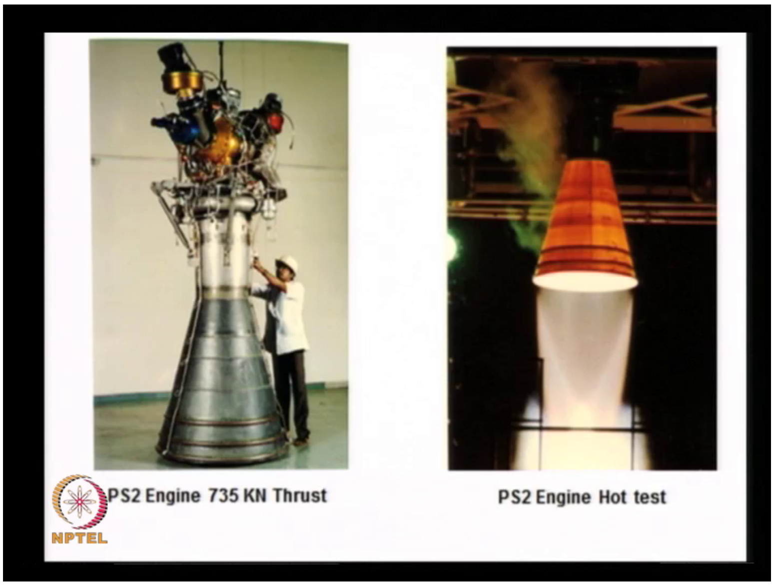

Let us take a look at few liquid propellant rockets. Well, this is the thrust chamber of the liquid propellant rocket engine, which was seen earlier. It is taller than this man over here, this is the cylindrical combustion chamber, this is the pump above it, this is the nozzle and this slide shows the rocket firing.

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Well, the same engine assembled together as a rocket stage is shown with large tanks to carry fuel and oxidizer. We have the oxidizer tank over here, I have the fuel tank, I have the pump over here below the tanks that push the fuel and oxidizer it into the chamber and it generates thrust using expansion in the nozzle.

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Let us take one more example. If instead of using N_2O_4, we use liquid oxygen and in place of UDMH we use liquid hydrogen.

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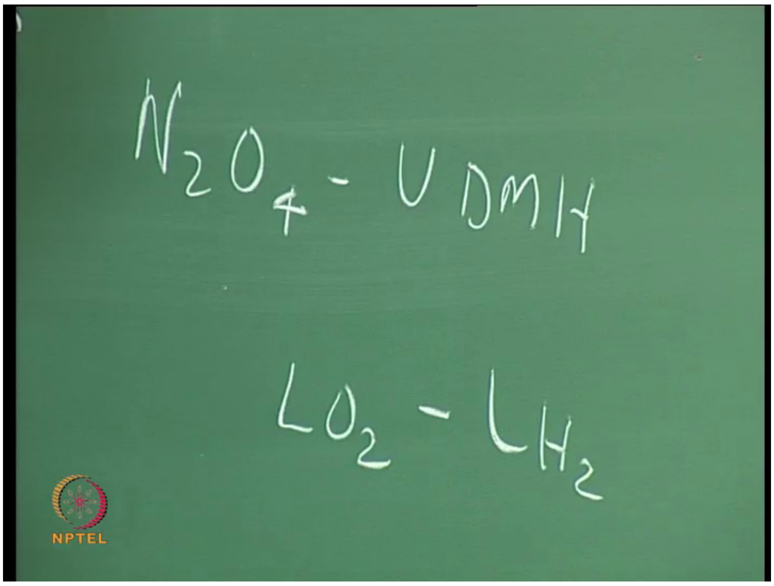

The oxidizer in the earlier case was N_2O_4 and the fuel was UDMH. We also talked in terms of fuel could be liquid hydrogen; the oxidizer could be liquid oxygen. And when we carry the propellants like liquid oxygen and liquid hydrogen well, liquid hydrogen is not very dense and we need a larger tank. We have this liquid hydrogen here, we have liquid oxygen here, a pump over here which pushes them into the combustion chamber where it burns. This is what a cryogenic liquid propellant rocket is like.

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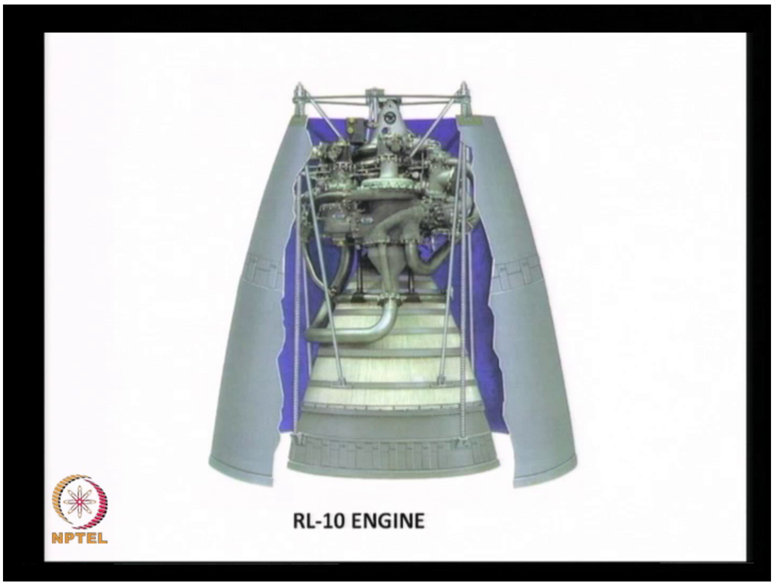

Well, this slide shows a cryogenic propellant rocket known as an RL 10. This was the first cryogenic propellant rocket to be developed and this was in United States. This was in the period 1960s and here again you have the pump pushing the liquid hydrogen and liquid oxygen into the combustion chamber, which is here. And you see the nozzle is a relatively large portion of the liquid propellant rocket, I think this gives us some feel for the sizes of the different constituents in a liquid propellant rocket.

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A UDMH / N_2O_4 rocket is shown in this slide. This shows the chamber, the nozzle and these are the pumps supported above the chamber.

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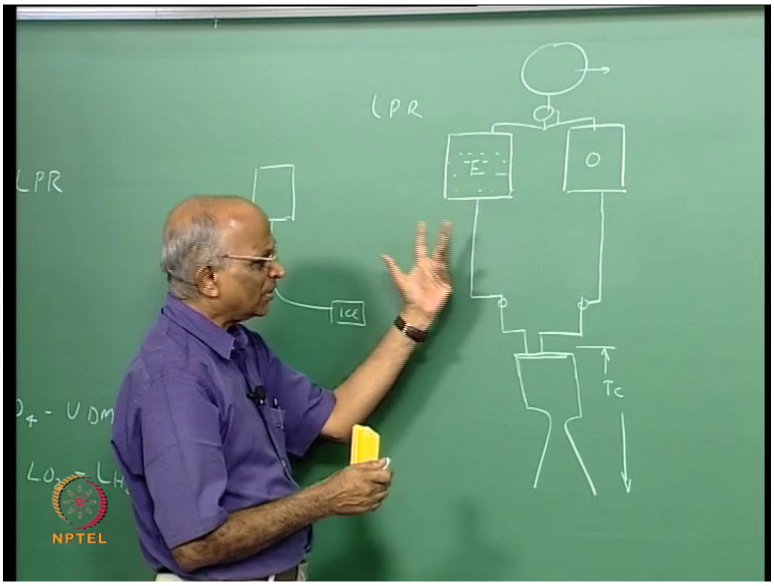

Therefore, what is it that we could infer from the few examples, which we saw? We need a fuel tank, an oxidizer tank, a pump to increase the pressure from low value at the tank to a significant value at the supply point to the chamber. At this pressure, we must be able to supply the required quantities and break up the liquid into droplets or particulates.

That means, we need something like an injector, which allows the required quantity of propellants to come into the chamber and to break it into droplets. And we have the chamber wherein reaction takes place and then I have this huge nozzle wherein we expand the gases. Well, this becomes the liquid propellant rocket. We have to put some flow control valves here to start the supply and stop of the propellants whenever we want. And maybe we have let say the liquid fuel over here, the oxidizer over here and here you have the thrust chamber wherein high pressure gases are generated by combustion and thrust is developed.

Now, you may immediately ask a question. Why do we need to have pumps in the first place? After all we have supply of the fuel and why not we supply it directly like when we do an experiment in our lab using diesel combustion and an internal combustion engine. We could have something like an overhead tank just as we have a diesel tank for an experiment and we directly connect it to the IC engine. Why not we directly connect the fuel and oxidizer and may be to push it through using a gas bottle here containing high-pressure gases?

And if we put a pressure regulator in which case we can reduce the pressure of the gases pressurizing the liquid to any level that we require. We have a reduction mechanism for pressure through the pressure regulator. We have a high pressure source of gas so that we could do with a smaller gas bottle. We pressurize the propellants to the required high pressure and send it into the chamber. Therefore, we need not always have a pump, but to be able to understand whether pumps are really required, we need to do a little more exercise. Let us again re-examine the issue.

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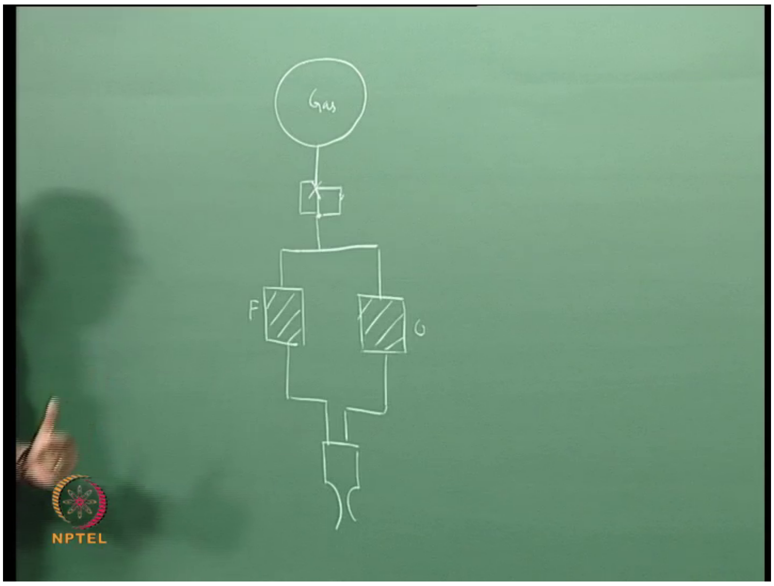

We have something like a gas bottle, which stores gas at high pressure. We have a pressure regulator downstream of it and what does the pressure regulator do? Maybe from high pressure of the stored gas at maybe 30 MPa, maybe 300 bars to 400 bars, since we do not want such high pressures and we want much lower pressure maybe 10 MPa or 1 MPa. Therefore, we put a pressure regulator, which will reduce the pressure by regulating the opening through a spring, it is a feedback control to give constant supply pressures. And then we connect this gas to the fuel tank and to the oxidizer tank, which contain propellants and then we supply them into the combustion chamber at the required pressures.

We are talking of having a high-pressure gas bottle and regulating the pressure to a lower value to push the fuel and oxidizer into the combustion chamber. Well, this becomes something like we use a cold gas, a high pressure gas and this what we call as a regulated gas pressure fed system.

We started with a pump. Let us see under what conditions we would really require a pump. Under what conditions can we use a regulated pressure system? Well, it may not even be necessary to have a gas bottle and the regulator and we can still think in terms of a simpler scheme or configuration.

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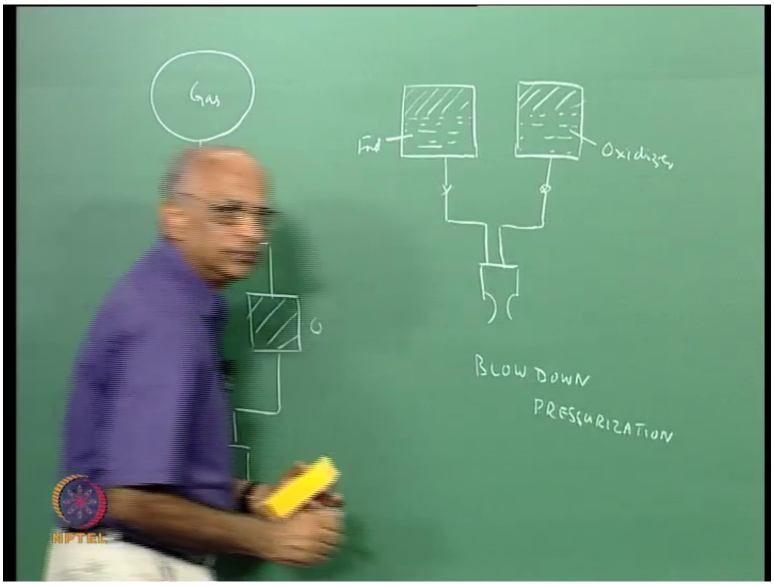

We could take a tank as such may be a fuel tank, may be an oxidizer tank and do not have to fill the propellants fully in the tank. Let say this is the fuel tank with liquid fuel filled in to a certain height. We have the oxidizer tank with the liquid oxidizer over here. We fill high pressure gas in the free volume over the liquid and have a valve downstream of the tank. Once the valve is opened, immediately propellant flows. When we want to stop the flow of propellants, we close this valve. And therefore in this system, the gas is contained in the tank itself and it blows the propellant into the combustion chamber. This scheme is known as a blow-down system.

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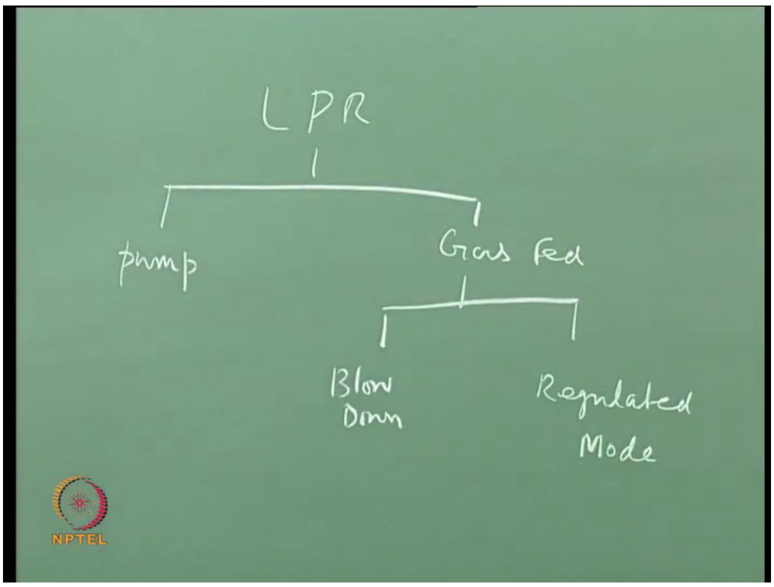

In the case of the liquid propellant rockets, we need to supply the propellants to the combustion chamber. We started looking at the beetle and told that a pump may be required. But we also told that may be a gas, a cold gas at high pressure can possibly be used. This gas can be directly filled, and what will happen when it blows down? The pressure keeps decreasing and therefore, the thrust keeps decreasing. Whereas, if we give something like a regulated gas we maintain constant pressure over here and therefore we get a constant thrust.

Therefore the gas fed, high pressure gas fed system could either be in a blow-down mode or in a regulated mode. For instance, if you have a satellite which is orbiting in space and we were to use liquid propellant rockets for its control, which one would you prefer?

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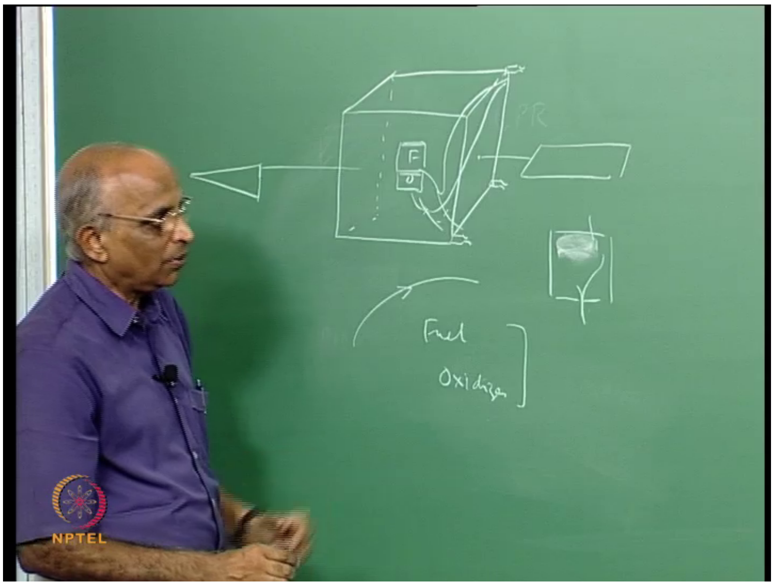

The satellite has a box-like structure. It has solar sails protruding over the box structure. And when the light falls on the solar sails, you know it creates pressure so we have booms to balance this pressure. We will study this method of propulsion using sails and pressure during the end of this course. You have to balance the pressure from the sunlight falling on this; you put something like a balance over here such that it does not get tilted over here. Then to control the attitude and orbit, we wanted small rockets placed over the different faces of the box. And how do we supply propellant to these small rockets? Inside this structure we have a propellant tank and oxidizer tank; at the bottom of this oxidizer tank we have the fuel tank may be in the common bulk head configuration.

That means we have a single connection from the tank for the fuel and oxidizer. We could introduce some gas pressure over the liquid column in the tank. We could have the liquid lines to the different rockets with a flow control valve on each of the rocket. Whenever we want a particular rocket to operate, we open the particular valve and it fires. And this is the model of this particular blow-down mode. And if you are going to see what is inside the box, we have among the electronic packages, the fuel tank and oxidizer tank. And these red knobs correspond to the thrusters or liquid propellant rockets.

And what is done is, whenever you want the rocket to be fired you just open the valve of the particular rocket. The tank is already pressurized. The liquid fuel and liquid oxidizer flows into these thrusters and they generate thrust and that is how you control the spacecraft. This is how the liquid propellant rockets are used in satellites. But there is a problem. Whenever we have fuel and oxidizer and a spacecraft is revolving in a given orbit at a constant velocity, we found that in the frame of reference of the satellite it has a centrifugal force, which is balanced by the gravitational field. Therefore, it is in a state of weightlessness in its own frame of reference and it creates new problems.

Therefore, we have to see under weightlessness how do we supply the propellant? We will take it up after some time. That means if I put a propellant in a tank that the propellant may sit on top, it may not really come at the bottom. And when I pressurize it with the gas, the gas may come out while the liquid may not come out. That means supply of a propellant when we are in a state of weightlessness is again going to be a problem. May be we will take a look at it later on. But right now, let us take a look at what constitutes, let say a gas fed system, which can either be in a blow-down mode, a regulated mode and then let us come back to the pump.

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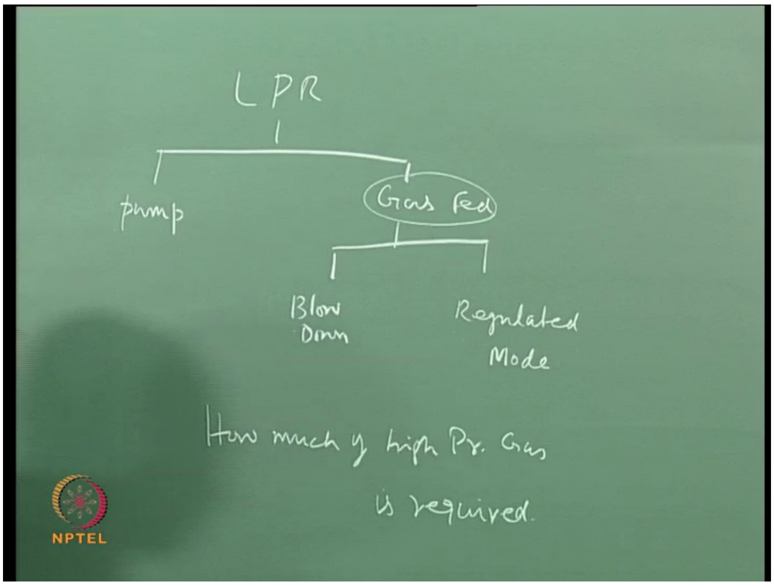

To be able to do this, let us first try to estimate how much gas, how much of high pressure gas is required. The first thing we have to determine is the quantity or rate of supply the propellants to the chamber for a given value of thrust. We must know what must be the mass flow rate of propellants and how do we calculate it? Let us refresh ourselves.

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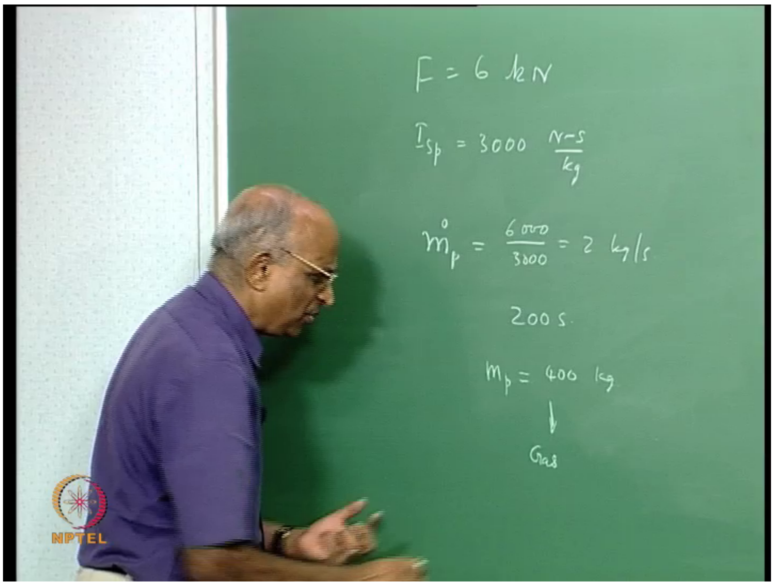

We suppose the thrust of the rocket as 6 kilo Newton. Let say the specific impulse of the rocket is equal to 3000 Newton second by kg. Then we know the mass flow rate of total propellant fuel and oxidizer is equal to 6000 Newton divided by 3000, which is equal to 2 kg per second. If the duration of operation of the rocket is 200 seconds let say, we take a small firing rocket for a small time of firing let say 200 seconds, then I need to supply a total mass of 400 kg during the 200 seconds. We talk of 6 kilo Newton, 6000 Newton thrust rocket with a specific impulse of 3000 Newton second per kg requiring a flow rate of 2 kg per second with the total mass of propellant being 400 kg. We want to know how much gas is required, how much mass of gas do we require to expel 400 kg of propellant. If the gas requirement is large, well the rocket cannot takeoff.

How do we estimate it? We again follow the same figure, but now let us simplify it. Let us simplify this and say well I have gas pressure over the propellant and we also told that gas can be stored at fairly high pressures.

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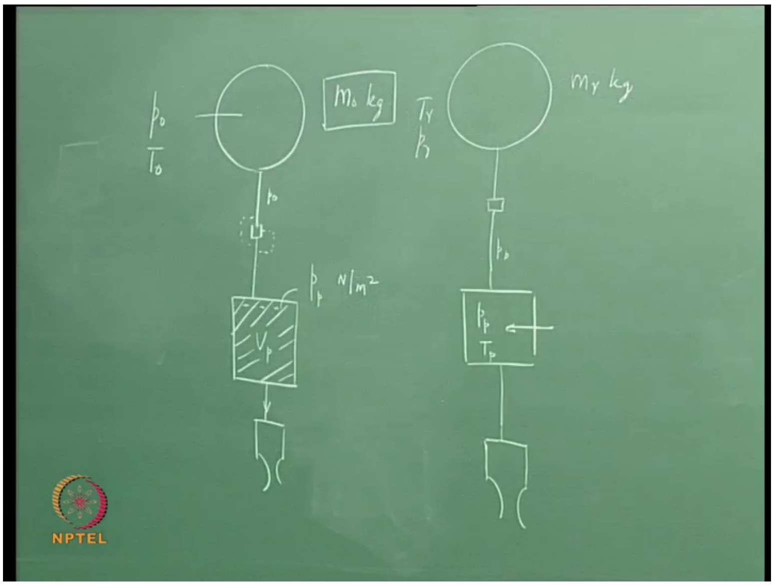

We have a gas bottle. It contains let say m_0 kilograms, m_0 kilograms of air or gas. This is what we are required to find out in order to expel the propellant from the tank into the chamber. Let say it is at a high pressure P_0 and at the ambient temperature T_0 because we do not know at this point in time whether a hot gas or a cold gas is to be preferred. May be when we derive the expression, it will be also clear to us what type of gas is required and what must be the temperature of the gas.

What is it that we do from this high-pressure gas source? We put a pressure regulator here and reduce the pressure from the value of P_0 and it must communicate the two tanks. We put the two tanks together as one. Let say the total volume of propellant to be expelled is V_P and this is the volume that must be supplied to the thrust chamber.

Let us say the pressure at which we would like to supply is a pressure p_p, p_p let say in Newton per meter square or Pascal. And we have to reduce the pressure from P_0 to p_p in this type of regulator. Now we want to find the value of m_0 kg. It is a straightforward thermodynamic problem, but before doing this problem it is also required for us to put the parameters required to solve the problem.

Let us do it as a general derivation. The quantity of propellant liquid, which is to be supplied at constant pressure p_p is V_P meter^3. After the volume is expelled at constant pressure p_p, some quantity of gas at pressure p_r would be left behind in the gas bottle.

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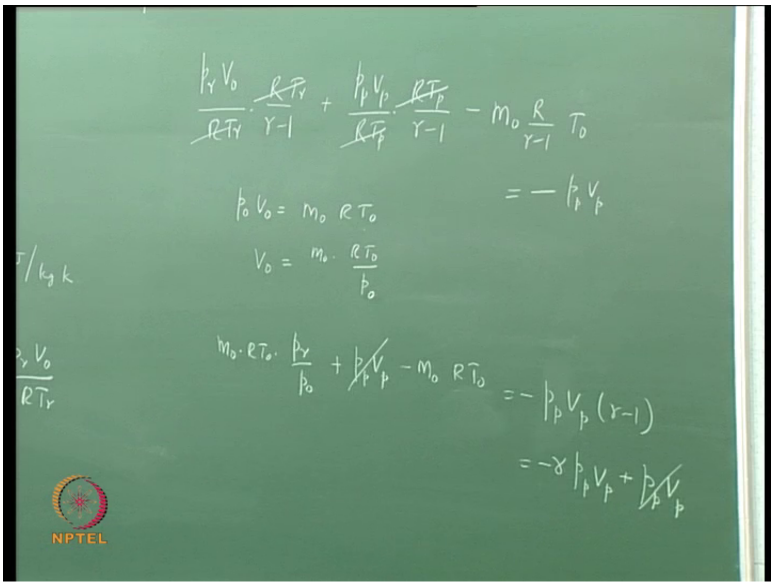

At the end of operation, let assume the m_r kg of gas is left in the gas bottle. Let the temperature of this residual gas be T_r and the pressure would be p_r. At the end of the depletion process, the volume occupied by the propellant in the tank will be filled with the gas at the pressure p_p. We have the same tank, V_p m^3 of the propellants are expelled and the volume it is now filled with gas. And since we have the regulator, we have reduced the pressure to p_p. When the propellant has just got out of it, it will be filled with gas at a pressure p_p and the temperature T_p, which is the temperature of the propellant. Since, it is a slow depletion, the gas reaches the temperature of the propellant T_p.

Let us make the figure complete. We have exhausted or pushed out, a volume of propellant V_P of propellant and we are left with the gas occupying this volume in addition to this volume of gas in the gas bottle. This is the final condition of the gas. We want to write an expression and determine the value of m_0 kg.

How do we do this problem? Let us write try to write an equation for the expansion process of the gas and determine the value of m_0.

Let us say that the system does not have any heat transfer taking place i.e., the tanks are fairly well insulated, gas bottle is insulated there is no heat transfer taking place. And therefore, we ask what is the work, which is done by the gas in pushing out a volume V_P of the propellants.

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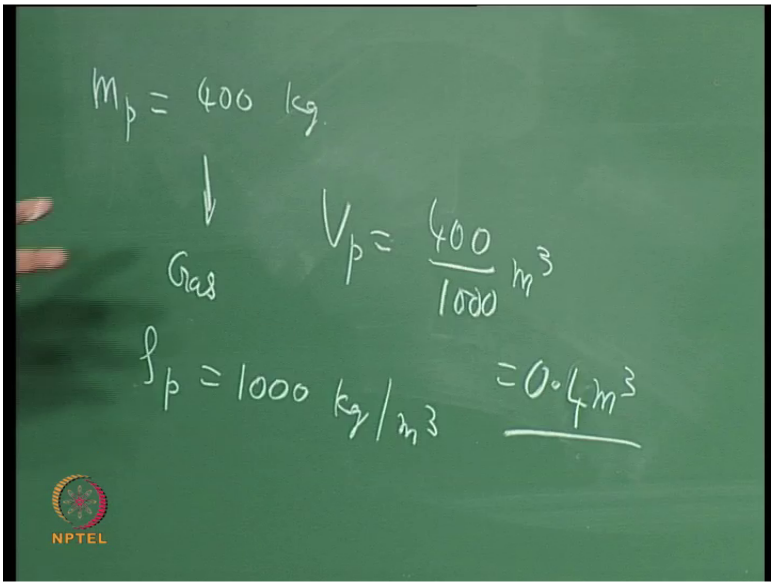

Let us calculate V_P for this particular problem, V_p, if I take the density of the propellant to be same as water, density is equal to 1000 kg per meter cube that is the density of water 1 gram per cc. And therefore, the volume V_P over here is going to be 400 divided by 1000 meter cube which is equal to 0.4 meter cube. In other words, for this rocket we have to get rid of or expel 0.4 meter cube at a given constant value of pressure.

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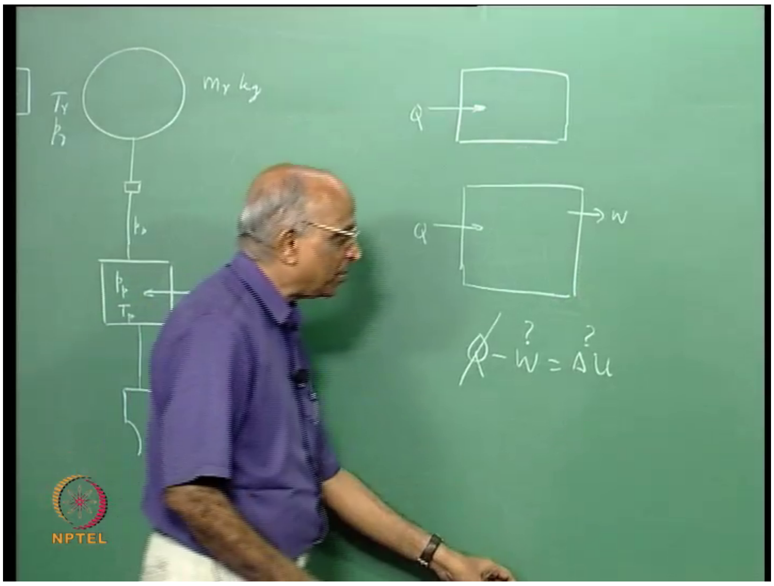

We consider the system of the high pressure gas. The initial state of the gas over and the final state are known. The gas has moved from the bottle and occupied the propellant tank. We note there is no heat transfer; Q is zero and the expansion process of gas is adiabatic. During the expansion, the system does some work at the boundaries by expelling the propellants at constant pressure. We can write Q minus W is equal to the change in internal energy for a system. Nothing is getting in, some work is being done and that change is what is the internal energy. We need to find out the value of W and the value of change in internal energy.

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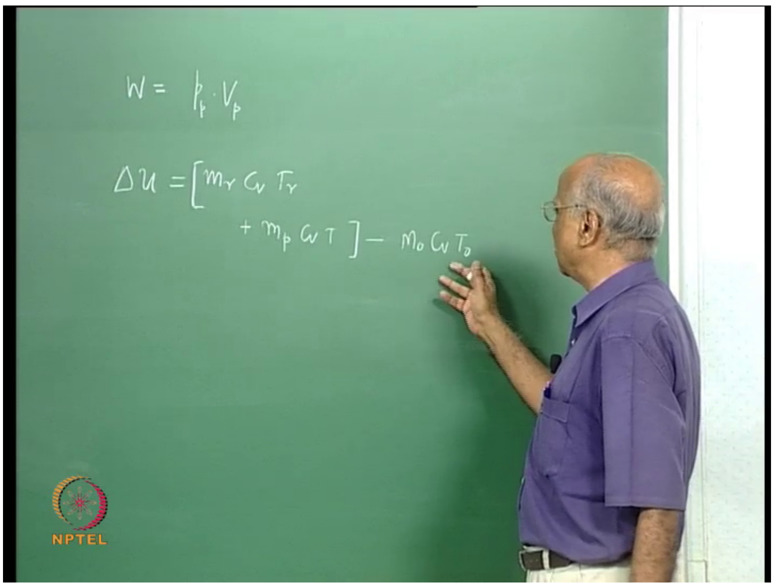

Let us write the expressions for these two. The work done by the gas is in expelling the liquids. Well, we have a constant pressure, which is applied over here during the displacement V_P, the work done is equal to p_p, the pressure into volume of the liquid V_p. Is it ok? What is the change in internal energy? It is final minus initial value of internal energy. Well, finally, I am left with m_r of the gas over here; we know that du/dT where u is the specific internal energy and T is the temperature is C_V. And dh/dT = Cp. Since we are talking of internal energy therefore, u is equal to C_V into T. And therefore the change in internal energy is equal to the final gas m_r which is available in the gas bottle into C_V into T_r. This corresponds to the final mass which is left in the gas bottle; we say it is at a reduced pressure and the reduced temperature because it has expanded. Some gas comes over in the volume originally occupied by the propellants, which is the m_p into C_V into T_P. The final value of internal energy is the sum of these two internal energies. We presume that the volumes of the lines over here, plumb lines, are very much smaller and can be neglected. And what is the value of the initial internal energy minus the final value? What will be the initial value of the internal energy of the gas in the gas bottle? It is m_0 into C_V into initial temperature T_0. The work done − W is equal to delta U i.e., the change of the internal energy. W represents the work done by the system.

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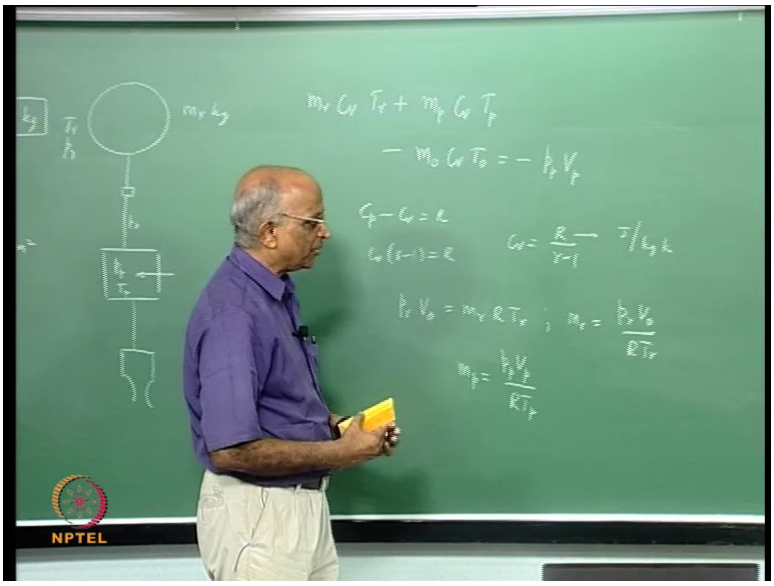

We use this part of the board. We therefore have $m_r \times C_V \times T_r + m_p \times C_V \times T_p - m_0 \times C_V \times T_0 = - W$ and $W = p_p \times V_p$. Is it all right? Q minus W is equal to the change in internal energy. We want to solve this equation, to be able to solve this let us see what C_V is, we know Cp − Cv = the specific gas constant R. And therefore, Cv $(\gamma - 1)$ = R into gamma or Cv = $R/(\gamma - 1)$. The specific gas constant has units of Joule per kilogram Kelvin and Cv also has units of Joule per kilogram Kelvin.

Now, what is the value of m_r? From the gas equation, we have $p_r \times V_0 = m_r \times R \times T_r$. Or rather I can write the value of the final mass after expansion left over in the gas bottle is equal to $p_r \times V_0 / (R\ T_r)$/ Similarly, we can write an expression for $m_p = p_p \times V_p / (R \times T_p)$.

We need to find the value of m_0 therefore, let us not touch this. Let us substitute these two values of m_r and m_p and the value of Cv in this expression and try to get the value of m_0. Let us say m_r is equal to $p_r \times V_0 / R\ T_r$ and Cv $= R/(\gamma - 1)$ and similarly we get $p_p \times V_p / (RT_p)$. We get the value of m_0 into $R/(\gamma - 1) \times T_0$ and equal to minus p_p into V_p over here.

Now we find that $R\ T_r$, $R\ T_r$ cancels; $R\ T_p$ and $R\ T_p$ cancels. And now if we were to simplify further we take gamma minus 1 on the right hand side because all the three have $(\gamma - 1)$ and therefore we get $p_r V_0 + p_p V_p - m_0 \times R\ T_0 = -(\gamma - 1) \times p_p V_p$. $p_p V_p$ cancels on both sides. With $V_0 = m_0 RT_0/p_0$, and $mRT_0 - p_p V_0$ simplifies as $m_0 \{RT_0(1 - p_r/p_0)\}$

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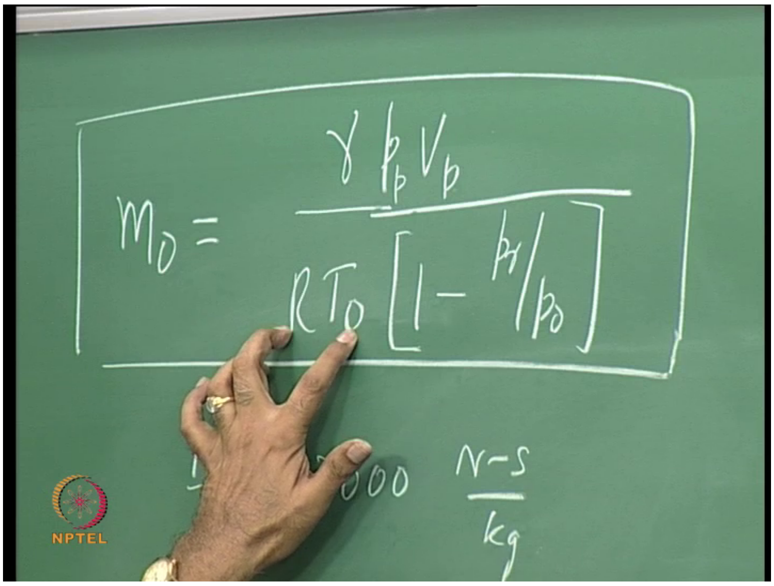

We are left with $\gamma\ p_p\ V_p$ on the left and hence mass of gas $m_0 = \gamma p_p V_p/\{RT_0[1 - p_r/p_0]\}$. This was done by collecting the similar terms. We get $R\ T_0$ which will come in the denominator. We have in the numerator the value γ on the right hand side into P_p V_p. In the term R T_0 we have $(1 - p_r / P_0)$. Please check how we come to this expression.

Now, we wish to examine under what conditions it holds good. We say had the process being isothermal, what would be gas that was required? m_0 will be equal to $Pp \times Vp/ RT_0$ because it is an isothermal process.

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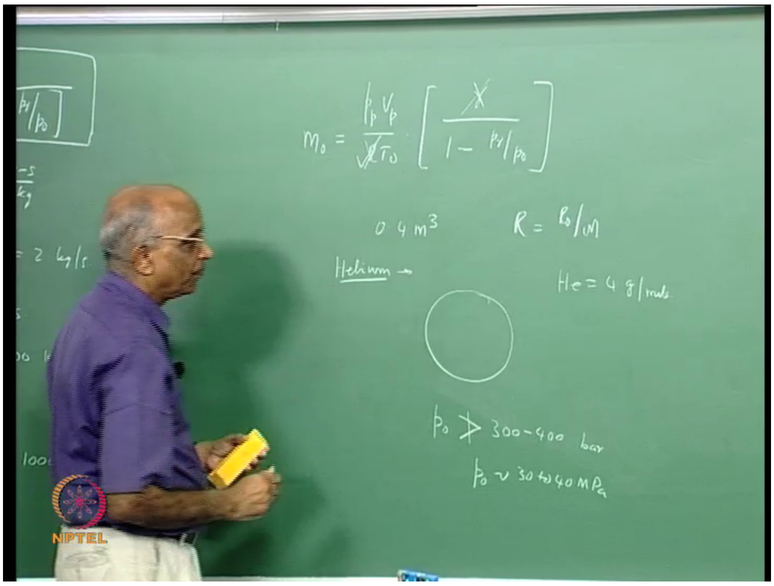

Therefore, what happens when gas is expanding and that also irreversibly? Instead of a mass of gas under isothermal expansion of p_pV_p/RT_0, we have an amplification taking place by $\{\gamma/(1 - p_r /P_0)\}$. We write p_p V_p by R T_0 because m is equal to pV by R T_0 and temperature is a constant for an isothermal process. The term in brackets is the multiplication factor for the actual mass of gas required.

Now, we want to find out may be for this engine, which we said is 6 kilo Newton the mass of the gas which is required. Let us go through this example and then we can extend it for different pressures and different thrust. Let say in this case the volume is equal to 0.4 meter cube. How much gas do we require? Well, this expression also tells us, what is the type of gas, which we require? Do we require a light gas or a heavy gas? Can we all infer something from the equation? Should we pressurize the initial volume with a high molecular gas, low molecular mass gas or at a high temperature or under what conditions should I do? All what I can tell you is the value of P_0 is limited because I need a gas bottle which can hold certain pressure and that pressure cannot be greater than about 300 to 400 bar. Because beyond that to make something hold such high pressure gas is difficult and the mass of the bottle goes up. Normally the value of P_0 is around 30 to 40 MPa.

How can we choose the other parameters like gamma, R and temperature, which conveys the type of gas which is required? We do one more exercise let say R is equal to universal gas constant divided by the molecular mass; 8.314/ molecular mass. If the molecular mass of the gas is smaller, we get a very large value of R. If we get a large value of R, we can have a smaller mass of the gas. Therefore, this immediately tells me the lighter the gas the better it is. Hydrogen is the lightest with a molecular mass of 2 gram per mole; whereas helium has a molecular mass of 4 gram per mole. But hydrogen is very flammable. Therefore, invariably we would like to choose helium, which is a light gas for the pressurization. You may observe that the expression is able to tell us what we are looking for.

But helium has large volume of gamma 1.67 compared to air or preferably of nitrogen of 1.4. The value of 1.67 to 1.4 is in the numerator whereas R could be something like 4 and 28 seven times more in the denominator. Therefore, we choose a light gas for pressurization. But this expression also tells us a higher temperature is suited because higher temperature means we have a smaller value of mass of the gas. Rather than choose a cold gas, a higher temperature gas is advantageous.

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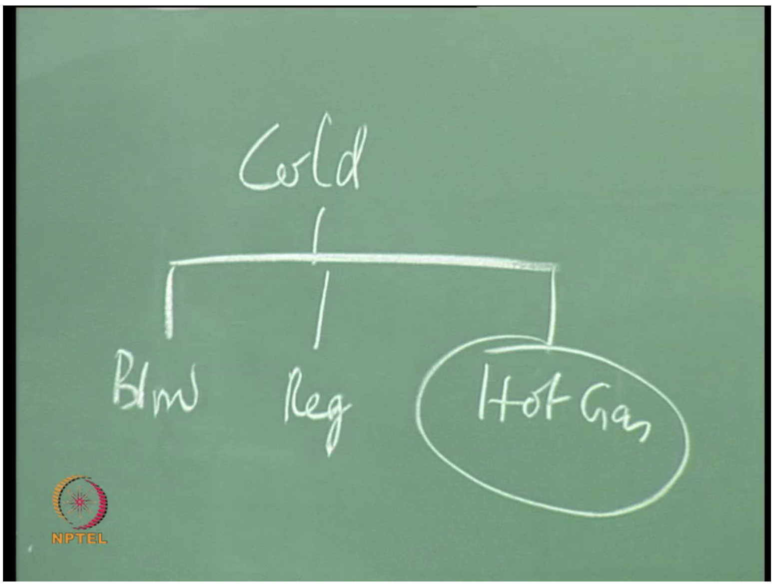

That means we initially said that a cold gas is used for pressurization. Why not use a hot gas? Why not have some chemically reacting gases taking in the combustion chamber to be used for the pressurization? Well. This is also an option and in addition to a cold gas for the blow-down mode and regulated mode, it is also possible for us to have hot gas. And the hot gas is more efficient. But in practice it has been difficult to use it. Several countries have tried, but it has not yet found a commercial application. But we should keep the advantage in mind and in future it may be a strong contender for a gas pressure system.

Having said that let us do a small numerical problem on the amount of gas? You know we should have some feel whether we need a few kilogram of gas or whether we need a few grams.

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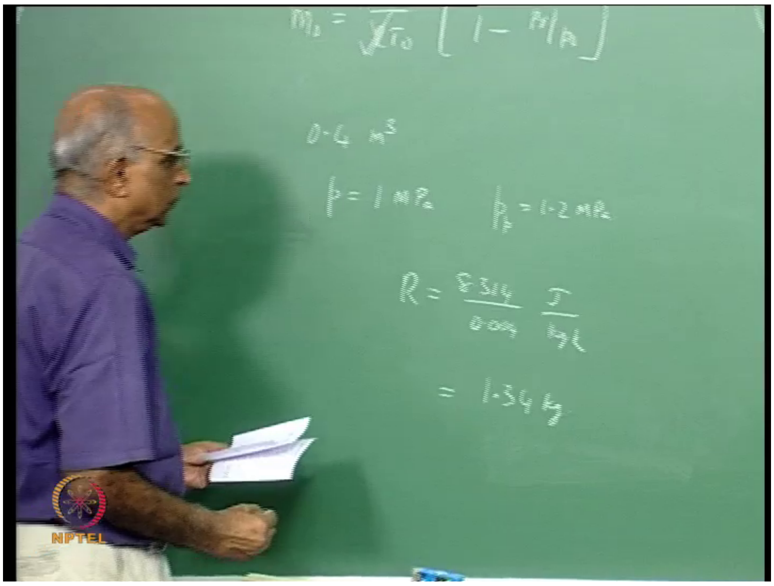

For the particular example, we found V_p to be 0.4 meter cube. Let us assume the chamber pressure to be small; chamber pressure let say is 1 mega Pascal. If the chamber pressure is 1 MPa, we have to force propellant into it let say Pp which we assume as equal to 1.2 MPa. The final pressure, the lowest p_r is equal to this supply pressure of 1.2 MPa. The volume V_p is known. The value of the specific gas constant R for gas helium is equal to 8.314/0.004 so much Joules per kilogram Kelvin. The initial temperature of the gas is 300 K. We substitute the values and get the value of mass. And this value of mass for this particular thrust when the supply pressure is 1.2 MPa works out to be 1.34 kg.

If we have a similar rocket, which is developing a thrust of 6 kilo Newton, what is the mass of gaseous helium required for pressurization? It is twice the value.

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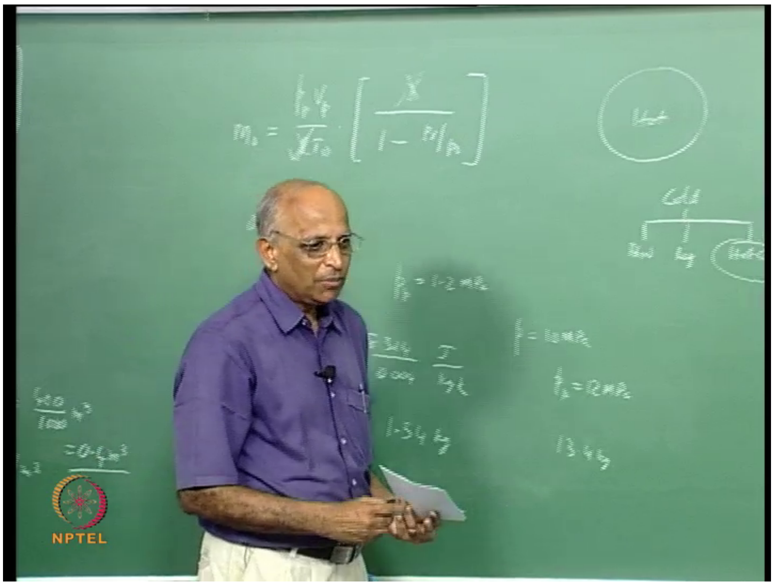

But if the chamber pressure instead of being 10 bar or 1 Mega Pascal is now changed to pressure is equal to 10 MPa and the supply pressure therefore, becomes let say 12 MPa, the mas of the helium gas becomes directly 10 times that is something like 13.4 kg. Now, if we talk in terms of thrust which is much larger, may be 600 kilo Newton, the quantity of gas increases so also for the chamber pressure. Let me summarize it through slides; a regulated pressure system and a blow-down system.

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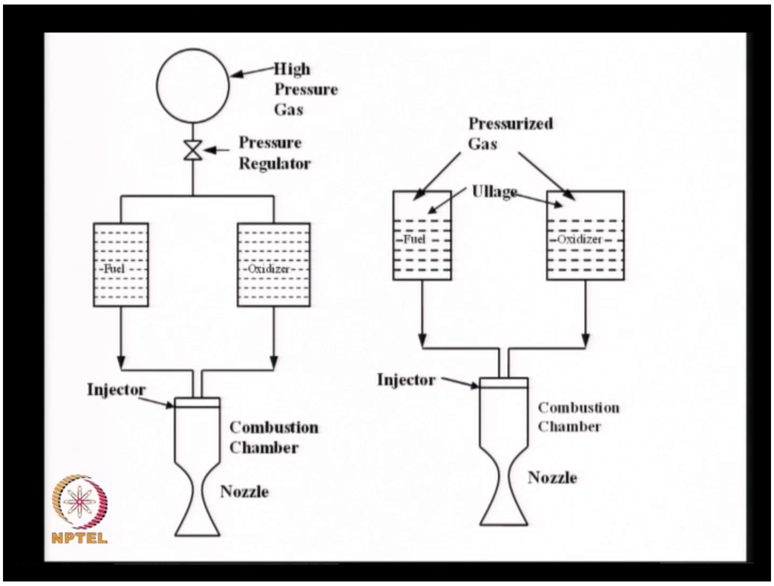

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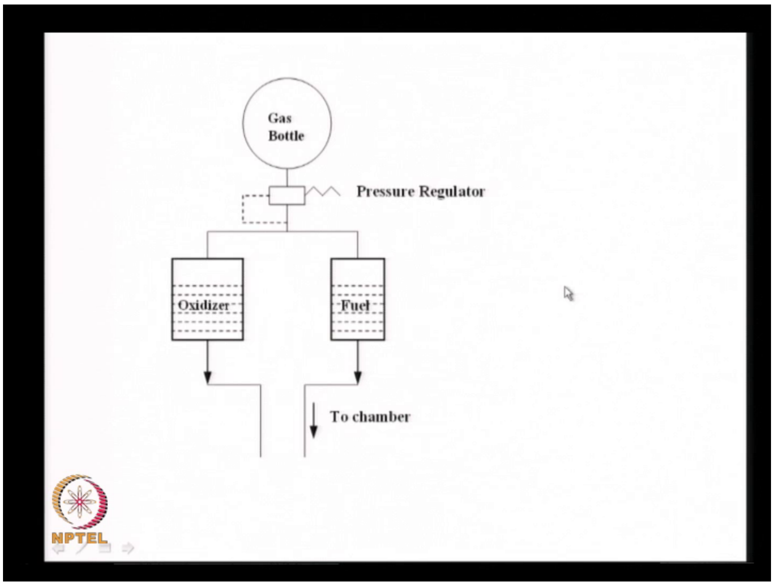

We wanted to find the mass of gas required in the gas bottle for a regulated cold gas pressure fed rocket. The cold gas pressurizes the oxidizer and fuel to supply them to the combustion chamber.

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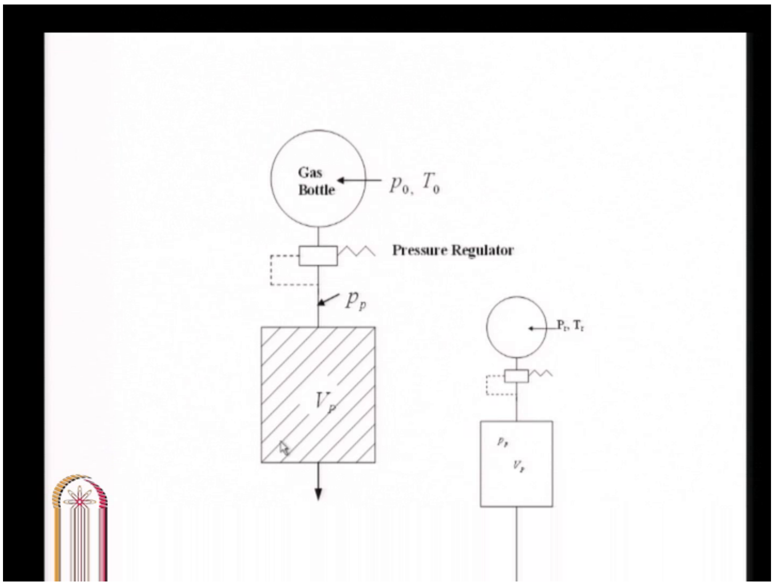

And we simplified it. The initial condition of the gas is in the bottle while the final condition is it is in the bottle and propellant tanks.

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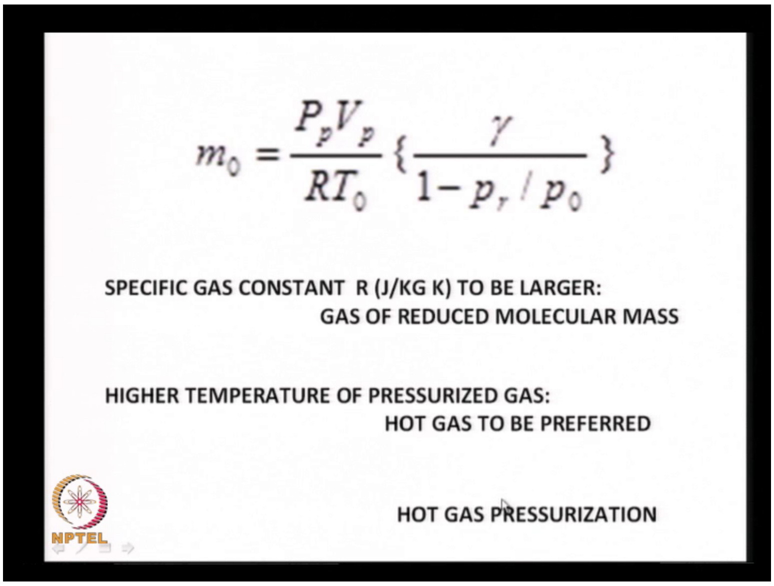

And we found that m_o mass of the gas required is equal to p_p V_p by R T_0 into gamma by $1 - p_r / P_0$ and then we found that hot gas pressurization is a better option.

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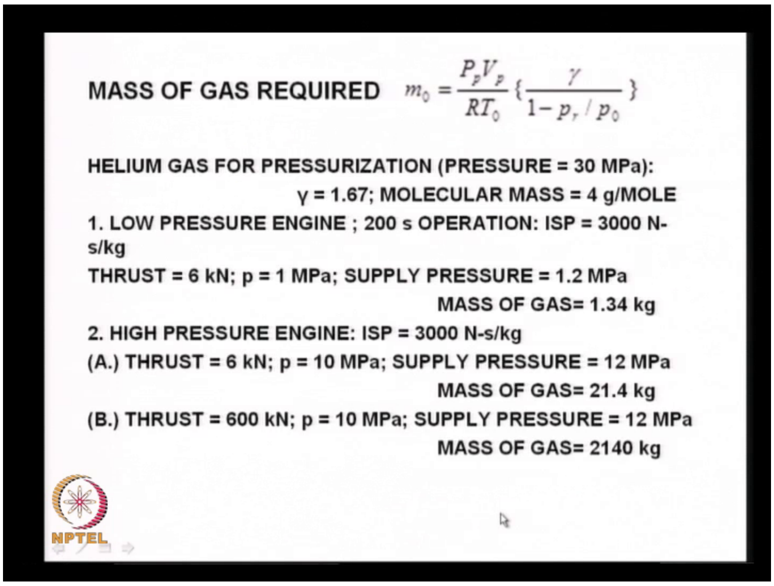

And then now we calculate the value mass of the pressuring gas when we have a low pressure engine of thrust of 6 kilo Newton, the chamber pressure is 1 MPa, the supply pressure is 1.2 MPa, the mass of gas required is 1.34 k g. Then the same 6 kilo Newton is operated at a high pressure of 10 MPa, the supply pressure is 12 MPa, the mass of gas becomes instead of 1.34 kg becomes 21.4 kg.

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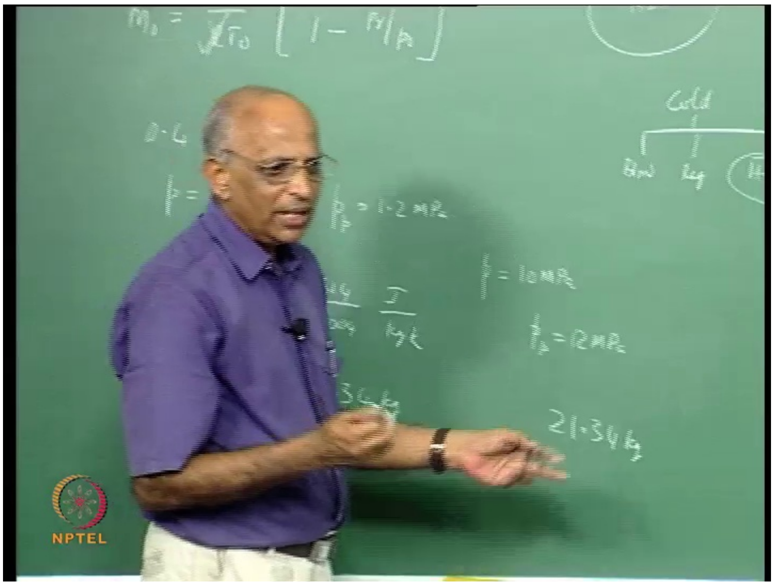

You see when the chamber pressure increase by 10, the quantity of gas is increased by almost twenty times. Whereas, if I have a high thrust engine of 600 kilo Newton at the same pressure value, the quantity of gas required is something like 2000 kg. And therefore, it is not humanly possible to have such large amounts of gas being carried in a rocket and that is where it becomes necessary for us to have a pump, which can supply the propellants to it. This explains the necessity of a pump for larger thrust engines.

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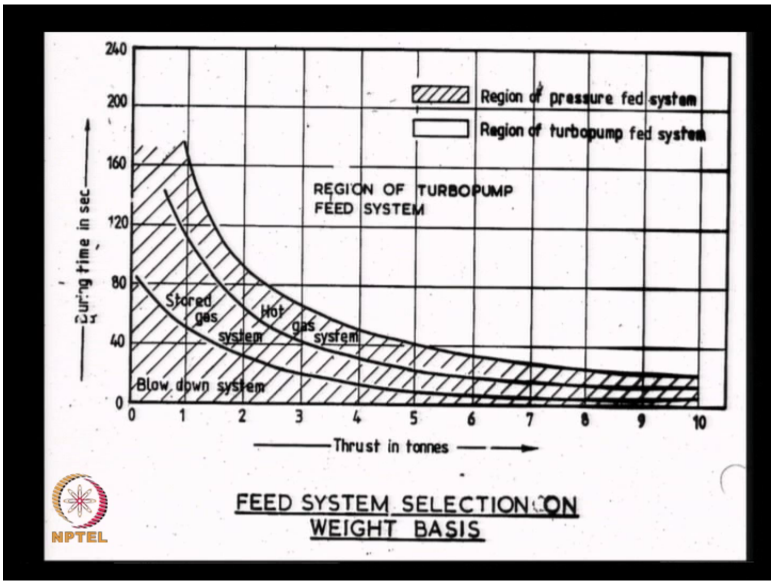

If we go back and compare the different systems that we discussed; a blow-down, a stored gas regulated, and hot gas, we find when the thrust is small and the burning time is small, we can manage to have blow-down system like what was used in the spacecraft. We need very small thrust and the rockets are operated at low chamber pressure. When we want to operate at slightly larger time, slightly larger thrust, may be something like a regulated gas system is required. But if we want still better performance, may be a hot gas system would be advantageous.

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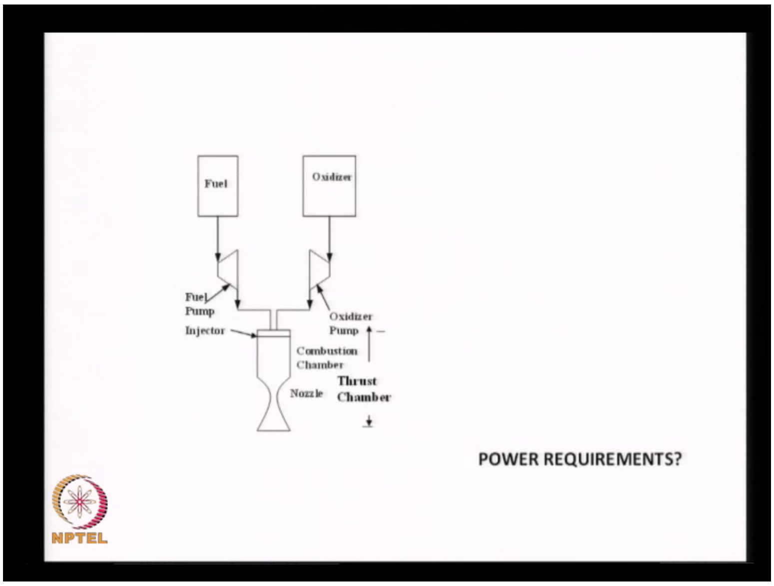

But beyond some thrust and beyond some burning time, we need to operate in this region which can only be done using turbo pump or a pump system. Therefore, the feed system of a liquid propellant rocket could consist of different options depending on the thrust, duration of operation and chamber pressure.

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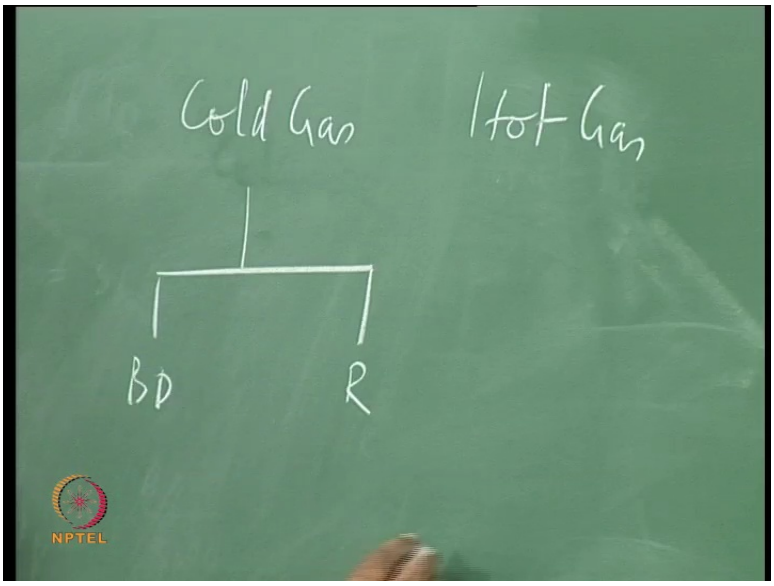

We could have gas pressurization that means, we have a gas bottle containing a cold gas or a hot gas. The cold gas could either be in a blow-down mode or in a regulated mode. But if that duration of the rocket operation is for a longer time and if the thrust is large or the chamber pressure is large, we essentially need a pump to take the fuel from the tank into the chamber and this is what we must remember.

Let us now calculate what is the power of the pump, which we require in case we need a pump for the pressurization of the propellants. Let us let us take this example.

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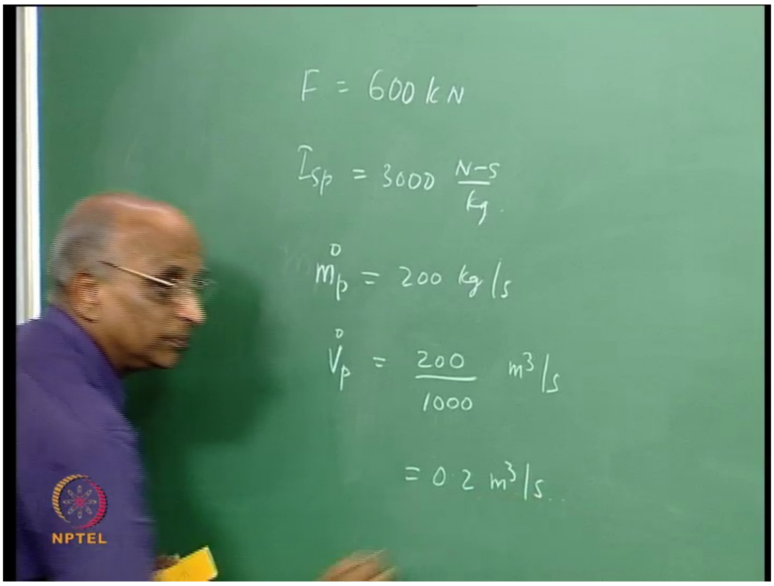

The thrust of the engine is equal to 60 kilo Newton or better still 600 kilo Newton. We had seen this engine and it used UDMH and N_2O_4 at a thrust of around 600 kilo Newton. And the specific impulse of this engine is 300 Newton second by kilogram. Therefore, the mass of mass flow rate of propellant is equal to something like 200 kg per second. Therefore, if we have to supply this quantity to the combustion chamber, let us again take the density of the propellants same as the density of water. The rate at which the volume has to be supplied is something like 200 divided by 1000 meter cube per second which is equal to 0.2 meter cube per second. What is the power required for a pump to supply 0.2 meter cube per second at a given pressure? Let us take the same value of the supply pressure of 12 mega Pascal.

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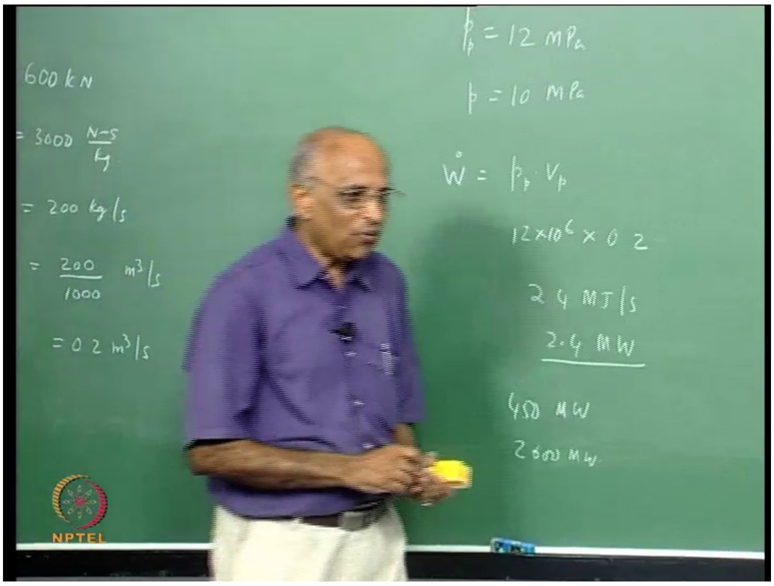

What is the work to be done by the pump, which is to supply flow rate of 0.2 meter cube per second at a pressure of 12 MPa. The rate of work done is equal to p_p into V_p and this comes out to be 12 into 10 to the power 6 into V_p is 0.2 meter cube that is equal to 2.4 mega Joule per second which is equal to 2.4 Megawatts. Can we have some feel for this number? The power produced in the power plant at Ennore, which supplies entire electricity to Chennai is something like 450 Megawatt. If we take a super thermal power plant like Ramagundam, the power generation is like 2400 or 2600 Megawatt. That means the power we are talking is enormous. We cannot have a battery or an electrical power for running such pumps.

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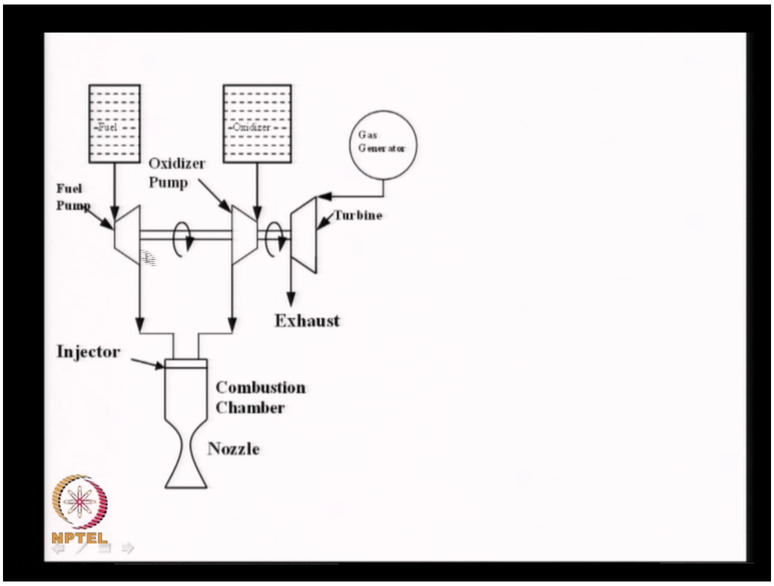

And therefore, what we normally do is, we need something like a gas generator, which can supply work to a turbine and using the turbine we drive the pump. It becomes a pump and a turbine and is known as a turbo pump. I require another gas source, but to have a dedicated gas source is going to be a problem.

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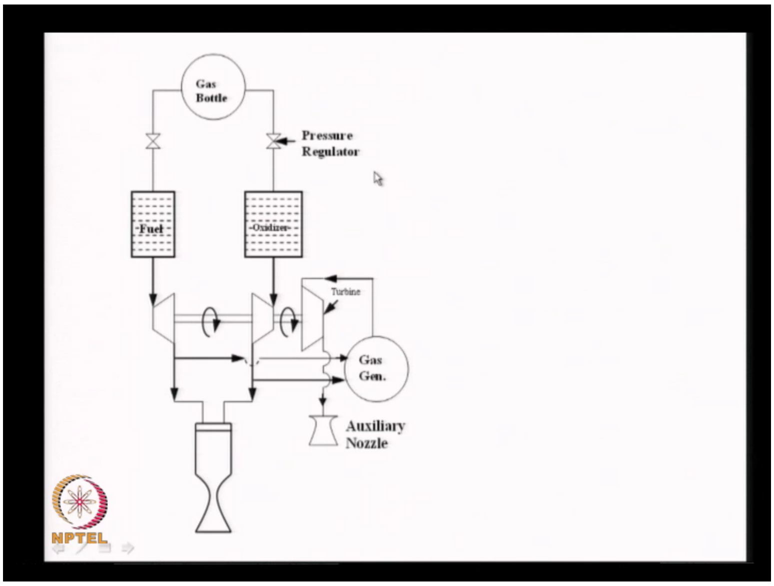

And therefore, what we do is that we take the fuel, we take the oxidizer and increase the pressure. We remove some fuel from the fuel line, we remove some oxidizer from the oxidizer line, we burn these gases separately in an auxiliary chamber and generate hot gases. These hot gases are used to run a turbine, generate work, which drives the fuel pump and oxidizer pump and supplies the fuel and oxidizer to the chamber. And the exhaust from the turbine is left out through an auxiliary nozzle. This means that part of the fuel is used in generating high temperature gases, not very high because the turbine cannot take very high temperatures and thereafter we leave it to the ambient. And this becomes what is known as a gas generator cycle. We have a turbine running the pumps and we use hot gas from a gas generator for running the turbine. This is the gas generator cycle for feeding propellants into the chamber.

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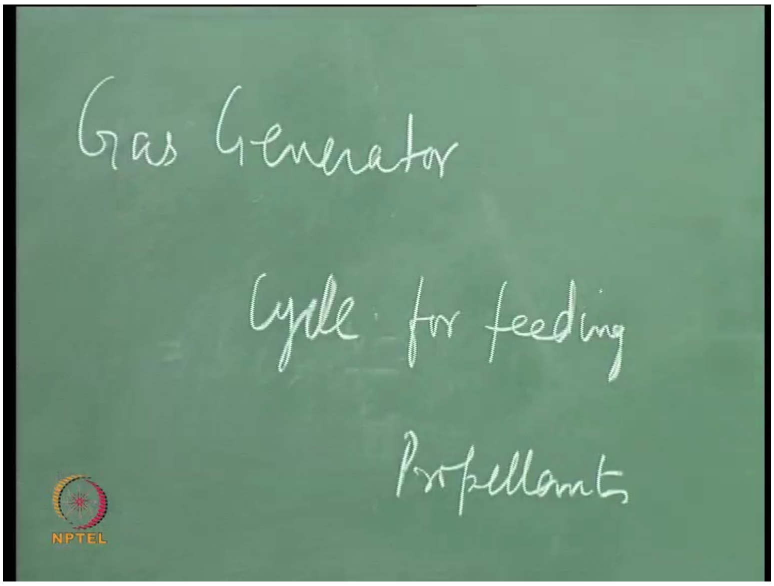

To sum up, all what we did in today's class is we looked at the bombardier beetle, and said well a liquid propellant rocket is quite similar to it. We talked in terms of cold gas pressurization consisting of blow-down, regulated, and also hot gas pressurization, and then found that when the duration of the rocket operation is large and the thrust is large or the chamber pressure is large, it is just not humanly possible to carry such huge masses of gas which are required. We need a pump, but then we found a pump demands huge amount of energy to run it. We needed a gas generator to run a turbine, which in turn ran the pump and this is what we called as a gas generator cycle. In the next class, we will see what are the other cycles for the feed system and calculate what is the performance of a rocket corresponding to the cycles. And then we will go into the components of a rocket.