Indian Institute of Technology Madras
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NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion

Non- air breathing engine II

Lecture 7

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In the last class we had looked at water solid propellant rockets now in this class let us look at water liquid propellant rockets.

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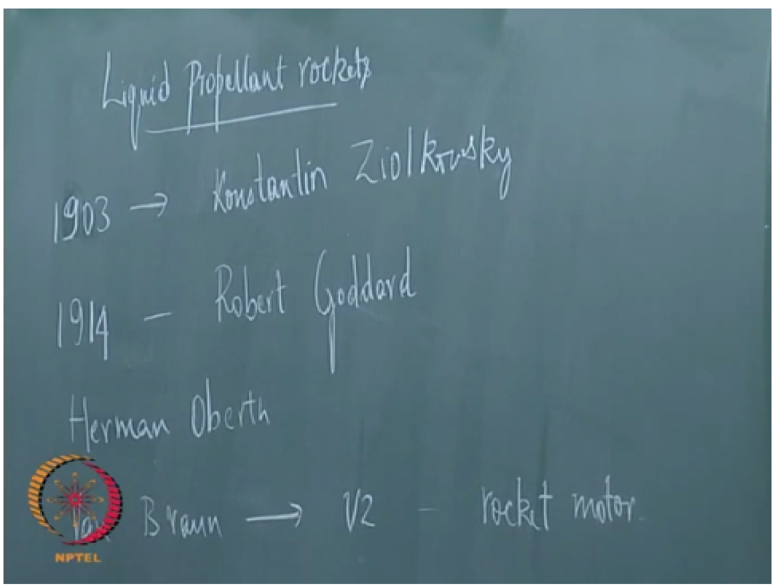

Remember I told you while discussing about the history of solid rockets that around the beginning of the 19th century solid rockets kind of became obsolete primarily because if you look at gun powder and the specific impulse that gunpowder used to give it was around 1500 okay and during that time there was the science fiction about how to travel to outer space and that kind of caught on and people were interested in space travel and things like that.

So then they realized that if they have to go for such a kind of mission using gunpowder or solid propellant essentially both were the same at that point in time they could not achieve this mission so they started looking for different kinds of systems in order to get there and liquid propellants suddenly became popular the reason liquid propellants became popular is if you look at solid propellants solid propellants both the fuel and oxidizer are in the solid phase and they are stowed together in the same chamber and that is also the combustion chamber as you seen.

So therefore there is an issue of compatibility and you cannot choose the best if you choose the best they might still not be compatible now in liquids the advantages you can store them separately right you can store them in separate tanks and therefore you can choose the best fuel and the best oxidizer because there are no issues of compatibility there and therefore that was thought of as being able to give higher specific impulse and therefore possible to make interplanetary missions and other things at those liquid rocket motors.

And in 1903 Konstantin Ziolkowski Russian school teacher he came up with a paper which talked about exploration of space with reactive devices wherein he discussed about how to escape from Earth's gravitational field and what are the Rockets that had to be used and he also talked about how to use multiple stages how they would be beneficial and all those things then in 1914 an American by name Robert Goddard he was a professor of physics he got a patent for the design of rocket motor combustion chamber nozzle feed system and then multiple staging.

He also talked about the liquid hydrogen liquid oxygen systems and he carried out a lot of experiments on liquid high liquid oxygen and kerosene systems between 1920 and1940 never really built a system that could fly and it was tested in that sense tested for a short range but not for a long range and in Germany Herman Oberth around the same time he proposed a design using hydrogen and alcohol fuels with oxygen for interplanetary applications all this was catching up and you know people in the1930s were doing all sorts of crazy stuff as putting a liquid rocket motor on a car and trying to run it and trying to see how fast it goes.

So they were involved in all these kind of amateur activities which was in essence helping the rocket motor develop faster now with the advent of the world war the Germans very seriously thought about building a rocket motor that can hit the enemy and the result was V2 Von Braun develop the V2 rocket motor which was alcohol plus liquid oxygen and these missiles were capable of hitting from Germany to Britain and Britain had absolutely no defense during that time against these incoming missiles and it was like very scary to be in that situation where in you could do nothing.

When an incoming missile comes and hits you it is believed that the Germans also developed a much longer version of the V2 which was capable of hitting from Europe America the eastern parts of America that is especially the coastline Newyork and cities on the coast eastern coast but this was in the late years of the war that is around 43, 44 but they never really tried it or they never really fired it primarily because they were at that time losing the war and they did not want to anger America further by firing these missiles at them they would not have hurt anything in America because they could only reach the coast and if they farted they would only anger Americans more rather than hurting them.

So they did not want to do fire these missiles and after the war all the Russians and Americans kind of took away things that they could the Russians were able to get to the papers and other things the Americans caught hold of Von Braun and Von Braun was instrumental in designing the Saturn for right Saturn for mission where they put man on the moon this was how liquid rockets developed and liquid rockets there are different kinds of liquid rockets.

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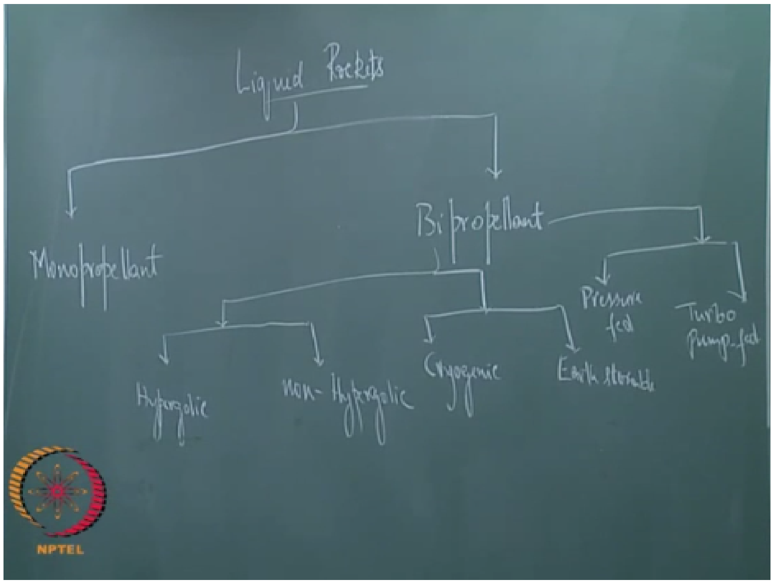

Monopropellant & bipropellant if you use a single propellant and it disintegrates to give you high temperature high pressure gases that constitutes a mono propellant system and if you use explicit fuel and oxidizer combination that gives you the bipropellant system in the bi propellant system there are different kinds one is hypergolic and the other is non hypergolic what we mean by hyperbolic is the fuel and oxidizer as soon as you bring them in close proximity they will start igniting and reacting.

So a hyperbolic system that is a system which uses hypergolic propellants does not need any ignition source whereas a non hyperbolic system will need a ignition source and you have cryogenic and earth storable propellants what we mean by cryogenics is the cryogenics is the science of low-temperature now if you cool hydrogen and oxygen to very low temperatures they then become liquids and you could use them as liquids if you can store them at those temperatures and they would give you better specific impulse we will see that as we discuss later in the course.

Now that is a cryogenic system that is systems that use these kinds of liquids which are cooled below the ambient temperature if you can keep the liquids at the ambient temperatures itself then they are known as earth storable liquids.

And lastly you have pressure fed and turbo pump flight systems we will see what these area little later that is how the propellants are expelled what is the mechanism used to expel the propellants is the last classification okay now let us look at mono propellant thruster.

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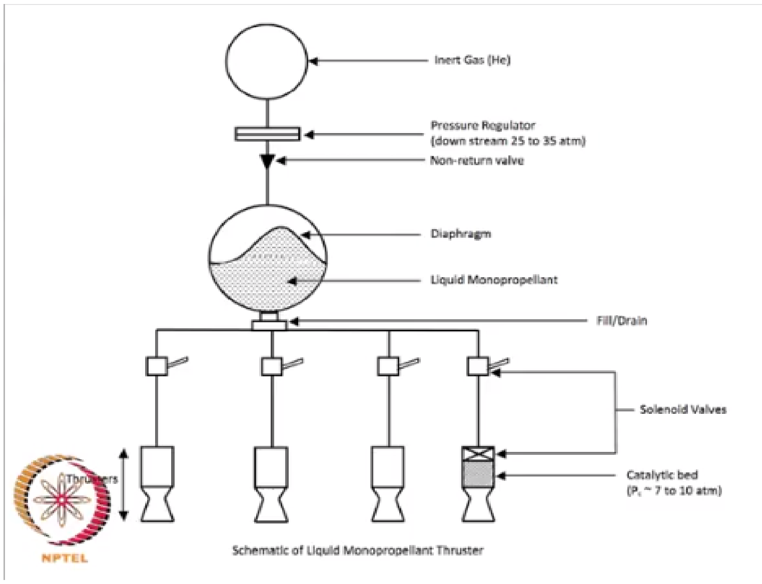

If you take a look at this figure here you have a mono propellant thruster here it consists of a large helium gas bottle then you have a pressure regulator the pressure in the helium gas bottle is very high typically around 350 bath and then you regulate the pressure and bring it down to something like 25 to 35 atmospheres and then you have a propellant tank remember this is a single propellant so therefore you will have only one tank and there is a diaphragm here.

The reason for the diaphragm is most of these systems monopropellant systems are used essentially in satellites where there are near zero-g conditions so it would be difficult for the propellant to flow down as such and therefore you need a diaphragm to push it in a particular direction the pressure acts on one side of the diaphragm causing it to push the liquid out in the other direction okay and here you have a large number of thrusters connected to it okay these are called as thrusters this portion here it consists of a combustion chamber and a nozzle.

That is known as a thruster and the rest of the systems here are known as feed system in between the stirring the tank you have something known as a Solenoid valve in this Solenoid valve you can supply a particular voltage and the valve will open it there are two kinds one is always closed and always open you want to use the always fluid version because upon giving the correct voltage it will open and allow for the fluid to pass through the thruster in the thruster you have a catalytic bed.

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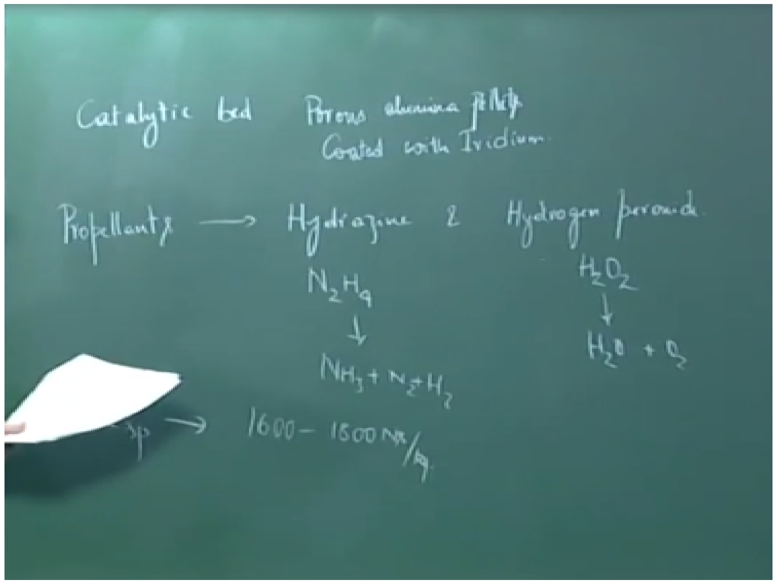

Catalytic bed made of Porous alumina pellets coated with iridium now because of this catalyst the propellant breaks up and reactions do take place and you get high temperature high pressure gases okay now the typical propellants that are used here are hydrazine and hydrogen peroxide hydrazine is nothing but N_2H_4 and this is H_2O_2 okay this breaks up into H_2 + O_2 whereas this broke up into NH_3 ammonia + N_2 and H_2 are not balanced this you can balance this okay.

Depending on the amount of ammonia that is formed you get varying ISPs and the typical is ISPs that you can obtain with this systems is somewhere between 1600 to 1800 Ns/kg now these systems are typically used for on-off applications they are not used continuously but they are used in a on/off mode that is they are pulsed.

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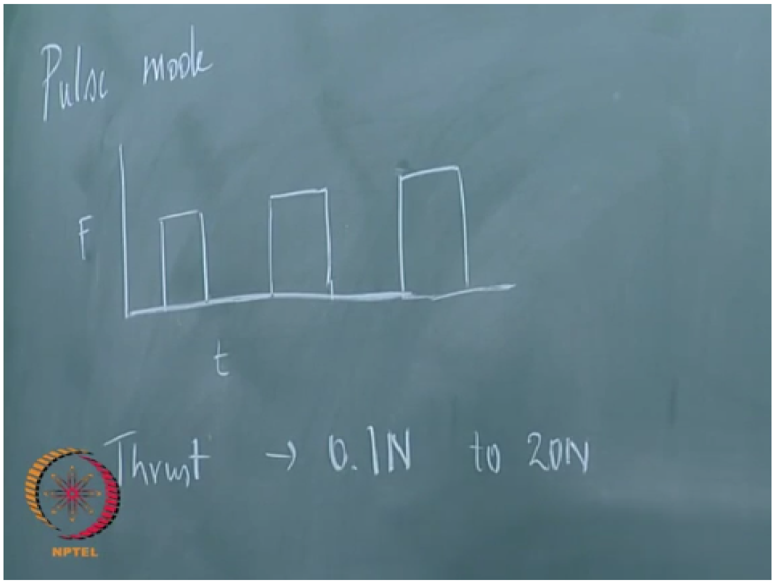

So these are operated in pulse mode that is if you take a look at thrust versus time it will be something like this we will have a large number of pulses like this and the typical thrust that one can get varies from something as small as 0.1N to 20N, 0.1N is how many grams something like 10grams 10 grams of thrust a very small thrust but remember these are on satellites there is no sensible atmosphere.

So you would want to use this for station keeping that is to make sure that it is stays in the same orbit as you want it to be so you need only a small for corrective force to get it back into that orbit that is why these are designed for very small systems and typically during the life of a satellite these have to go through millions of cycles in fact the life of a satellite is not determined by its electronics and other things but it is dependent on how much propellant you can carry on board if you can carry a large amount of propellant then you can do station keeping for a larger time and therefore the life of the satellite will be longer okay.

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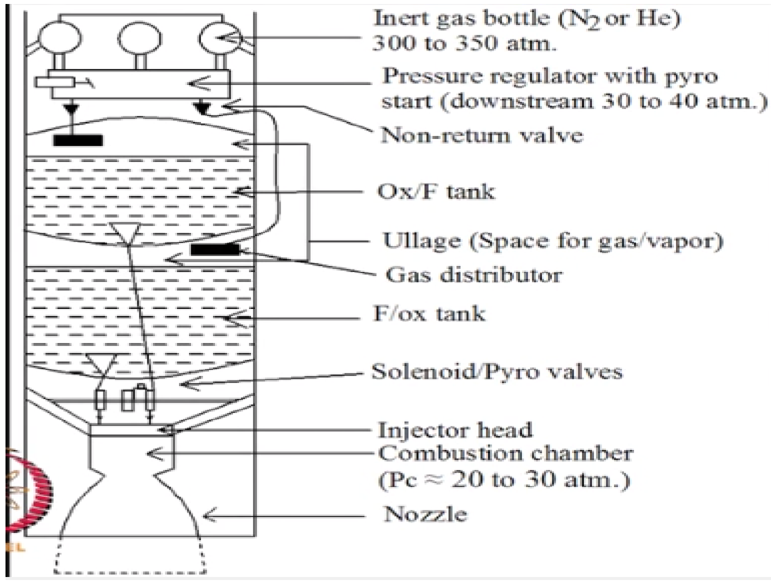

Now let us look at the next set of systems that is by propellant systems if you look at this figure here this shows the pressure fed by propellant system you have helium gas bottles here and then pressure regulator and two tanks one for the fuel one for the oxidizer and you have solenoid valves and then it comes in to the thruster okay now notice that the pressure inside the thruster is around20 to 30 atmospheres in the previous case it was a very small pressure of around 7 atmospheres or so.

So here the pressure is large and the gases the propellants coming here the liquids that come here react vaporize and react and form high temperature high pressure gases and then these are expanded through a converging diverging nozzle okay this is a schematic of a pressure fed system and typically pressure fed systems.

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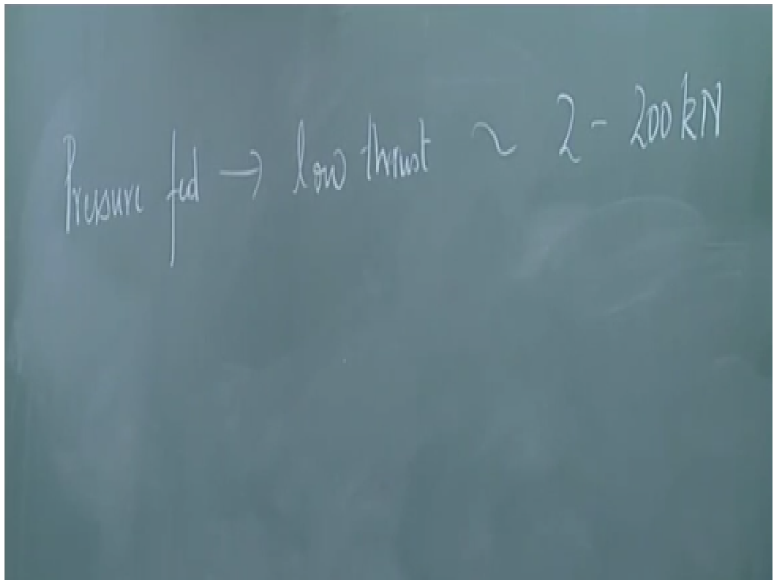

Pressure fed systems have low thrust are designed for low thrust in the range of something like 2 to 200 kN.

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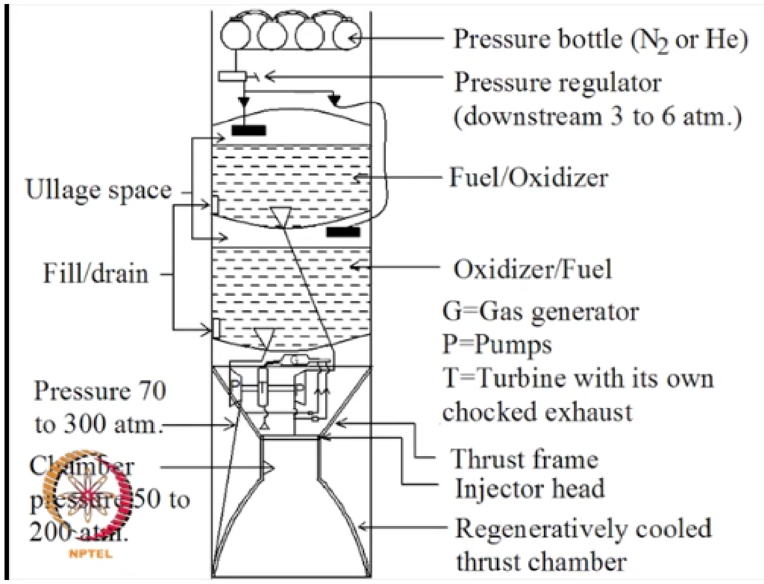

And the next system that is the turbo pump fed system is usually the large thrust producing system I suppose to the previous one in this case also there are helium gas bottles in the previous one pressure fed system all the pressure was given to the tanks from the gas bottle itself so the tanks were operating at a very high pressure the tanks were pressurized to a large pressure if you look at the previous one you see here that the pressure in the tank is somewhere around 30 to 40 atmospheres whereas in this if you notice it is around 3 to 6 atmospheres much lower pressures what happens then if you store the liquids at a much lower pressure the weight of the system comes down because the weight of the system depends on what is the pressure it is designed for okay.

So the weight of the tanks come down and you can get the required pressure that you want in the engine through a set of pumps now these pumps will have to be operated by a turbine and the turbine needs part of these gases to be fed into a gas generator here and then pass through the turbine so typically you can get very high pressures at the end of the pumping and the pressures inside the combustion chamber can range from something like 50 atmospheres to 200 atmospheres. So therefore you want to use this enlarged thrusters.

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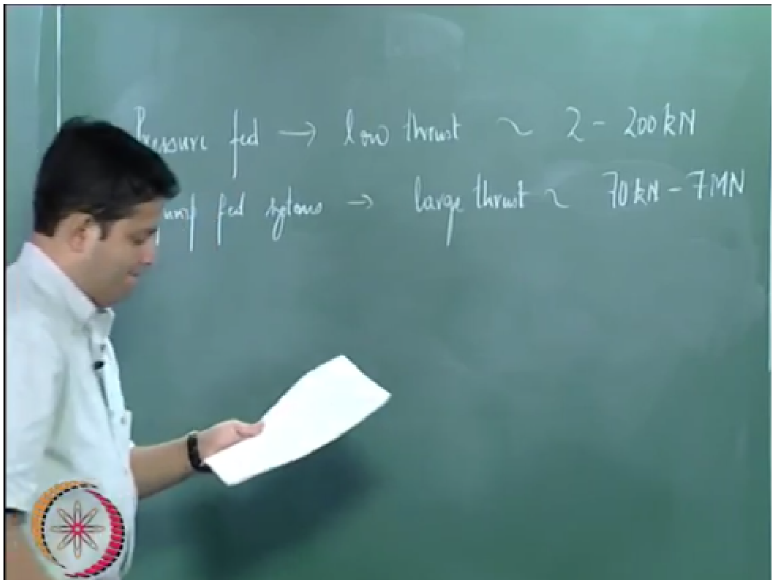

So the thrust of turbofan first system is much larger something likes 70 kN to 7 MN if very large thrust systems and if we were to plot.

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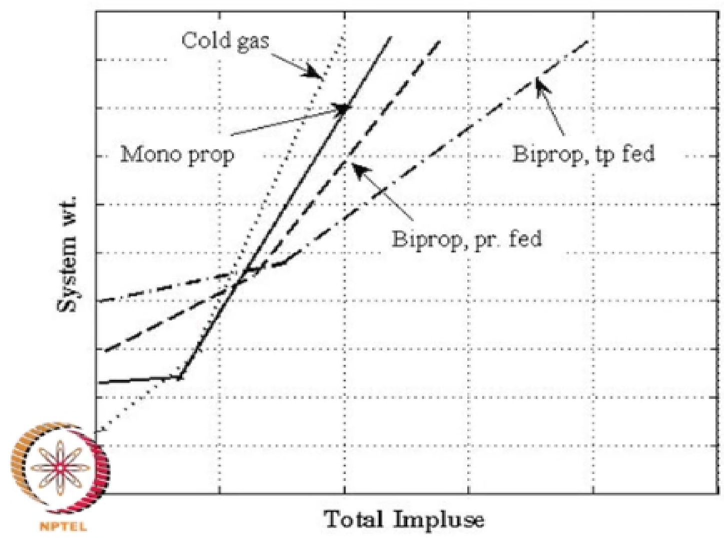

In this plot what is shown is on the x axis it shows the total impulse in kN second what do we mean by total impulse.

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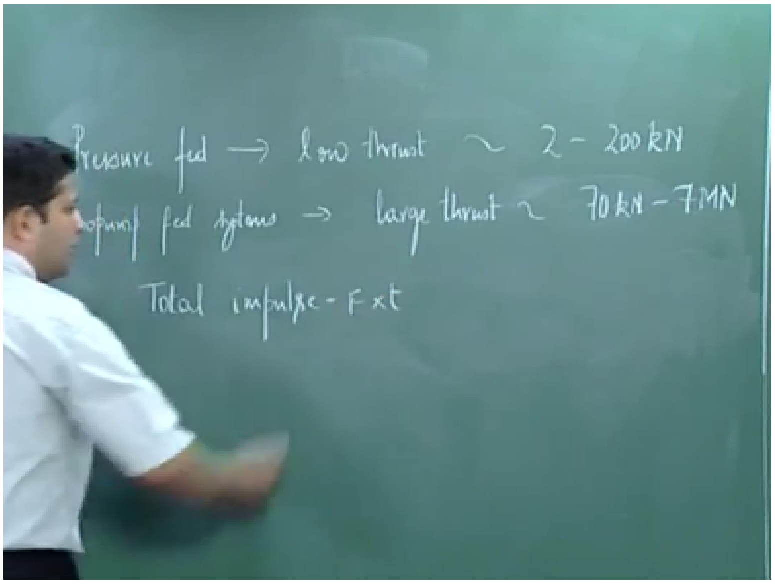

That is total impulse is equal to F into D that is the thrust into the operating time why is the operational time important because if you look at the tank size the amount of liquid you want to store in the tank that depends on how long you want to operate it for if you are looking at a very short time of operation then probably a pressure fed system would be better oka.

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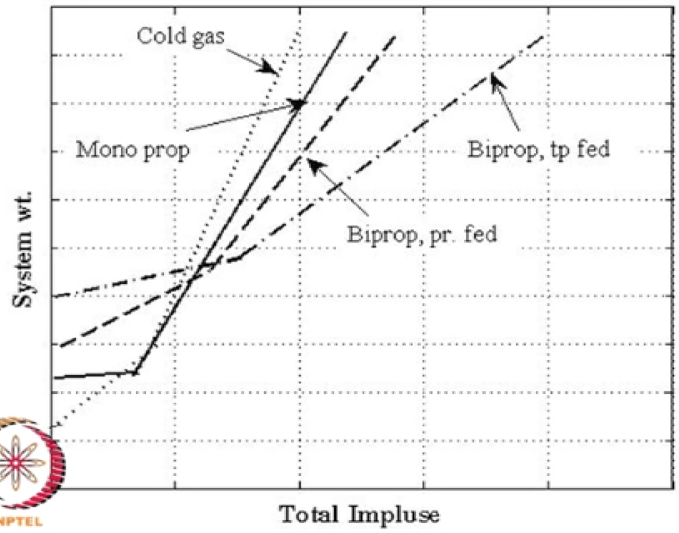

Now on the y axis you have the system weight shown here you have total impulse on the x axis and on the y axis the system weight this is on a log-log scale and if you notice here if you just use cold gas okay if you just use coal gas then the variation of system weight versus total impulse goes like this you notice that within this small region here it is better than the monopropellant system that is if you have a very small total impulse to be delivered then you can use a coal gas system that is pre high pressure gas just passed through a converging diverging nozzle that is a cold gas system then you have the mono propellant system which is better than the cold gas system in this range right.

From this particular total impulse to this one if your total impulse goes beyond this then you need to go in for a monopropellant system and if it goes beyond this you need to go for a micro plane system up to this the monopropellant system is better sorry the pressure fed system is better than the pump fed system because you have a smaller impulse to be delivered so the tank size will be smaller right.

So even if you pressurize it that will have a particular weight but beyond certain point if you want to increase the burn time and the thrust then the tank size goes up right and pressurizing it will increase weight much more the complex system has a dead weight or an inertial initial weight that is of the pump and the turbine and the gas generator and all that so it is not useful if you have a lower total impulse to be delivered that is in this range it is not useful but beyond this it is better than the rest of the systems. So which is why we will tend to use for a large burn time and large thrust we tend to you go in for pressure fetches a turbo pump fed systems.

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Liquid Rocket Engines

Engine	Vehicle country	Thrust kN	Propellants	I_{sp}, kN s/kg	Chamber pressure atm	Weight kg	A_e/A_t	O/F	Pump fed?
HM7	Ariane	70.1	LOX/LH_2	4.25	35.0	14.5	48	5.1	Yes
F1	Apollo	6860	LOX/RP1	2.61	76.3	8353	16	2.3	Yes
Vikas	PSLV India	735	NTO-UDMH	2.95	54.0	775	31	1.9	Yes

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and I try to put together here a list of different engines and what are the ISPs that are delivered by them and what is the kind of feed system that is used if you look at the first one it uses liquid hydrogen and liquid oxygen and it gives a specific impulse of around 4250 Ns/kg okay and it uses a pump fed system its thrust is somewhere around 70 kN if you go for a smaller system that is thrust of 3.87 kN you go in for something like a pressure fed system okay smaller ones you can go in for pressure system as you see here up to 6 kN you have pressure system pressure fed systems this is the only exception probably And larger systems are typically using turbo pump fed system okay.

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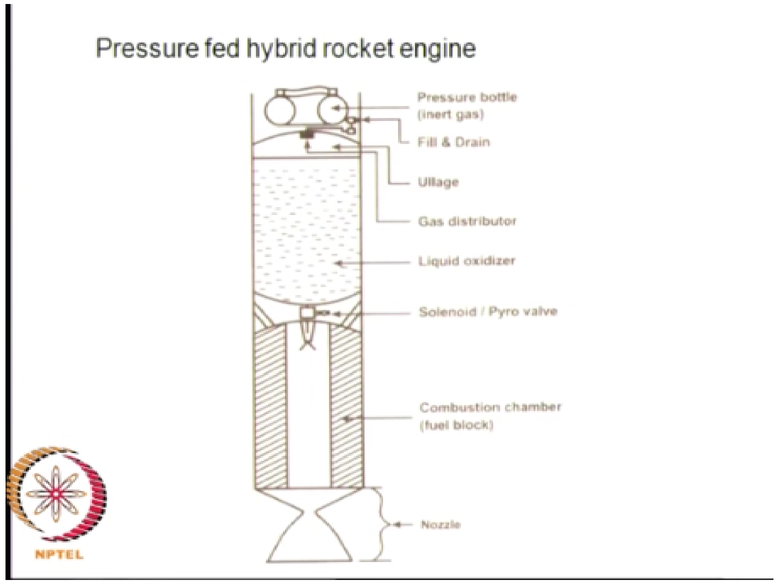

Now let us go on to the next you have discussed about liquid rockets and solid rockets let us now look at what a hybrid rocket is.

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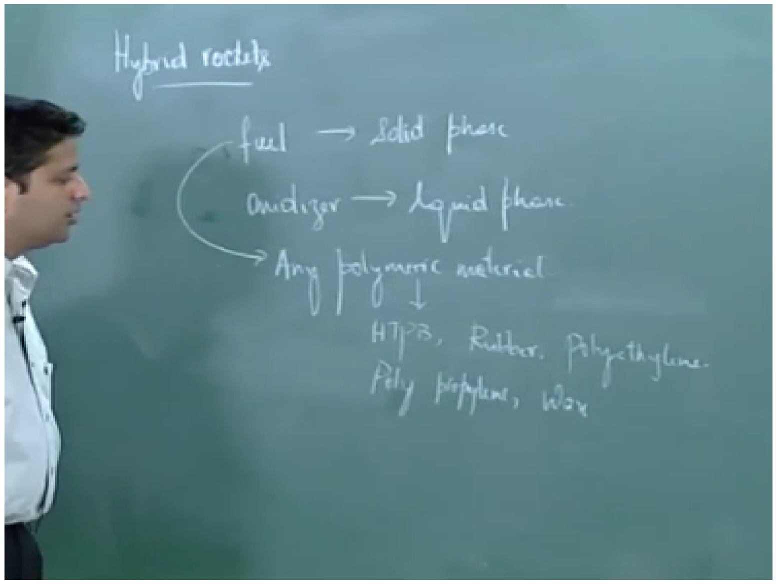

As the name suggests this is a combination of solid and liquid rockets okay so here typically you have fuel in solid phase and oxidizer in liquid phase we do not have the other one that is solid oxidizer and a liquid fuel because all the oxidizes solid oxidizes that are known to us are crystalline solids okay now if you want to make a propellant grain out of a crystalline solid crystalline solids are typically salts that you have come across if you want to make a grain out of it will have a lot of cracks and the structure will not have very good mechanical properties therefore you cannot use it as a propellant grain.

Because if you make a propellant out of it we will all crumble up and you will not get the desired performance from it so therefore you end up using solid fuel and a liquid oxidizer because here you can use any kind of polymeric material that is the typical fuels that are used are hydroxyl terminated poly butadiene rubber then polyethylene polypropylene wax okay so there is a scope for using a large number of different fuels and cheaper materials here and oxidizers typically are liquid oxidizers of that are used in liquid rocket engines is what you tend to use here.

Now why did this hybrid rockets come about if you look at solid rockets solid rockets are very simple device they are start and forget kind of devices that is if you start the solid rocket motor it is very difficult to stop it is not impossible to stop it is difficult to stop it unless it is designed to be stopped at some stage it is not possible to stop it as such okay.

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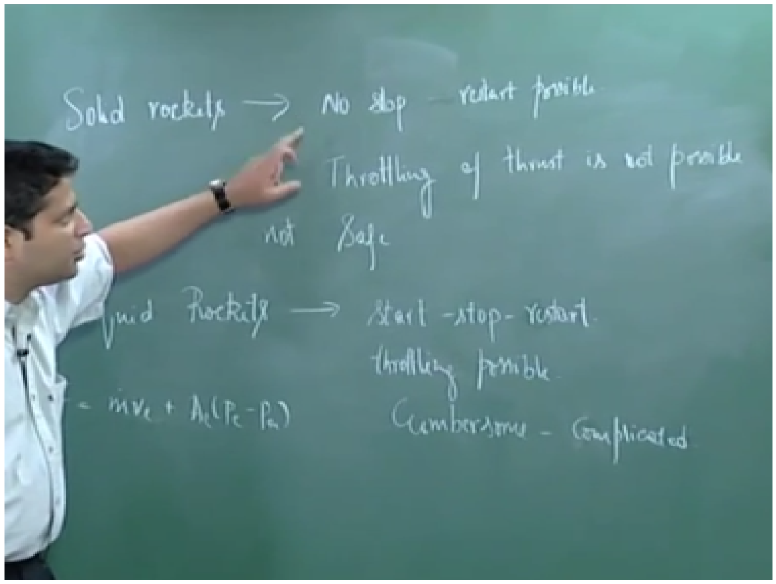

So solid rockets to stop restart as possible also the you cannot throttle the thrust that is you cannot change the thrust produced by the solid rocket motor it is designed for a particular value and it stays that way okay so in solid rockets and if you look at solid rockets both the fuel and oxidizer are always in close proximity okay now during the making of the propellant and storing it and transportation all this there is a hazard of explosion as a risk of explosion because you have both fuel and oxidizer in close proximity and risk of accidental ignition.

So therefore it is not very safe whereas if you look at liquid rockets they have there you can start stop restart remember when we talked about monopropellant thrusters for satellites we wanted to pulse the rocket motor that is it will be on for a certain period of time and then we switched off and again switched on like that so it has start stop and restart facility which is very simple in liquid rockets because they send liquids you turn off the solenoid valve then the liquid soon flow and there will be no thrust okay.

Whereas in solid rockets it is not possible as such and in liquid rockets you can throttle the thrust that is you can change the flow rates of oxidizer and fuel and therefore get a different thrust through the rocket motor remember a specific impulse is something that is set depending on what choice of fuel and oxidizer you make and if you remember our thrust equation was something like this F = mvc right.

Now even if these things are fixed let us assume for the time being this is fixed V is also fixed V in some sense is the specific impulse we will see that a little later now if you change the mass flow rate you can get a different thrust okay so throttling is possible in liquid rocket engines but the trouble with liquid rocket engines is that you need to separate pipelines to separate storage tanks to separate pipelines and then you have to have all the pressure relief valves solenoid valves all of them for two pipelines okay.

So it is a little more cumbersome or complicated okay and you need to machine these things very carefully in liquid rocket motors now if you look at hybrids if you look at hybrids hybrid is a combination as I said between solid rockets and liquid rockets. Now here is a schematic of a hybrid rocket sorry.

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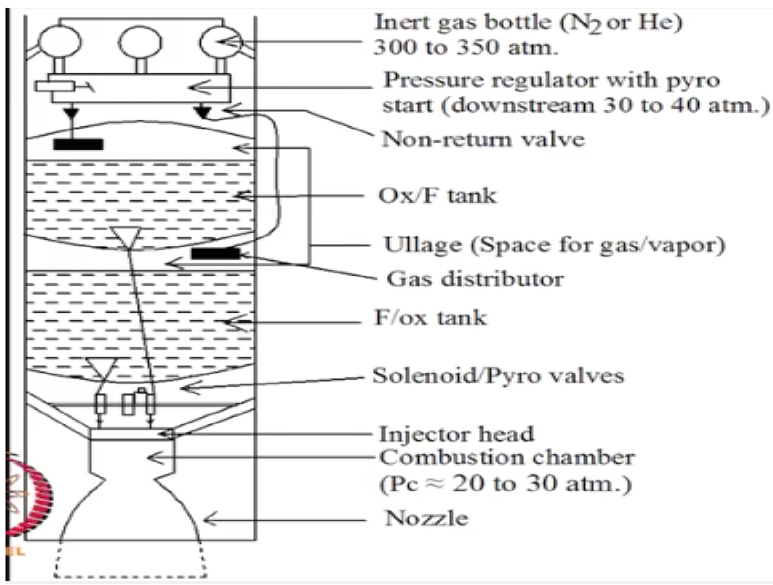

Schematic of a hybrid rocket pressure fed system again you have one liquid that is the oxidizer stored in a tank and you have gas bottles here and here you have the solenoid valve and this is the fuel grain okay the oxidizer is sprayed onto the combustion chamber here or the port here and the fuel vapors and oxygen vapors mix and then they burn here to produce high temperature high pressure gases which are then expanded through a nozzle okay.

This is how a hybrid rocket works you can inject the liquid at high pressures because you are pressurizing the system okay and therefore the combustion chamber pressure can be controlled right now you know as opposed to solid rockets it can because you are dealing with one liquid here you can do good this right.

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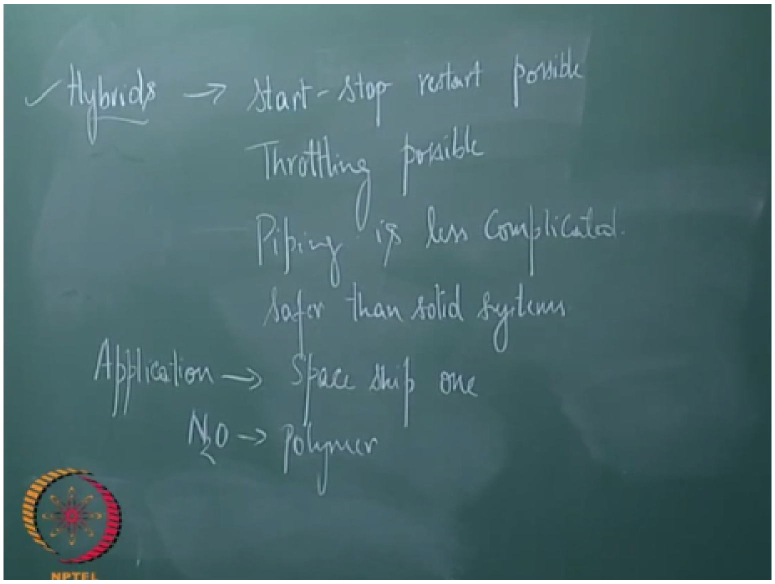

So you can do both start stop and restart possible and throttling is also possible because if you stop the flow of the liquid then the rocket motor will switch itself off okay because you are supplying you are not supplying the oxygen at oxidizer and therefore it cannot burn on its own the fuel cannot burn on its own and it will switch off so both of these as possible and as compared to liquid which wherein you had to have separate pipelines for fuel and oxidizer this is only one pipeline requirement.

So piping is less complicated and it is much more simpler than the liquid system and because here you are storing the fuel and oxidizer separately it is much more safer than solid systems but all this is fine if you look at any literature or if you look at all the systems that are being currently used most of the chemical systems that are currently used fall under these two categories only okay you will not find anything using hybrids the reason for that is one of the problems with hybrids we will discuss that a little later is it has very low burn rates fuel burn rates are very low.

And therefore you cannot get a very large thrust unless you go in for a larger surface area we will discuss that a little later so it cannot give you high thrust okay and it is also seen that in these systems that the oxidizer to fuel ratio keeps varying as you operate it we will discuss also that a little later in the course so because of these two drawbacks hybrids have never been used in any real life application the only application wherein it has been used in the aerospace industry is the recent spaceship one program.

What a spaceship one program you it was a challenge that was put up that somebody has to be transported from earth to a low Earth orbit and then brought back suborbital flight and back to earth and the task has to be repeated within the next 15 days okay with the same systems that was the task that was given and spaceship one was able to do it this was designed by Burt Rutan and it was able to accomplish this task spaceship one used N_2O and polymer combination as oxidizer and chilled and it was able to do to accomplish this mission.

But there is a slight problem in this as compared to the regular missions that missiles or launch vehicles have to accomplish if you take a look at what missiles have to accomplish missiles will have to hit their target within a very narrow spread they call it center Arab probable that is CEP that for a strategic missile that has a long-range missile is usually in terms of a few meters okay now solid rockets and liquid rockets have been the design has been mature enough and people have been using it for a long time and they have been able to deliver that kind of accuracy in missiles.

Whereas hybrid Rockets are not yet really there so that they can accomplish any of this and if you look at launch vehicles launch vehicles need to put the satellites in a very particular orbit okay there is a small band in which it has to be put it has to have that particular velocity and that particular altitude only then is it deemed as a successful mission otherwise you put it in some other orbit and some of the velocity it is not considered a successful mission and the satellite will be lost which means a huge loss in terms of money okay post to that the spaceship one program was something like this you just have to take it to a suborbital flight and come back.

It did not matter whether it was a few kilometers higher few kilometers lower and what velocities you entered it that okay there was another factor that was very important that it carried a human being on board and remember this entire task was a non-governmental task not that human beings have not traveled to space and come back most of these were government-funded and therefore there was an elaborate security as well as safety taken into account even with the other systems.

But in this case it was an amateur effort and still they were able to ensure the safety of the person going there and coming back primarily because they use hybrids are very safe okay and therefore they found a use in this kind of missions they also planned to have this kind of space tourism in future where and they just want to take people and make them feel the low Earth low gravity sensation and then bring them back so such missions probably will have hybrid rockets on them but otherwise on the regular kind of missions hybrid rockets have still not been used.

Okay I think we will stop here in the next class we look at what are the efficiencies involved in terms of air breathing engines and non air breathing engines and what is propulsive efficiency and what is overall efficiency how do we derive them thank you.

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