Fundamentals of Combustion for Propulsion
Prof. H S Mukunda
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture - 21
Liquid propellant rockets - Part I

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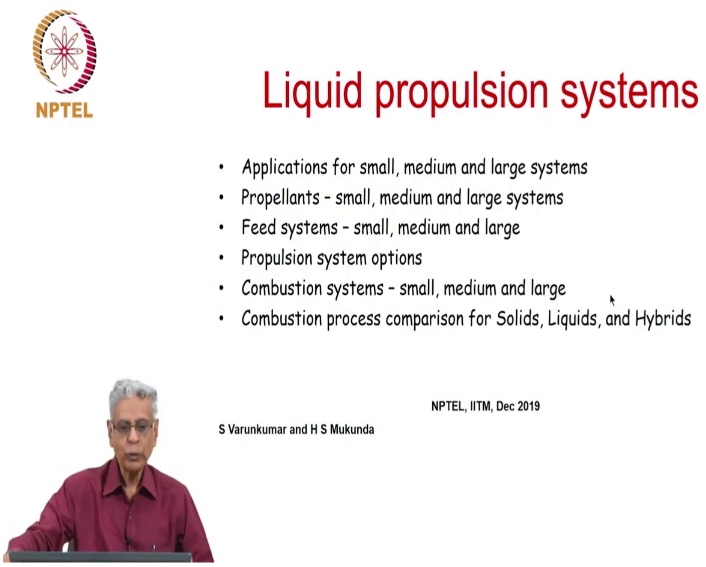

Good morning to the third day. I am going to speak to you about liquid propulsion systems. This is subject in which I have got involved from about 1970 onwards both with DRDO and ISRO in a variety of propulsion systems, technical discussions, review committees and so on. So, I am going to not necessarily speak about all those, but some fundamentals which come out of the experience as well.

We will begin by looking at the applications for a small and medium and large systems. The propellants which are meant for small, medium and large systems. Feed systems small, medium and large, the propulsion system options. You have pressure fed and turbo propellant and so on we look at them. The combustion systems themselves small medium and large and a certain combustion process comparison for solids liquids and hybrids.

While I think the prime interest is only in combustion systems when you look at liquid propellant rockets it is important to look at all the associated aspect a feed systems and so on so that you get a comprehensive view of what happens inside the combustion chamber.

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Well, we will look at the in the case of small systems which is essentially this satellite propulsion for orbit transfer and on orbit stabilization for life. Normally people use monopropellants which are self igniting or decomposing storable with one or more starts or pulse mode and mostly they are pressure fed.

Medium systems which usually belong to upper stages of launch vehicles or propulsion system for missiles. They are usually single start, storable, self-igniting and cryonic cryogenic bi-propellants with ignition turbo-pump or pressure fed depending in the options. Large systems which have essentially lower stages of launch vehicles usually they are single start they are semi-cryogenic or full cryogenic systems with ignition, turbo pump fed they are mostly.

There are new developments in small systems called green propellants and in large systems you have LOX-Methane propulsion systems. What is the purpose of this propulsion systems? Essentially to provide a velocity increment to the payload the payload better not to be stages above the level at which it is functioning. Stage 1 gives the velocity increment to stages 2 3 etcetera and satellite finally.

The performance of each of these stages is measured in terms of the velocity increment of delta V. Propulsion system control system also provides correction for station keeping or some major correction on satellites. These can be provided in a single long burn mode if required or 2 burn mode or a number of pulses of a fixed duration right.

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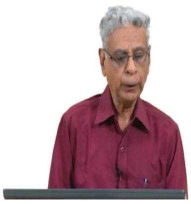

Range of Propulsion Requirements

Maneuver	ΔV, km/s
Orbit transfer: LEO to GEO LEO to GEO GTO to GEO (1) GTO to GEO (2) LEO to Earth escape LEO to translunar orbit LEO to lunar orbit GTO to lunar orbit LEO to Mars orbit	3.95 (no plane change required) 4.2 (including plane change of 28 deg) 1.5 (no plane change required) 1.8 (incl. plane change of 28 deg.) 3.2 3.1 3.9 1.25-1.4 5.7 8.7
Orbit control: Station-keeping (GEO)	50-55 m/s per year
Orbit control: Drag compensation •alt.: 400-500 km •alt.: 500-600 km •alt.: >600 km	 < 100 m/s per year max. (<25 m/s average) < 25 m/s per year max. (< 5 m/s average) < 7.5 m/s per year max.
Attitude control: 3-axis control	2-6 m/s per year
Auxiliary tasks: •Spin-up or despin •Stage or booster separation •Momentum wheel unloading	 5-10 m/s per maneuver 5-10 m/s per maneuver 2-6 m/s per year

LEO = Low Earth Orbit; GTO = Geo transfer orbit; GEO, Geosynchronous Earth orbit

If you look at a range of propulsion requirements you have a such a large range you just look at some of them. LEO to GEO means Low Earth Orbit to the Geosynchronous Orbit and it has a delta V typically of the order of about 4 kilometers per second and you have variety of them LEO to GEO of inclined plane of inclination being change that also causes demand on the propulsion system and you have low earth orbit to earth escaping so on.

Those numbers are given there for various applications. Orbit control this is station keeping essentially you need to correct it till level of some 50 to 55 meters per second per year ok. There have been corrections which are needed because of solar radiation which comes and falls on this (Refer Time: 04:30) cause of movement of these satellite. And therefore, you need to continuously keep correcting and keep the satellite in position both in terms of altitude as well as attitude.

Drag compensation various levels attitude control and auxiliary tasks like spin-up or despin and stage or booster separation so on so forth. So, all these are the applications demanded of the propulsion system.

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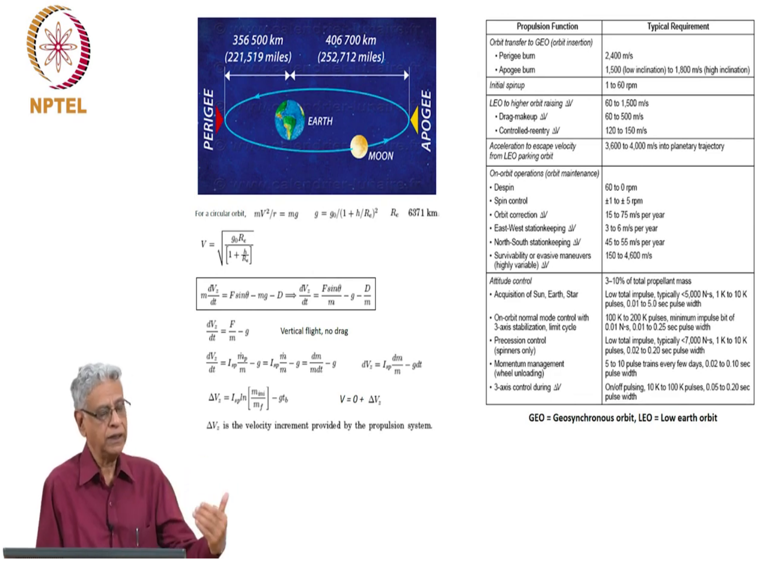

They took you know features which come in called PERIGEE and APOGEE the PERIGEE is essentially the one which occurs closer to the what you are looking at. If earth is this position you are looking at the PERIGEE is the closest to the earth APOGEE is the farthest from the earth and you can see that in the case of moon the numbers are shown there 3,56,000 kilometers to the closest and 4,06,000 plus kilometers are the APOGEE for the largest distance.

And if you are looking at a circular orbit around a planet in this case the earth then the gravitation must be balanced by centrifugal force. And let us remember the gravitational value for the g is not simply you know 9.81 meters square per meter per second square, but it is also dependent on the altitude and that is shown here. You can see in one of the places g equal to g naught divided by 1 plus h by re whole square. re is the radius of the earth value shown here is 6,371 kilometers and you can compute the velocity. It goes at the square root of g naught which is the gravitation and the surface of the earth radius of the earth and the altitude above the earth.

So, this velocity keeps going down with altitude and this what is reflected in many of the behaviors of the satellites which are located both in the low earth orbit as well as the geosynchronous orbit. What you see is a set of equations for the motion of a vehicle in a trajectory when the vehicle is shot off from the earth and you see the acceleration of the vehicle is balanced by the difference between the force that is supplied because there is propulsion then the gravity and a drag. And you can do a simple analysis as shown there and what you get if the velocity increment or the delta V which is the function of the specific impulse and then a logarithm of the initial mass to the final mass.

This is in fact the key equation which is used in the design of the mission in some way first look at estimates are obtained from that. And you can derive a lot of conclusions from this namely the specific impulse is very important parameter for enhancing the lost increment of any launch vehicle.

And if for example, the a density the propellant is larger you will discover that analysis shows that the density in the propellant times the specific impulse will play a important role. And you will find on the right hand side a large number of data provided for typical requirements the orbit transfer 2.4 kilometers per second after you burn some point 1.5 kilometers per second and so on so forth ok. The details here which you can observe later.

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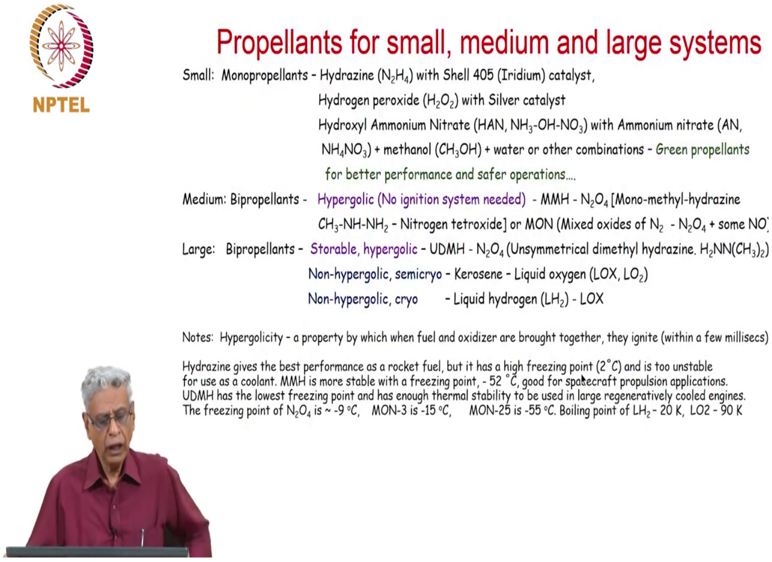

So, let us go to the propellants meant for small, medium and large propulsion systems. For small propulsion system that is largely satellite applications the monopropellants used are hydrazine and (Refer Time: 08:35) uses a catalyst a bit called shells 405 which are iridium based catalyst. Its a special catalyst and till now there is no other catalyst which has performed as well as this. So, whenever hydrazine is used in propulsion systems it always involves use of shell 405 catalyst.

Hydrogen peroxide can be used, but it is a silver catalyst. Then there are pace and generation propellants which are been contemplated. Only the one shown here is hydroxyl ammonium nitrate or HAN and with ammonium nitrate methanol and water and these are called green propellants. We will look at some of this later and these are meant for better performance and safer operations.

So, for medium systems are concerned they depend only on bipropellants which are hypergolic; that means, when the 2 fluids are brought together there is a liquid phase reaction which is exothermic and leads to a flame. Therefore, no ignition system is needed and are many options. The one that are used are mono methyl hydrazine and nitrogen tetroxide which is N 2 O 4 or what is called MON which is mixed oxides of nitrogen which are essentially nitrogen tetroxide and some nitric oxide. Depending in the amount of nitric oxide which is present we will find MON 3 MON 25 so on so forth.

In large propulsion systems which are only based on bipropellants you can use storable hypergolic propellants like UDMH N 2 O 4 like for example, Newton the cause engine here. Non-hypergolic systems which are essentially semi-cryo kind kerosene and liquid oxygen again non-hypergolic systems cryo systems which are liquid hydrogen and LOX. I made a statement about hypergolicity here which I discussed a little earlier.

The ignition delay is a crucial parameter which is in the range of a few milliseconds and the crucial point is that some of them need to operate in vacuum at extremely high altitudes. Because of that the ambient pressure in the chamber will be very low near vacuum. So, when the propellants are injected they must burst into flame otherwise the gas phase reactions will not go on whether the low very low pressures and the flame will not become. So, its a very serious problem and the choice of the hypergolic propellants will make a difference to the way the things operate.

I want to provide some input here. Hydrogen gives the best performance is a rocket fuel, but it is a high freezing point and it is too unstable for use as a coolant. So, quite often it is not thought of for main propulsion systems. As a monopropellant it is it works very well and if the temperature goes low you provide a heater to make sure the temperature is about its freezing point. MMH is more stable with a freezing point of minus 52 degree centigrade and it is good for spacecraft propulsion applications.

UDMH has the lowest freezing point and enough thermal stability to be used in large regeneratively cooled engines because the engine thrust chamber needs to be cool particularly de troop and some other regions as well. And therefore, you need to have thermal stability for it to be able to we use as a coolant. The freezing point of nitrogen tetroxide is minus 9 degree centigrade and MON minus 3 minus 15 and so on. And it is also good to know that the boiling point of liquid hydrogen is 20 Kelvin and LOX is about 90 Kelvin. So, both are cryogenic fluids.

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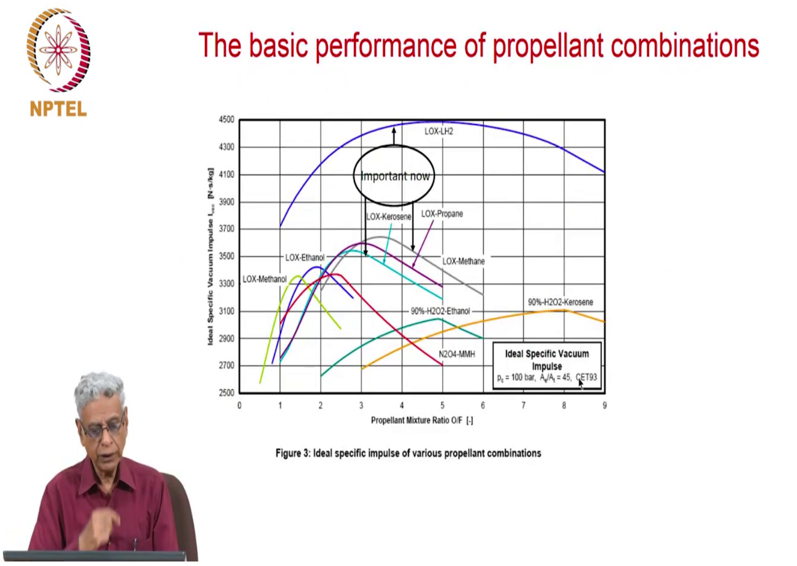

If you look at the basic performance of the propellant combinations, I did the correct notation to use is Newton seconds per kg. There many other notations which are used seconds and so on, but you can convert one from the other. Since, we in India as well we are using this propulsion systems is good to know what the performance level you like. The highest performance will obtained by LOX hydrogen and 4,500 Newton seconds per kg, but the density is quite low because of hydrogen.

LOX kerosene is being thought of specific impulse using the range of 3,550 and so on Newton seconds per kg and notice that in the case of LOX-LH 2 the O by F is about 5 close to that right. It optimization depending on emission can differ from this value and in the case of kerosene LOX kerosene system it is more 2.7. So, also there are other full of laser combinations. They are not necessarily used LOX methane is currently under discussion in ISRO they have been doing some developments.

We have other propellant combinations like 90 percent hydrogen peroxide is kerosene and so on. These are conceived tried out in laboratory experiment and tests in various countries, but no major propulsion system they applies that.

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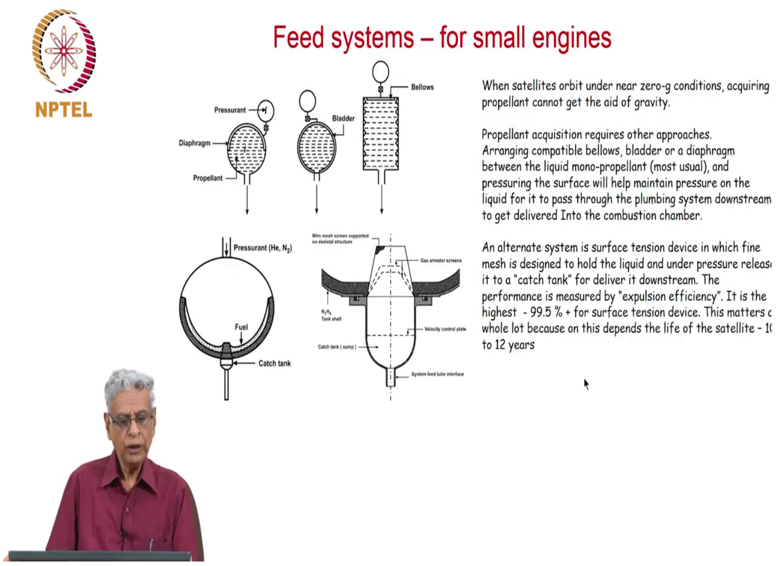

So, we move to feed systems a small engines. Let us remember that these systems have to function under it is near 0 g conditions when acquiring propellant cannot get the aid of gravity which is present in the lower stages.

So, the fluid make float around anywhere in the chamber. So, the propellant acquisition requires other approaches arranging compatible bellows are bladders, a diaphragm between the liquid and the chamber is what is recommended. You see diaphragm being used bladder as well bellows and there is a measure of how well this feed systems work is the amount of propellant which is which you can be extracted from the system till the end.

Typically them of 98 percent for many of these systems. Now not considered adequate because when we are looking at satellite propulsion systems or for the purpose of station keeping and such applications you need to the only thing the life of the system will depend on is only the amount of mono propellant present there for propulsion. Now, if that is in short supply then so is the life reduced. The typical life is about 10 to 12 years and to manage to have that it is said that better to look for higher expression efficiency system. An alternate system which got developed from a I think project in of a student in MIT is the surface tension device.

You can imagine is a very simple device. You have a mesh which is created very fine mesh and you put liquid because of surface tension liquid is held in the meshes. It is so strong that you can apply pressure and still the fluid will be delivered through that system out because it is able to stand up to the pressure difference across the thin space is present between the wire mesh. And this expulsion efficiency is supposed to be better than 99 percent 99.5 percent and therefore, this one of the standard developments which are deployed in propulsion systems. In fact, (Refer Time: 16:28) types of propulsion systems in India have surface tension based explosion devices.

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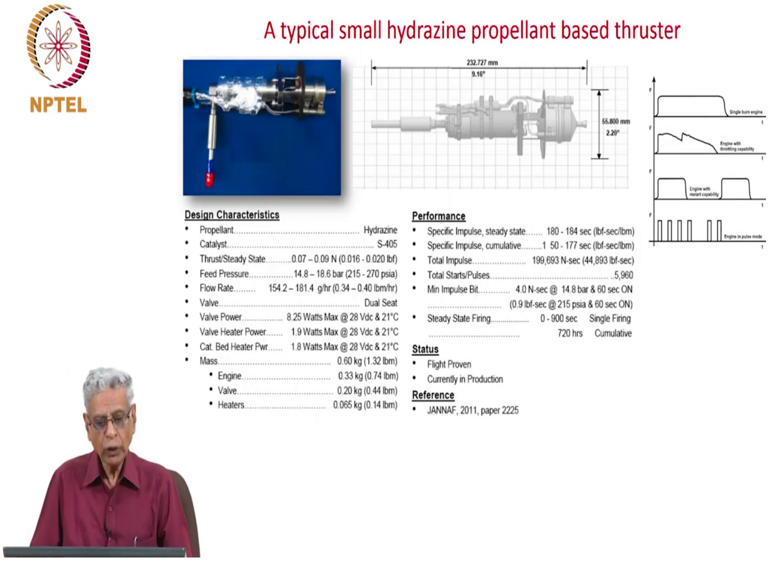

If you look at a typical small hydrazine propellants based thruster. And this has developed in many countries and we have our own in the countries as well, but I am picking up one example which I got and to show you what kind of specifications are required to meet with the development of such a system. As you see catalyst the shell 405 the thrust some number it is in terms of 90 milli Newton's very small. In fact, the smallest one is above 1 milli Newton. There is also something has been developed.

Feed pressure about 15 to 20 bars flow rate in terms of grams per hour and you need (Refer Time: 17:21) wires which are electrically controlled you give a signal it opens or closes. And therefore, specifications in the valve power all that important and you have a bus which provides electricity and that is set at some level usually satellite as you see here in the 28 volts dc is what is used the other standards which are being pursued as well.

Then you have engine mass form so forth. You need a heater to make sure that the temperatures are brought up. There are occasions on the satellite and the temperatures goes very low and you cannot operate it. The specific advantage of hydrogen propellant thrust or catalyst thrust are is that you are able to start it even at ambient temperature of 25 degrees.

I will show you the sketch of how it operates you will recognize that. So, you need to bring up the temperature to that level. Specific impulse as I show is in seconds, but is 1,800 Newton seconds per kg . Well, you have total impulse which you have to deliver in its life that needs to depends on the mass of the propellant with you carry multiplied by the specific impulse.

But, the mass is what is available to it in its life let us say the expulsion efficiency becomes a key parameter for the high efficiency design. There is something called minimum impulse bit which is what is important when you are doing pulses. Well, you will see that this particular system has been frightful one currently in production. So, people can buy it. In fact, it is available for sale to many countries.

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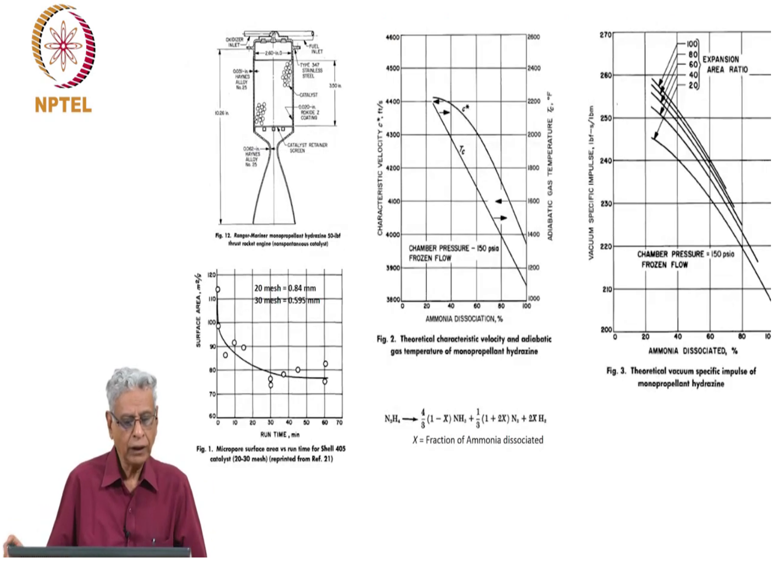

Well, this is how the propellant thrust would look like in a chamber in which you put in catalyst this catalysts are essentially alumina porous alumina on which they coat iridium, but is a special process. I am saying this because a fair amount of effort was put in ISRO to develop a comparable system and it did not perform as well as this material. It is very expensive, but you see is far more expensive to have a satellite running around to give performance to a country in terms of various services like television and so on so forth and it has to last for 10 to 12 years and you cannot based on the cost of a catalyst. So, they disbanded the effort and which all the satellites most in most parts of the world depend only on the shell 405 catalyst ok.

So, the liquid is introduced with it spray the top. If the spray falls on the catalyst bed reaction occurs at the surface and therefore, decomposition occurs. When decomposition occurs it occurs in the way ammonia break and hydrogen breaks into ammonia hydrogen and nitrogen, but its a specific fraction.

Now, the reason why you find this particular equation is because the fraction which we are talking about is related to the amount of ammonia that decomposes. Ammonia decomposition is endothermic and it also does not occur so completely it takes time. In fact, the performances very interesting features. You see the performance in terms of characteristic velocity is written in terms of put per second because I took the data from a JPL report and you can look at it in terms of meters per second as well typically 1,200 2,003 meters per second.

And you see that the flame temperature comes in comes down with ammonia dissociation because ammonia dissociation is endothermic. But you will also see that the amount of decomposition depends on the catalyst bed. You provide large residence time it means large the bed then you will find more ammonia decompose in the performance goes down you do not desire that. So, you choose a bed of some kind, but many other things happen in actual operation. Because of the fact that you are using this many number of times, the spray falls on the catalyst bed. You throw the pieces of the catalyst will break down due to attrition they go out of the nozzle and the bed thickness comes down.

So, you will find that some of these parameters are actually to be experimentally evaluated and in fact ISRO has a facility in Bangalore where this tests are done for 100 1000 cycles for full duration they have to demonstrate how it works ok. So, the curious point is the performance when the system is not in equilibrium is in this equilibrium. Since the dissociation is not complete means the operation is not in equilibrium. Equilibrium means ammonia is completely dissociated. The performance of such a situation is better than that of an equilibrium.

Now, I am saying this very specifically this is in contrast to what happens in solid rocket or you know or liquid rockets of the kind hypergolic are non-hypergolic systems large systems where you will discover that the actual performance lies between what is called frozen in equilibrium. If word frozen means that the equilibrium composition you get at the end of the combustion chamber is the same one which prevails through the nozzle. Now, this is the pessimistic estimate.

The optimistic estimate full optimistic estimate is that this particular composition see end with the beginning of the entry to the nozzle, goes through the nozzle at each pressure and temperature because as you go to the nozzle pressure comes down temperature comes down. The equilibrium property will decide what the composition is and you will discover that at the end of the nozzle there are some other composition not frozen ok. Because of that the performance is better actually.

So, equilibrium has a performance then frozen condition is the performance, the actual performance is in between. The reason why it is in between is because as the flow goes through the nozzle the higher and higher pressure and temperature enable the reaction to occur very fast and so it is a clear equilibrium condition as you go up to the throat and it will be add.

Once it crosses certain portion of the nozzle the pressures go so low. They no longer will be able to sustain the rate and so the assumption is its at frozen condition beyond some point this approximation works very well. And typical recommendation is if I have equilibrium value take 0.7 of that the frozen value 0.3 of that add the 2 that number will be somewhere in between and that actually will be the realized specific impulse this system. This is standard recommendation and roughly follows.

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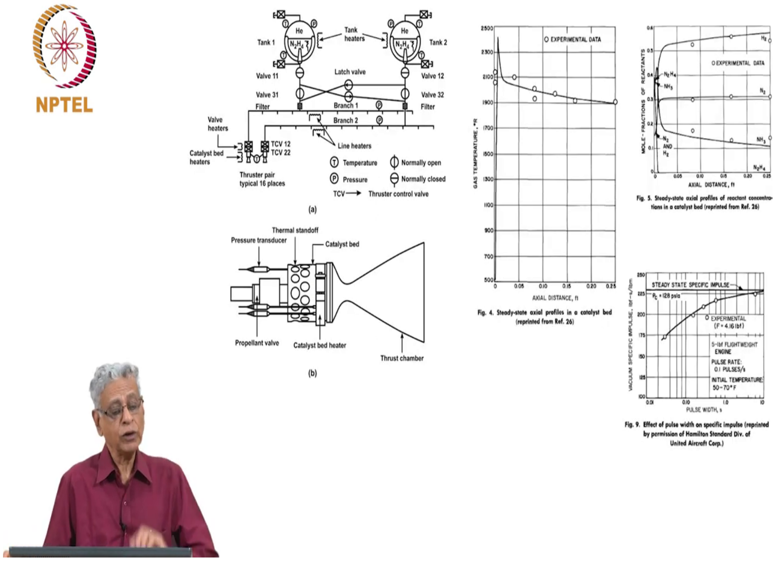

But you see that this is an exception for such an arrangement. Actual system is something for you work well for you to see. You have actually a pressure ranked which is a gas it can be helium or nitrogen. Helium is used is because it is lighter than nitrogen and every bit of kg counts a gram counts if you want to say that. So, that helium is put into the chamber and in this case what is shown is a bladder and you will below the bladder you have hydrogen and you have a device which takes away the liquid and you have valves which will draw it to whichever places.

In a typical you know satellite you may have a large number of thrusters in various directions 16 20 so on. In these direction you have thrusters and you depending on the corrections required you apply a pulse mode in one thruster inform that command is given from ground to the satellite control system and that will operate it. So, you will have valves with heaters. So, make sure the whole fluid is at the right temperature then it goes to the catalyst bed that also has heaters. Because if they go so cold it should not allowed to happen and then you that that particular thrust operates. So, you have various features like thermo standoff and things like that in the actual thrust chamber.

If you look at the temperature behavior through the system you will see that the temperature peaks and about 1,000 about 1,100 k is what the temperature you get at the end of the thrust chamber. You see it hits a high value and goes down to this value and you will see the composition as the distance here too.

Ammonia is coming down and hydrogen going up and nitrogen is going up. This is the way the system behaves see here also shown something interesting that you may want to see. You see that in pulse mode the duration is very short typically 100 milliseconds you will see here and you have pulse duration which is very small. The system does not has not had time to equilibrate. So, you will not be able to get the performance which you get when things have equilibrated. So, you will get the specific impulse in the steady state mode of some value here, but under the pulse mode you will find lower values.

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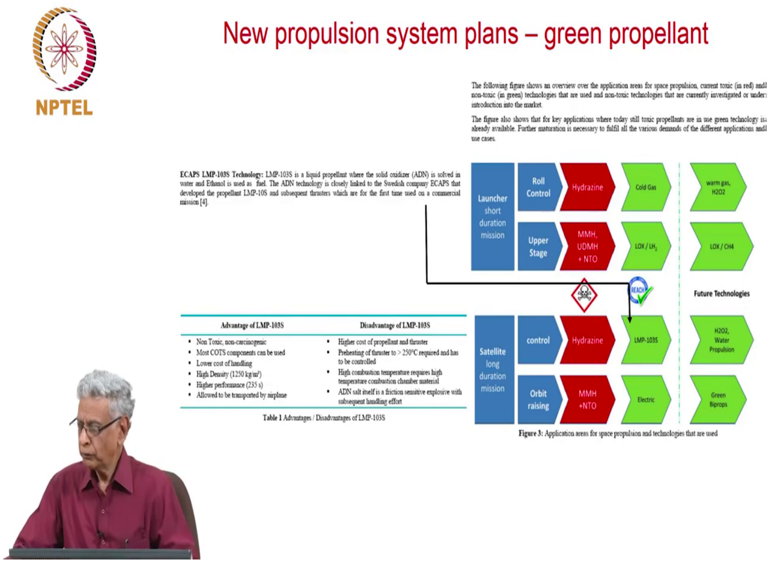

But these are things which are accepted the performance in the system all over ok. Let me show you what I think is in new propulsion system green propulsion propellant that have being talked about these days. See the issue is that even for main propellants which you are looking at UDMH NT O 4 LOX kerosene there are issues of so called environmental hazards. But you do not use them often. Also many of them operate from the surface of the earth. In the case of hydrazine for instance you are leaving behind products of combustion at an altitude where ozone layer is present and it is desired that you do not leave behind product which may cause problems and that environment.

Number 2 hydrogens are for difficult to operate and in terms of safety standards. So, they are looking for alternates and now the alternates is called ADN. I will show a little more details about it. We will find that when you are looking at the launcher which is of short duration mission you use hydrazine for certain applications like a roll control and so on.

Otherwise you could have used cold gas or a hot gas where hot gases meant you take hydrogen peroxide the small thruster we have silver catalyst, it decomposes to water vapor and oxygen and that you can utilize as a thruster too. This is also a possibility. In the upper stages you can use MMH and UDMH plus nitrogen tetroxide as I said or you can use LOX hydrogen is or LOX methane these are options which are available.

In the case of long duration missions for control you use hydrazine generally and for orbit rising you can use MMH N 2 O 4 it is a standard practice even in our country. You can also use choice of electric propellants or green propellants and one of them is what I have shown here is LMP 1035. I am pointing it out because it has already been used in a commercial basis. It is allowed I mean it is shown and therefore, can be deployed on satellites.

It is a based on a solid oxidizer called ADN dissolved in water and ethanol is used as the fuel. Some company in Sweden as developed it ok. There are some advantages and disadvantages listed here perhaps you can pursue them later.

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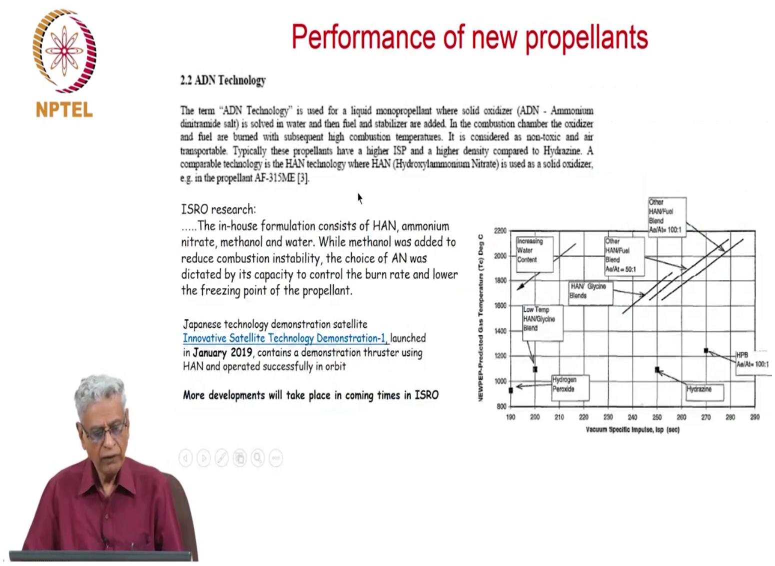

If you look at the performance of the new propellants this of the old propellants. This ADN I told you is ammonium ditetramide salt water and then with a fuel and stabilizer added. These fuel burned with high combustion temperatures compared to hydrazine for that matter. This consider is non non-toxic and air transportable and they have a higher ISP as you see here.

You will see in this domain you find higher specific impulse for them you have HAN and the HAN is one of the propellant features in developed in ISRO part of it is developed the propellant engineering division of ISRO and it is also coupled with the activities which are going on in satellite the activities in the liquid propulsion system center at Bangalore.

It uses ammonium nitrate, methanol, water along with HAN ok. There are some advantages of it and that is why it is being pursued. It is also pursued in other countries. In fact, in one of the systems which have already tested in Japan as I show here that mean its a demonstration thrust to use in HAN and it has already successfully operated in orbit with these developments are taking place and once you have this being done in many countries that a general pressure to move into green propellants. So, that is also happening in our country.