MEMS & Microsystems
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Lecture No. # 28
MEMS for Space Application

Today we will discuss on a very interesting topic. That is MEMS for Space Applications. Already we discussed on the accelerometer as well as gyro chip which are also used in space craft technology. But topic which I will discuss today is only meant for satellites. Positioning a satellite in a particular orbit is an important issue. So how the MEMS device is playing an important role for satellite positioning that is the topic of discussion in today's lecture. You know whatever the either airplane or satellite or the missile whatever you are going to send in space, one of the major concerns is the weight. So miniaturization one of the important issue miniaturization of the devices and different components is one of the major issue when you are going to integrate them either in a space craft or airplane or missile wherever it is.

So the weight and small size, small weight miniature size is the so and you know MEMS will give you a process or a technology where you can miniaturize devices as much as possible with lot of micromechanical action also. So today we will discuss on micro thrusters which are basically used for pico satellite program micro satellite and pico satellite is a topic of research today in many of the advance level institutions around the globe. So Indian Space Research Organization, ISRO is also thinking in near future for micro satellite or pico satellite program. So they had initiated and R&D effort to miniaturize different components and to get highly reliable space qualified low small mass and small size devices which may be helpful for reducing the weight of the space vehicle.

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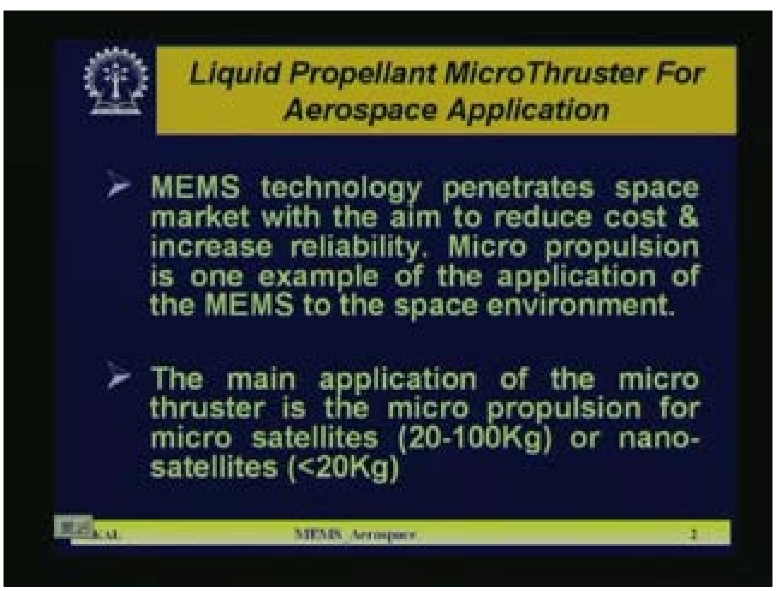

So one interesting area in space market today is to reduce cost and increase reliability. So micro propulsion and in one example of the application of the MEMS to the space environment. So my focus and discussion of today's lecture is micro propulsion system. The main application of the micro thruster is the micro propagation for microsatellite whose weight is within 2 to 20 to 100 kilo and nano satellites whose complete weight is less than 20 kg. So that is for those satellites, how those satellites will be position accurately in a particular orbital system by using a small size micro thruster. That we will see today in today's lecture.

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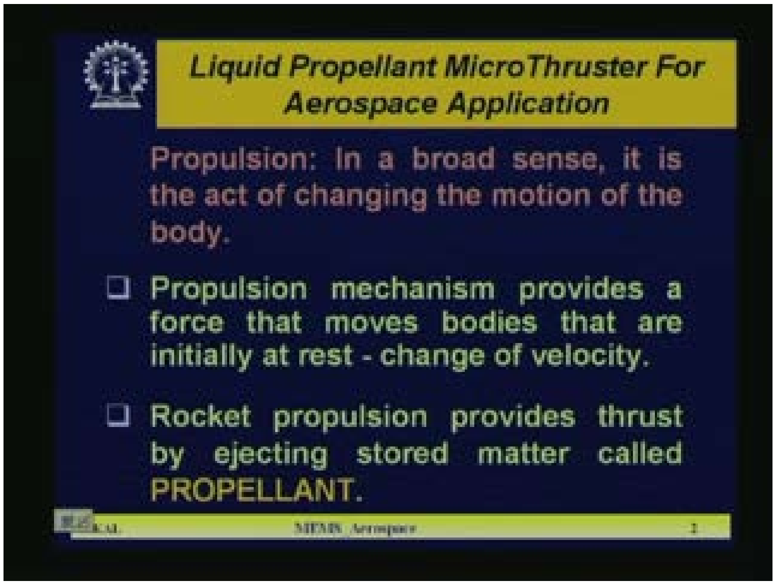

Now what is the propulsion in a broad sense? Propulsion is the act of changing motion of the body. So when you are sending a space craft in space so you have to many times you have to change the motion of the space craft. So that you can accurately position the space vehicle in a particular orbit location. So to changing its motion that is done remotely and by using certain devices which is known the thruster. You have to put some pressure so that the whole satellite could be changed from one location to another location. So propulsion mechanism provides a force that moves bodies that are initially at rest, then of velocity will take place. That is the propulsion. So basically propulsion means it has to change its velocity or motion from rest so that the bodies will move which were initially at rest. Rocket propulsion provides thrust by ejecting stored matter called propellant. So that is the material which is known as propellant there are various kinds of propellant lot of research is going on in the propellant, high efficiency propellant. Some of the propellant examples I will site also today. So that is the one major material research in propellant site using propellant how rocket propulsion can take place by using micro thruster, that we will see today.

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Now what are the issues? What are the different classifications of the propulsion system? They can be classified according to different categories? One is type of energy source that mean energy resource is chemical, nuclear or solar. Depending on the type different class of propulsion systems are there. Second category is a basic function whether function of the propulsion is attitude control or orbit station keeping. East-west orbit station keeping or north-south orbit station keeping that is one of the functions of the micro thrusters which use certain propulsions.
Attitude control attitude of the space satellite that you can control. Third one is type of vehicle which kind of vehicle you are using it may be aircrafts; it may be missile its size type of propellant, type of construction and method of producing thrust. There are various broad classifications based on which we can categorize a particular propulsion system.

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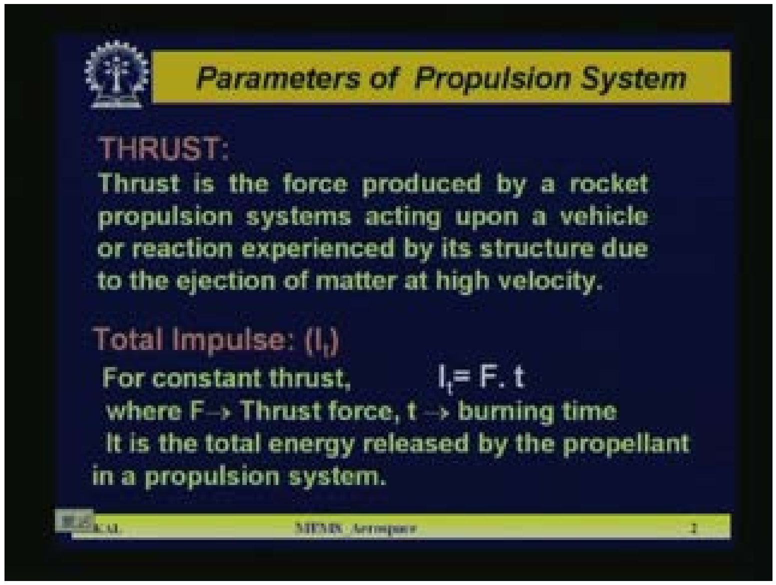

Now what is the thrust and impulse? There are certain parameters based on which the propulsion system is identified or is categorized. That is, one is thrust, that is the force produced by rocket propulsion systems acting upon a vehicle or reaction experienced by its structure due to the ejection of the matter at high velocity. So you see basically the main principle behind is Newton's third laws. So that is you are ejecting some of the fluids and because of that in opposite direction you will getting certain thrust. That is the basic mechanism. Total impulse which is known as I_t for constant thrust the I_t is given by F into t where F is a thrust force and t is the burning time. That is known as the total impulse; time multiplied by thrust force is called impulse. It is the total energy released by the propellant in a propulsion system that is known as impulse which is designated as I_t.

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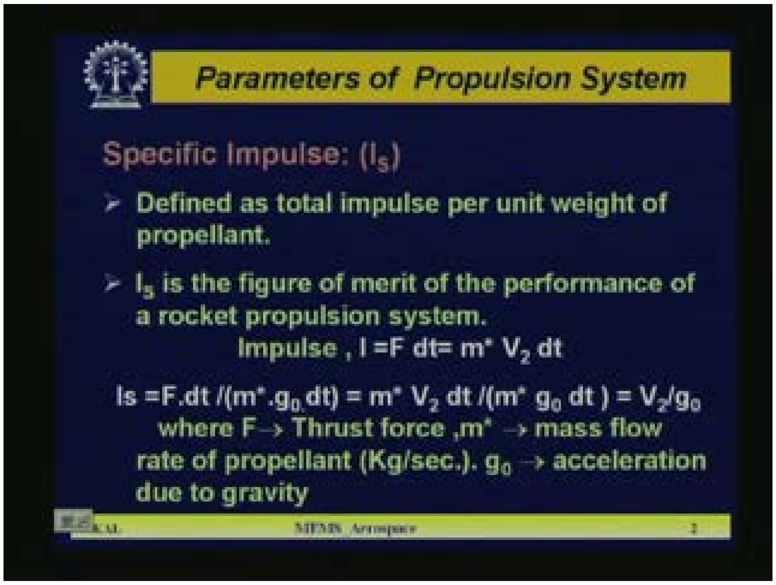

Other parameter is specific impulse I_s, one is total impulse other is specific impulse. I_s is defined as total impulse per unit weight of propellant. That means impulse per unit weight is known as specific impulse which is known as I_s. I_s is the figure of merit of the performance of rocket propulsion system. An impulse I basically F into dt which is force is m star into V_2 dot dt. So that is written here where F is n star V_2 then I_s is F dot dt divided by the m star g_0 and dt where g_0 acceleration due to gravity m star is the mass flow. This is acceleration and DT is the time and F is a thrust. So now if you simplify it then F dot dt is given by m star V_2 dt then it comes V_2 by g_0. So that is the specific impulse I_s is coming V_2 g_0 where g_0 is acceleration due to gravity and V_2 is the velocity in that direction.

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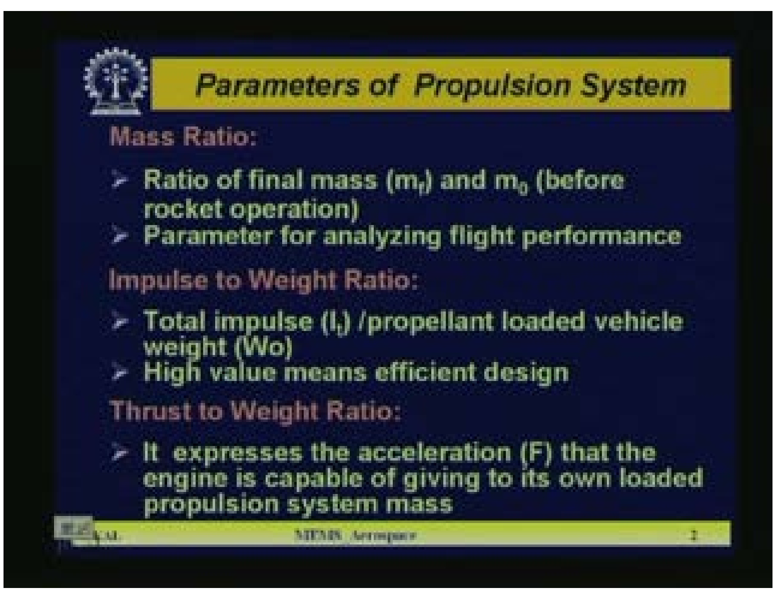

So other parameters are mass ratio, impulse to weight ratio and thrust weight ratio. Mass ratio is defined as ratio of mass, final mass m_f and m_0 that is mf is final mass m_0 is before rocket operation and parameter for analyzing flight information, that m mass ratio is one the job is for analyze flight performance. Impulse to weight ratio that is total impulse I_t divided by propellant loaded vehicle weight W_0. I_t by W_0 is an impulse to weight ratio its high value means efficient design. Impulse to weight ratio should be very high for an efficient propellant system. Another parameter is thrust to weight ratio. What is that? It expresses the acceleration F that the engine is capable of given to it over loaded propulsion system mass, thrust to weight ratio. So these are few parameters.

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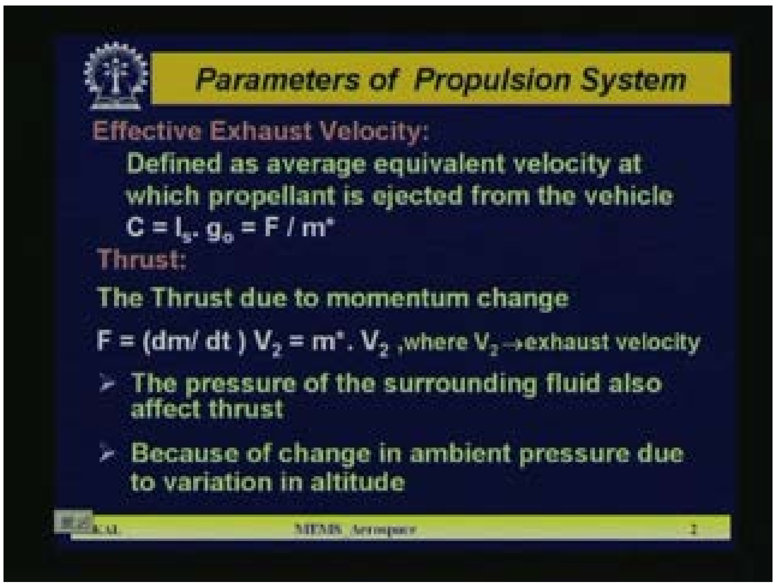

Effective exhaust velocity, this is another parameter define as average equivalent velocity at which is propellant is ejected from the vehicle and is denoted by I_s dot g_0 which is nothing but F by M star. The thrust due to momentum change is given by F equal to dm dt into V_2 is equal to M star dot V_2 where V_2 is an exhaust velocity the pressure of the surrounding fluid also effect thrust. Because of change is ambient pressure due to variation is altitude. You see with altitude the ambient pressure is going to change and because of the change in ambient pressure, the total value of the thrust will be change, because the exhaust velocity with altitude is going to change. Because ambient pressure is different with altitude.

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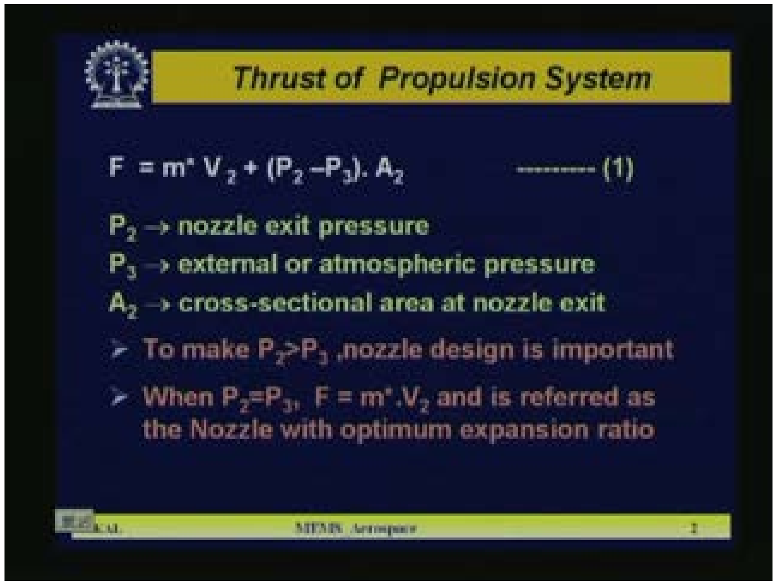

So the F is given by m star V_2 plus P_2 minus P_3 dot A_2 where P_2 is the nozzle exit pressure, P_3 is external or atmospheric pressure and A_2 is a cross section area at nozzle exit. So P_2 and P_3 is the difference of pressure between the nozzle exit and the atmospheric pressure. So that parameter is going to change with altitude and because of that total thrust F is going to change. To make P_2 greater than P_3 nozzle design is very important. Because here P_2 minus P_3 one is one relates directly relates to nozzle exit pressure and nozzle exit pressure depends on the design of the nozzle. When P_2 equal to P_3 then F is equal to M star dot V_2 and is referred as the nozzle with optimum expansion ratio. When P_2 equal to P_3 at that particular moment the F equal M star dot V_2.

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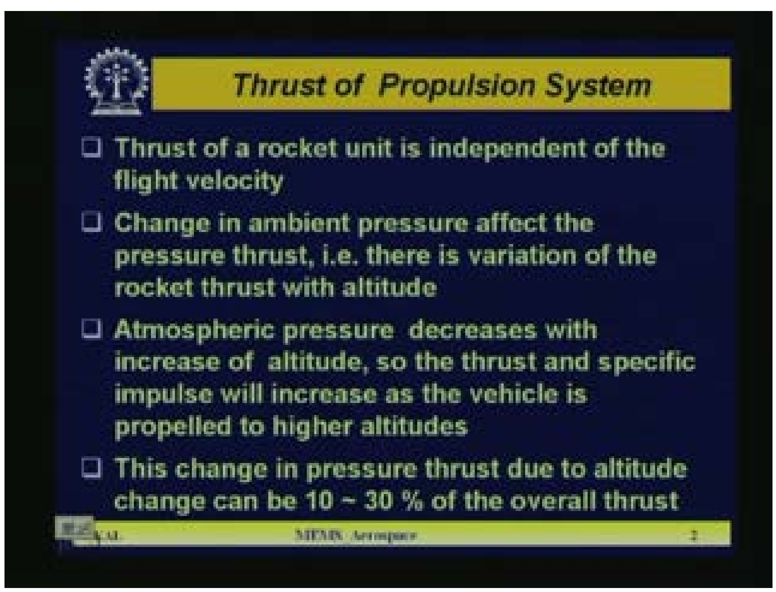

Now thrust of propulsion system. There are certain issues which are mentioned here relating to thrust in propulsion system. Thrust of a rocket unit is independent of the flight velocity. Change in ambient pressure affect the pressure thrust that is there is variation of the rocket thrust with altitude that I mentioned. Atmospheric pressure decreases with increase of altitude so the thrust and specific impulse will increase as the vehicle is propel to higher altitudes. From that relation its coming directly. This change in pressure thrust due to altitude change can be 10 to 30 percent of the overall thrust. Variation may be 10 to 30 percent of the overall thrust.

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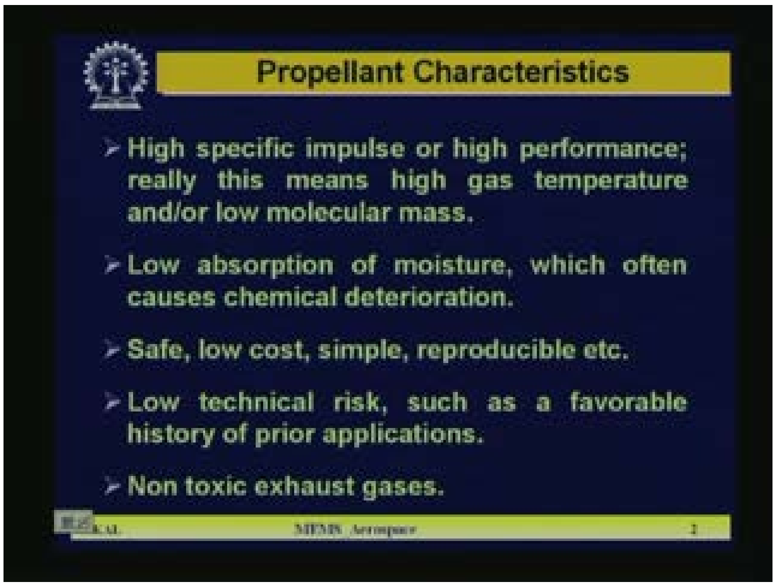

High specific impulse or high performance. This means high gas temperature and or low molecular mass. What is the gas temperature which is ejaculating from the propulsion system and low molecular mass. Next is the low absorption of the moisture which often causes chemical deterioration. Which chemical deterioration means the propellant is chemical if it absorb moisture then it cause some chemical deterioration composition may change and the efficiency of the propellant will also affect. Another issues of the propellant characteristic it should be safe because the propellant which you are going to use, it should be safe. Means safe in different aspects: safe from human hazard point of view and safe from environmental pollution point of view. Because when you launching satellite propellant is ejecting and this should not create nuisance to the atmosphere be which may deteriorate the environment for living beings. Low cost is another issue. It should be very simple and reproducible. These are some of the characteristics. Low technical risk, such as favorable history of prior applications. These are the technical risk that means you know anything you are going to adopt in space you have to know certain history.

Because any technical failure, we lead to loss of enormous amount of not only effort but also money. Because is particular program satellite launching program involves few 100 crores rather of money rupees money. So you have to be properly ensures from the history of that total method. That means before sending anything to the space you have to have in similar atmosphere. Lot of test without taking any risk, so that testing is not space qualification. When everything is qualified in that environment, an artificial space environment is created in that particular lab, specially design lab including pressure. So there all the components or electronic functions are tested and satisfied over the period of time. Then only it is used in any of the space vehicles for launching or any other function. Non-toxic exhaust gases that already I told you, it should not create pollution or it should not disturb the environmental atmosphere. So what is the exhaust gases coming out of the propellant after burning, so it should not produce any non-toxic gases. So these are some of the characteristics. Some of the examples of the propellant are shown here.

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One is double base mixture of some compounds are sometime use. Sometimes simply simple some chemicals are also used DB, AP, AL is basically aluminum, AP is ammonium perchlorate. Sometimes mixture of aluminum and HMX which is cyclotetramethylene tetranitramine. So these are the a few chemicals and apart from those for preliminary testing you can use simple water also has propellant for testing purpose. You can use water also without going to that. The chemical which may be highly expensive or which may in some cases is not much user friendly. The advantages these are solid propellants because water is the liquid propellant. At this, what I had mentioned here these are solid propellant.

There are two kinds propellant used: one is solid propellant, another is liquid propellant. Basically it has to burn; it has to produce some gases which will eject to the nozzle as a result of which your device push forward. A thrust is applied to the space craft or satellite whatever it is. That is the basic objective. So the advantage of solid propellant are it is a simple design, few or no moving part will not leak or spill if it is a liquid, there is a chances of leaking or spilling over can be stopped and restored few times if programmed can be stored for 5 to 25 years without any deterioration of the material. So this is the advantage.

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On the other hand the disadvantages of solid propellant are also there. What are those? Explosion and fire potential is larger compare to liquid propellant. It is an explosive material. Most of the cases and is a very proven to fire. Fire potential requires an ignition system because since it is an explosion, it has to be fired. You need an ignition system. Each restart requires a separate ignition system. Once you start it then second chamber you have to stop then again. If you have to fire the second chamber, you have to again put an ignition system. So each time you want to fire it. So you need an ignition system. Exhaust gases are usually toxic in case of the solid propellant. Some propellant can deteriorate in storage which is known as self-decompose. Cannot be tested prior to use because testing is highly risky. Although sometime it has to be done before actually implementation, but it is highly risky. Need very much safety precautions because of the total system is explosive system and it involves lot of fire hazards.

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Now this liquid propellant. Liquid propellants are water just I name water, ammonia and hydrazine. These are the three liquid propellants which are commonly used. Liquid propellant embraces all the various liquids used and may be one of the following it may oxidizer. That is liquid oxygen, nitric acid etcetera. Fuel that is alcohol, liquid hydrogen, gasoline etcetera. Chemical compound or mixture of oxidizer and fuel ingredients capable of self-decomposition. Any of the above but with gelling agency behaves as thick paint. If you put some gel, that it will not spill but can flow under pressure. So one of the advantages in case of the solid propellant we told that it since it is solid, it is spilling over problem will not be there. But in case of liquid with very low density, there is a leakage kind of thing and some spillover kind of things always that problem is there. So people try to mix some gelling agent. So that its density will be higher and problem of spilling over will be reduced. So these are the liquid propellant.

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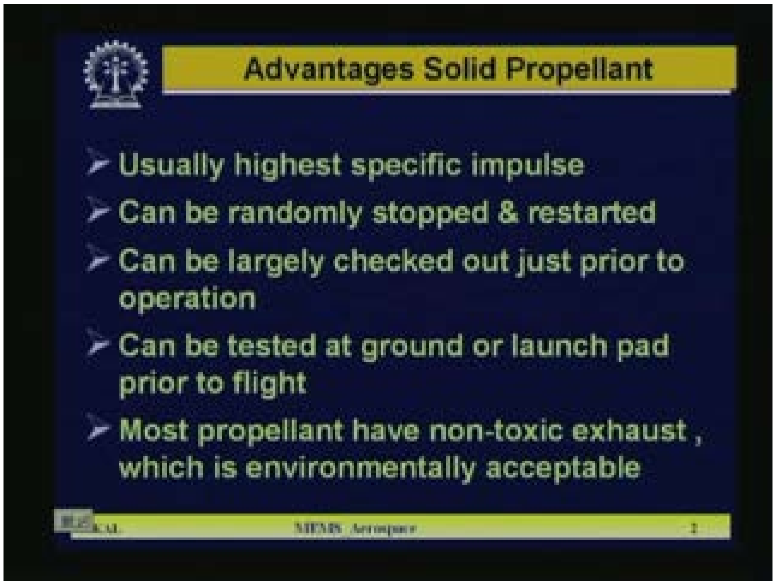

Now advantages of liquid this heading is solid distribute liquid advantages of liquid propellant. It should be it usually highest specific impulse can be randomly stopped and restarted which cannot be done. In case solid can be largely checked out just prior to operation. Can be tested at ground or launch pad prior to flight, most propellant have nontoxic exhaust which is environmentally acceptable. These are the plus point in case of liquid propellant.

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Now disadvantage of liquid propellants are these. A relatively complex design more parts are component leads to more things to go wrong. Since it is a complex a lot of parts will be assemble and any of the small parts may wrong which will compel us to leave the complete module.

Cryogenic propellant cannot be stored for long period except when tanks are well insulated.

Now this cryogenic propellant people are thinking of, so in that case you have to have a tank which is well insulated its liquid oxygen or liquid nitrogen liquid. Gases basically these are the Cryogenic propellant, leaks or spills of several propellants can be hazardous toxic. But this can be minimized with gel propellants which has mentioned in earlier slide also. Tanks need to be pressurized by separate pressurization system. If want to eject the propellant efficiently, few propellant gives toxic vapors red fuming nitric acid in some of the propellant like hydrogen, that is not user friendly at all.

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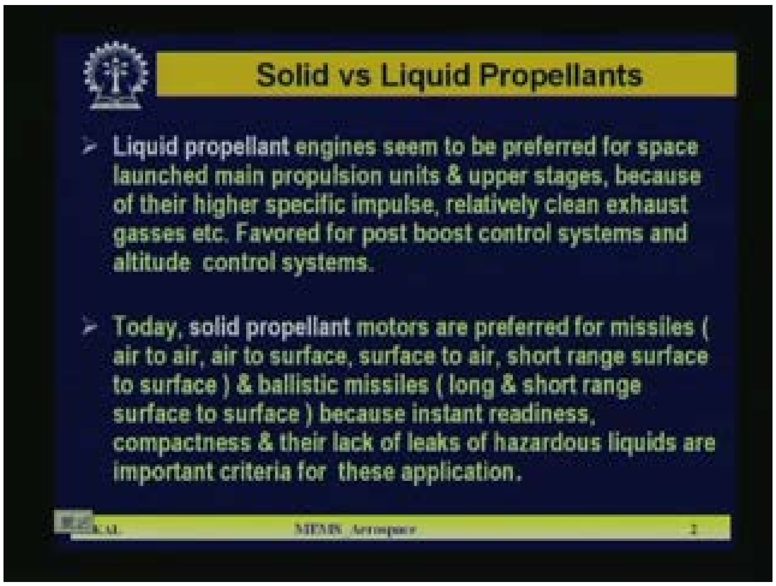

Now if you compare the liquid and solid propellant then we can summarize like this. Liquid propellant engines seem to be preferred for space launched main propellants and units and upper stages. Because if their higher specific impulse a relatively clean exhaust gases etcetera. Favored for post boost control systems and altitude control system. That is the plus points of liquid propellants. On the other hand solid propellant motors are preferred for missiles. Air to air, air to surface, surface to air, short range surface to surface, for this kind of missiles solid propellants are sometimes favor. It is also favored or preferred for ballistic missiles long and short range surface to surface. Because instant readiness compactness and their lack of leaks of hazardous liquids are important criteria for this application. So these are the main features of liquid and solid where to use liquid and where to use solid this is the, it depends on the choice of the application. One is the space satellite, there preferred is liquid and in case of missile program preferred is solid propellant.

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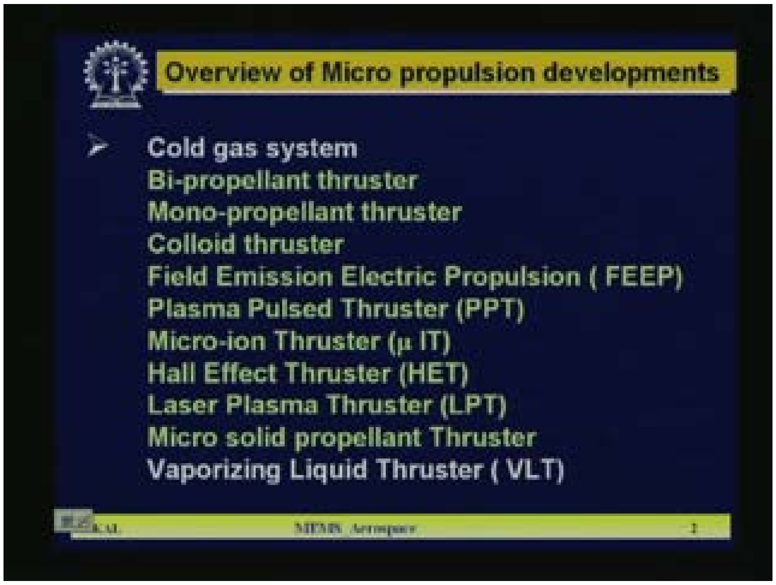

Now micro propulsion developments day by day. It proceeds like that; initially it is cold gas system then switched over to bi propellant thruster. That means not a single material it is mixture of material and the solid or liquid. Then monopropellant thrusters, then Colloid thrusters. Another kind of propulsion is a field emission electric because no liquid or solid propulsion systems are used is a field emission electric propellants are sometimes use long time back. Plasma pulsed thrusters PPT, microion thruster muIT, hall-effect thrusters, laser plasma thrusters, micro solid propellant thrusters and lastly vaporizing liquid thruster VLT. So in case of the micro or pico satellite program the VLT vaporizing liquid thruster is drawing lot of attention. Now we will just concentrate on the vaporizing liquid thruster which is very promising and lot of research is going on in that direction.

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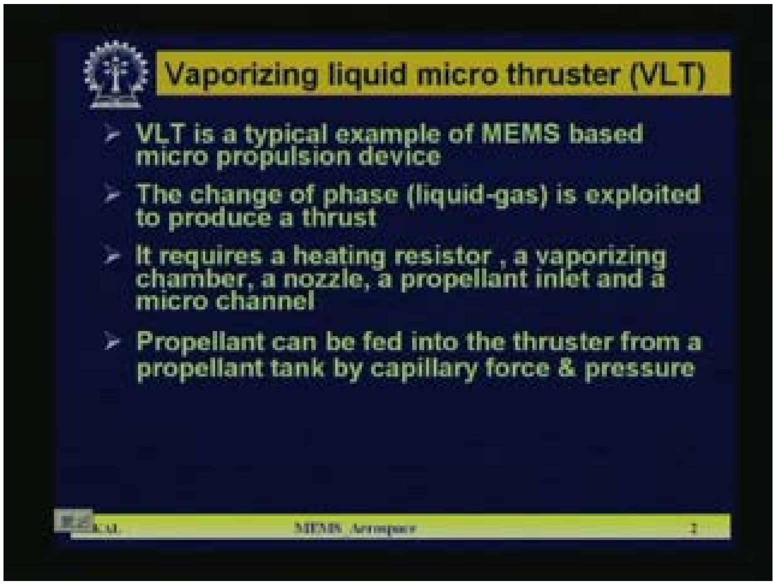

So vaporizing liquid microthruster VLT is a typical example of MEMS based micropropulsion device. It can be easily fabricated using MEMS technology, micromachining technology. The change of phase, what phase liquid to gas is exploited to produce a thrust. Liquid will use initially in the leak chamber propulsion chamber then convert into gas and will force the gas to eject from narrow nozzles which will produce thrust. That is basic principle it request a heating resistor, a vaporizing chamber, a nozzle, a propellant inlet, and a micro channel. So these are the components of the micro thruster. You have to have heating element resistor it may be embedded or it may be surface thin film resistance which can be power to heat any propellant. You have to have vaporizing chamber for ejection of the propellant in gases. You need a micro nozzle and inlet and outlet of the propellants as well as micro channel through which your liquid propellant will enter and gas will eject. So micro channel has to be formed.

All those things can be integrated together to have the micro thruster. If you have the technology for making micro nozzles, if you have the technology for making that small channels which is called micro channels and if you etch the chamber or cavity in silicon which may act as vaporizing chamber, propellant can be fed into the thruster from a propellant tank by capillary force or pressure for pushing the propellant into the cavity if you have to use a pump, then again another addition of components is there and which will increase the total weight for the micro thruster; as well as the cost also will increase. That is why in case of micro or pico program, so ordinary the capillary force or pressure inside the capillary is used to flow the propellant from the tank to the small capillaries inside the device through the micro channels basically.

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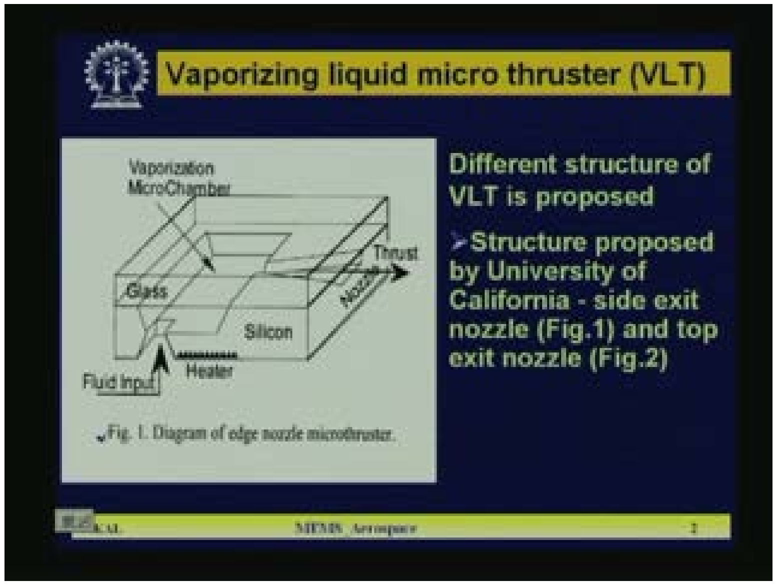

Now here is a schematic diagram vaporizing liquid micro thruster VLT. Different structure of VLT is proposed. Here is one structure which is being used by researches of university of California is shown here in the figure. You can see here the fluid input, here through the nozzle and it is completely made of silicon and here bottom piece is silicon and top piece is the glass and you can see here is a vaporizing micro chamber which has been formed by micromachining silicon and then here one small channel and at the end there is an exit nozzle. So now heater is used here, embedded heater into the silicon. Now if you heat this silicon, through that heater, then in the vaporizing chamber the propellant phase will change from liquid to gases and they will exit through the nozzle. As a result which, thrust will be created in opposite direction. If the gas propellant moves in this direction and thrust will be in opposite direction so that is the basic diagram of the age nozzle micro thruster.

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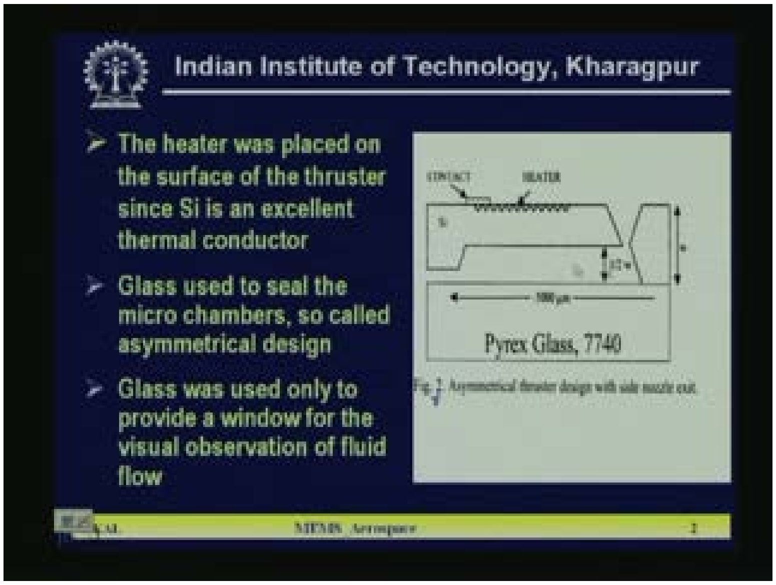

There is another category of micro thruster which is this design is an asymmetric and here instead of bottom the heater was placed on the surface of the thruster. Since silicon is an excellent thermal conductor, just they heat. They are not directly heating the propellant at the surface of the silicon. But they are heating the complete silicon material. Some contacts are made here then, is silicon you know is a good thermal conductor. So here the propellants are injected in one hole and now it is ejected all the design are very crucial to get greater efficiency and bottom plate is complete a Pyrex glass and if this is the width, so here the height of the chamber is half of that. Complete width of the silicon device.

This is the nozzle and here is a chamber and here another nozzle which maybe the input and other is the output nozzle glass used to seal micro chambers so called asymmetric design. Glass was used only to provide a window for usual observation of fluid flow. Since bottom piece is glass, you can easily see how the fluids are flowing to the chamber. Asymmetric means here the whole material is not made of same, whole structure is not made of asymmetrical, means bottom is glass and other is silicon there are certain micro thrusters were both the pieces are silicon asymmetrical structure you can get it. So this is some form of other form of the micro thruster.

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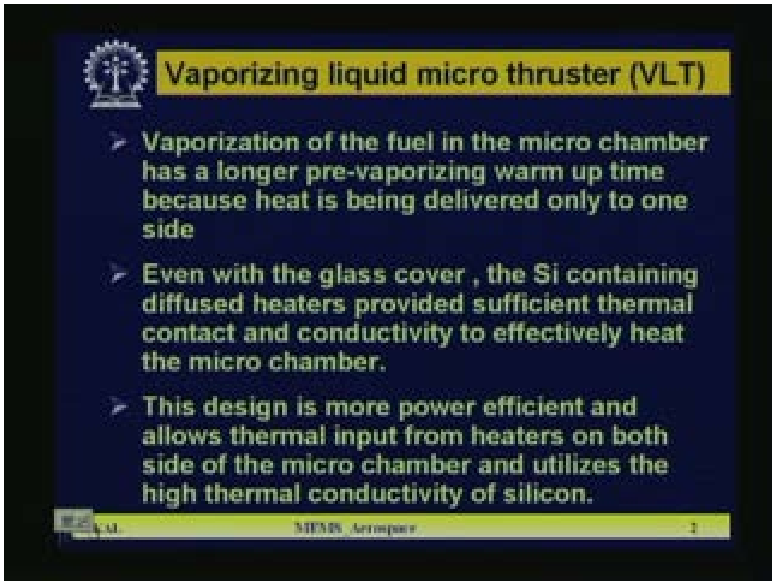

Now here in both the cases the basic principle is like this. Vaporization of the fuel in the micro chamber has a longer pre-vaporizing warm of time because heat is being delivered only to one side. Why one side? Because a heater you have put in one side, only in the silicon here, not in the bottom side. Bottom side is only glass. So that side you have to give some warm up time. So that the complete thing heat will enough to change phase from liquid to gases propellant. So now even with the glass cover the silicon containing diffused heaters provided sufficient thermal contact and conductivity to effectively heat the micro chamber. This design issues more power efficient and allows thermal input from heaters on both side of the micro chamber and utilizes the high thermal conductivity of silicon. Because you are fitting if you want resistor in one side asymmetric so your power requirement less. But if you allow certain time, so obviously that is why they call it is sufficient thermal conductivity get it is power efficient.

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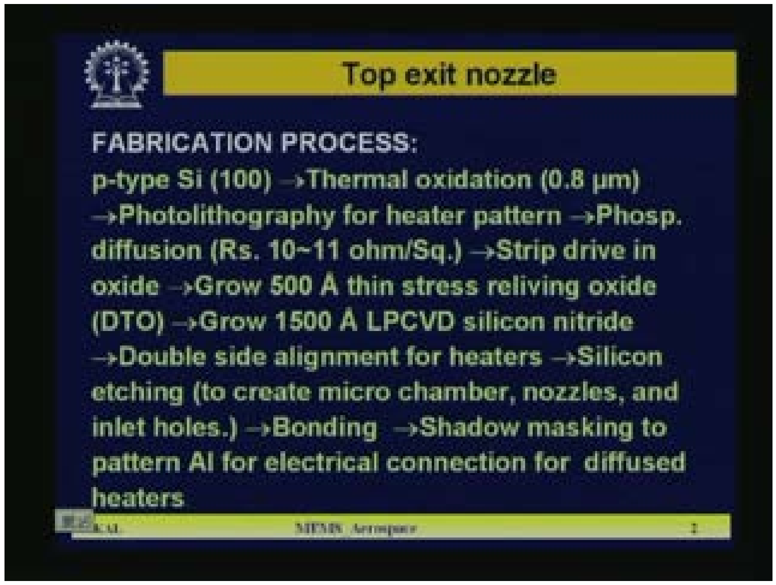

Now what is the fabrication procedure? Bottom was the glass and top was the silicon on which you are making nozzles, chamber etcetera. So they started with P type silicon 1 0 0 and the oxidized thermal. Oxidation which is 0.8 micron, photolithotrophy for heater pattern first you have go for the designing or fabrication of the heater and which is embedded heater. The heater can be made using diffused resistance through silicon and you can have the structure like meander line. So just like coil here instead of coil you are using some resistance which is a diffuse resistance into the silicon or if you put power apply power to that, the embedded, the coil embedded resistance into the silicon. So it will be heated and the heat since silicon is a conducting metal as you transmitted into the propellant. So prosperous diffusion is made 10 to 11 ohm per square stripe drive-in oxide grow 500 angstrom thin stress reliving oxide DTO.

That is the process which they followed they means from where it has been reported. They, after that they grow 1500 angstrom LPCVD silicon nitrite for insulation. Double side alignment for heaters silicon etching to create micro chamber nozzles and inlet holes. These are the 3 micro structures. One is the micro chamber another is nozzle and third is the inlet holes. Then bonding. Bonding is substrate to glass bonding. Shadow masking to pattern aluminum for electrical connection for diffuse heaters. Because at end if you make electrical connection the complete structure is not exactly planer. So you cannot go for the lithography regular lithography. So you have to go for shadow masking technique which I mention in earlier classes also by inside vacuum chamber through some tensile. You can just make the pattern of metals for making contact.

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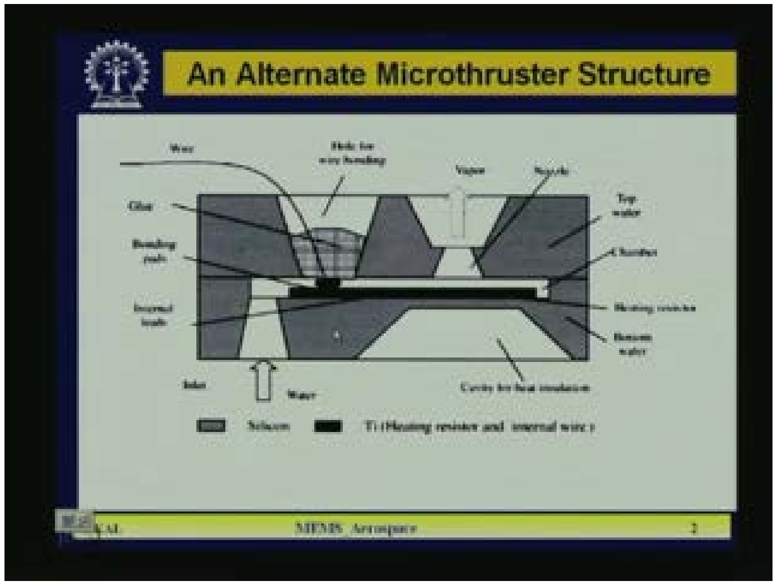

Now this is another alternate micro thruster structure which has been proposed in some literature. What they are doing? They are using the embedded heaters. Another instead of embedded heaters they are they going they used here the thin film heaters. So titanium material they have used for making heaters. You can see here is also there are 2 structures; one is a top or another is a bottom. What they do here is the inlet channel. Because bottom wafer is the inlet channel in earlier case you see this is homogenous structure earlier one glass and other is silicon and both inlet and outlet are made in silicon. But here both the silicon piece one inlet in the bottom piece and outlet in the top piece. So now in the bottom piece other than this inlet, they are forming the heater that is basically the titanium is patterned on the surface of the silicon and then there is a cross sectional view. Obviously you cannot see the total meander line you cannot see. Only some patch black patch you can see and they have some leads to leads and in the top wafer other than the nozzle they have etched another hole and through that hole they made the wire bonding and after making the wire bonding taking wires outside from the titanium heater.

They fill at the end the holes using some glue. So that this is completely covered. So in that case just directly you can heat the element. One advantage is here compare to other is there with minimum amount of power you can get, maximum the phase change and the ejection of the liquid. So in that case ejection of gas is basically liquid forms gas and that will eject. But embedded heater you may require more power. But here one another, one disadvantage is that, this titanium film which is used as a heater has to be insulated. On top of that you have to have certain passivating layer. So that is should not be directly contact to the propellant. So then propellant may react with the titanium and it may damage the resistance value or you may change in the resistance value and may be in due course of time, it can be completely etched away if the propellant is highly toxic and reactive. So this is the alternate micro thruster structure which has been proposed by some group.

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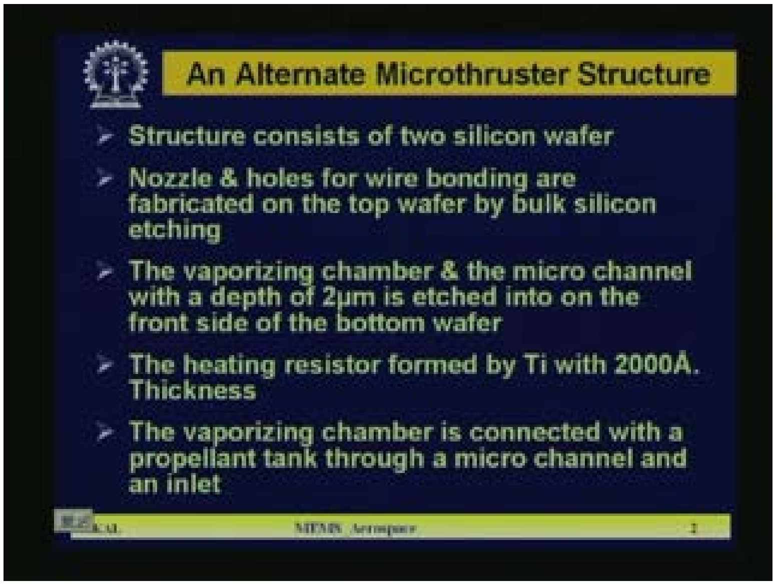

And the basic feature of that alternate micro thruster structure is the following. This structure consists of 2 silicon wafer nozzle and holes for wire bonding are fabricated on the top wafer by bulk silicon etching. So that means here you have to have and separate hole for bonding the heater which is inside the chamber. The vaporizing chamber and the micro channel with a depth of micron are etched into on the front side of the bottom wafer. The heating resistance formed by titanium with 2000 angstrom thickness. The vaporizing chamber is connected with propellant tank through a micro channel and inlet.

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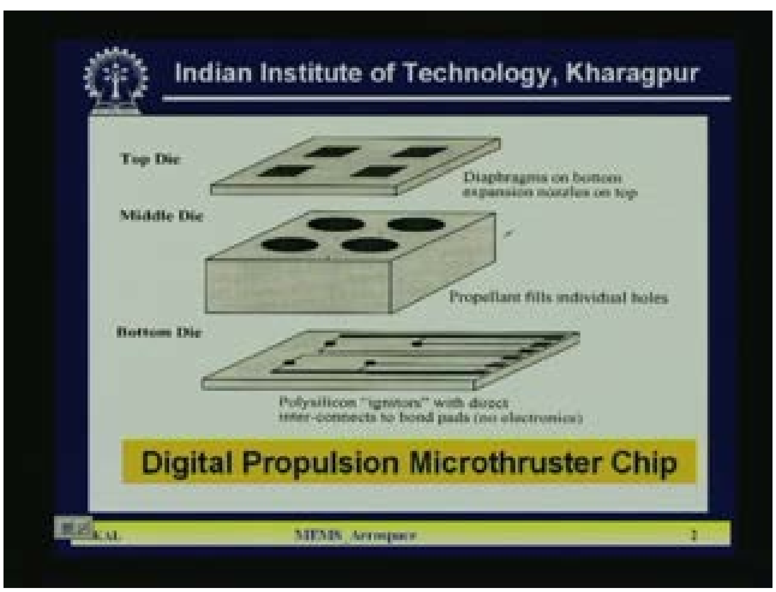

Now another class of the micro thruster is sometimes known as a digital propulsion microthruster chip. Earlier I have called analog here, we called digital. Why? It is some kind of discrete propulsion. In different direction you can give it. That is why it is known digital. Here the basic principle is like that. Basic principle is same. Same means some propellant will be there, it will be vaporized and it has to be ejected and then accordingly the third of Newton's 3rd law some thrust will be created in opposite direction. But here what is being done, there are three dyes are used. One is a dye where the diaphragms are made silicon membrane basically diaphragm by thinning down to make some membrane. In the bottom is the middle dye where you can etch some groups and each group contain some propellant. Propellants are filled in each group. In the bottom dye is having some resistor which is poly silicon resistance which we call the igniters with the direct interconnects to bond pads no electronics is here in the chip.

So you can see the 4 at the chambers. These are propellant chamber, below the 4 propellant chambers there are say small spots you can see here in the bottom dye 1, 2, 3, 4 these are basically the heating elements. So they are connected and here bond pads are taken out. Now when you bond all the 3 pieces substrate bonding you can do all the 3 substrates are bonded together. Now by selectively or judiciously you can choose to heat any of the resistors below desired the chamber. So you can lot of bonding the inputs are there. You can select the inputs depending on your application. So the selected if you select the inputs by some algorithm programming. So selectively you can heat any of the propellant chamber and if you heat the propellant chamber. So just above that propellant chamber which is diaphragm, so that will burst and the liquid will eject through that diaphragm.

So accordingly through which diaphragm liquid is ejecting the thrust will tilt or orient or move the complete satellite. So if similar kind of thing, if you fix on the satellite top surface, bottom surface side surface also, so you can have moment of the satellite either a tilted or directly pushing or little bit up or little bit down. Accordingly you do it by external a selective circuit you can make it outside this complete device. That is why it is known as the digital propulsion micro thruster chip. Here that option is there, selective ignition and selective the ejection of the propellant through a particular diaphragm and diaphragm is puncture. Because if you heat the particular group or particular the propellant chamber, so pressure will be created and due to the pressure the diaphragm will be punctured and the propellant will be ejected. So that is the basic principle of the digital propulsion micro thruster chip.

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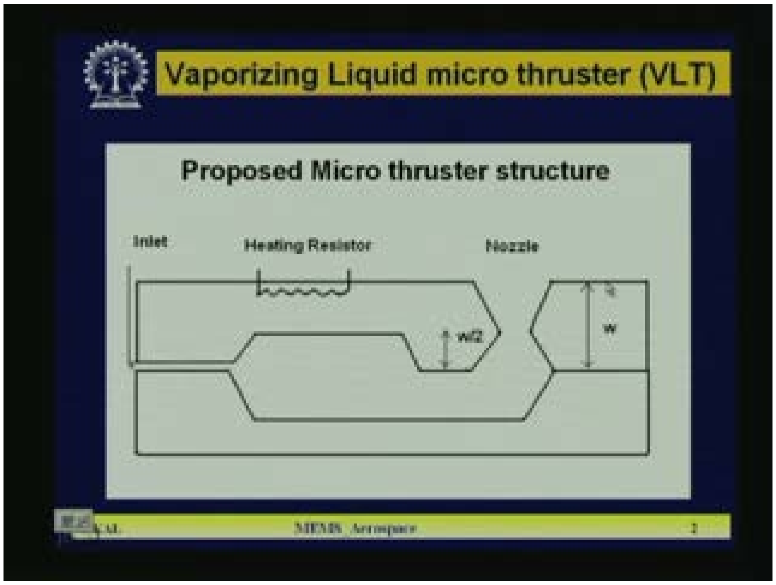

Now we propose a micro thruster structure which is very simple and homogeneous also. And there you can see is an inlet is here. This is the heating resistance and is nozzle and the top loop what will be the size optimum size that you have to have to choose. We have to select and what will be chamber size that is also selected. So a structure like this can be made very easily in the laboratory. So here top wafer we use diffuse, we just fabricate diffused resistors of 50 ohm.

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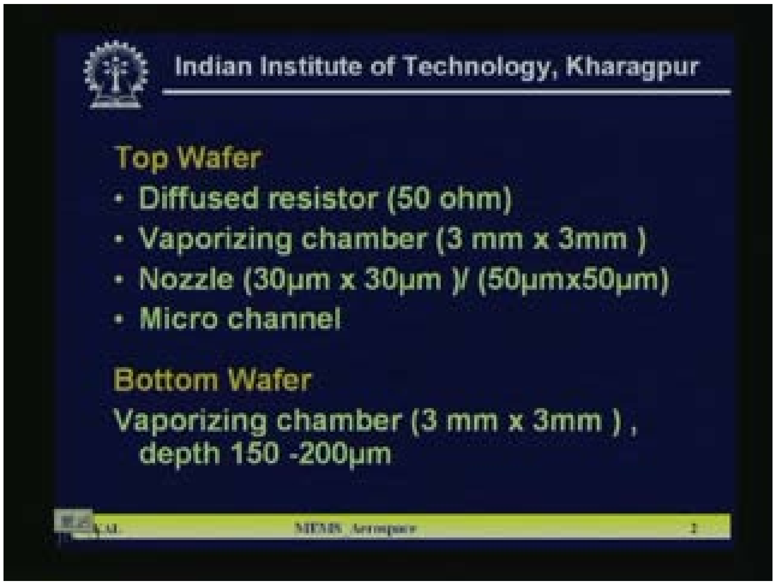

Vaporizing chamber is 3 millimeter by 3 millimeter nozzle is 30 micron by 30 micron. Micro channels will be there, bottom wafer is vaporizing chamber 3 millimeter by 3 millimeters depth will be 150 to 200 micrometer.

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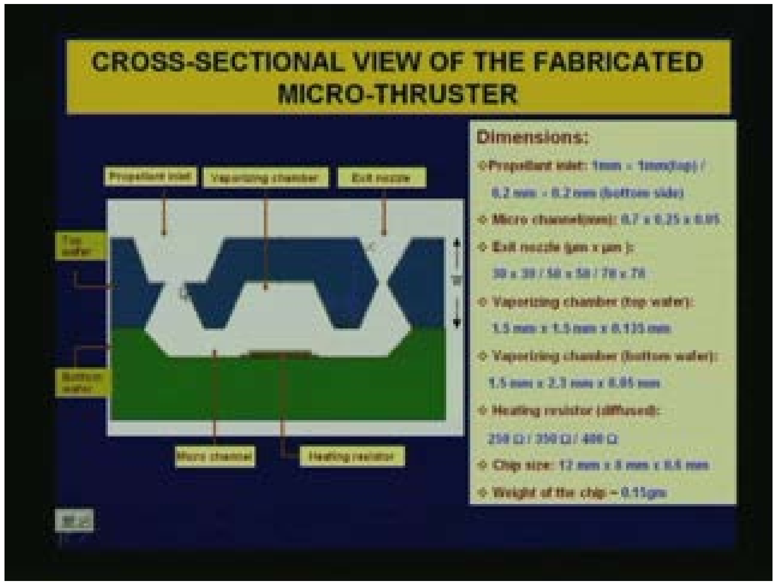

Now we just explain here one structure which we have fabricated in our laboratory at IIT Karagpur. So this structure we have selected because we have enough facility to create similar structure using the bulk micromachining technology. Here again we are using 2 wafers; one is the top wafer, one is the bottom wafer. In the top wafer you can see, there is a propellant inlet, this is the tank and through the tank here is a slow channel and through channel the propellant will flow. This is the vaporizing chamber and this is the exit nozzle and this is the complete width and we have the heater in the bottom piece. The propellant inlet dimensional in the top is 1 millimeter by 1 millimeter bottom side 0.2 to 0.2 millimeter because you see the propellant inlet. Here the dimensional bottom dimensional are different top is 1 millimeter by 1 millimeter bottom is 0.2 by 0.2.

Micro channels of 0.7 into 0.25 into 0.05 exit nozzles are the size 30 by 30, 50 by 50, 70 by 70. We have tested with different exit nozzle to see which is more efficient. Vaporizing chamber is here one point this is the vaporizing chamber, its dimensional 1.5 millimeter by 1.5 millimeter. Vaporizing chamber bottom wafer and bottom wafer in a both case you have etched so that these are top wafer, this chamber is created in bottom, this chamber created. Now invert it and you just seal it, so that the complete chamber you will get it. Heating resistor is diffused resistance you have use 250 ohm or 350, 400 different structures you have made it. Chip size total is 2 half millimeter by 8 millimeter by 0.6 millimeter is thickness 0.6. Weight of the total chip is a 0.15 gram and very low weight so that we have fabricated in our laboratory.

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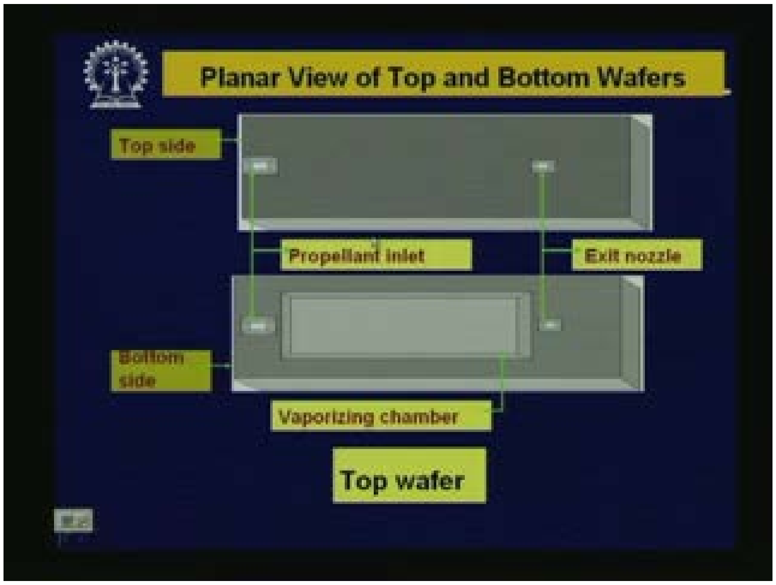

And you can see the cross sectional view of the top and bottom wafer. This is top wafer, top side is this is one chamber, this is propellant inlet, and this is the exit nozzle. If you look here this is the top wafer. Top wafer there are 2; one is the propellant inlet, another is exit nozzle and that if you see planer view you can see here top wafer top side. This is the propellant inlet and this is a exit nozzle and the same top wafer in the bottom side is looks like that. Apart from these two inlets and exit nozzles that is a vaporizing chamber, in the top wafer also etched vaporizing chamber. It consist both the wafer top and bottom. So in the top is looks like that.

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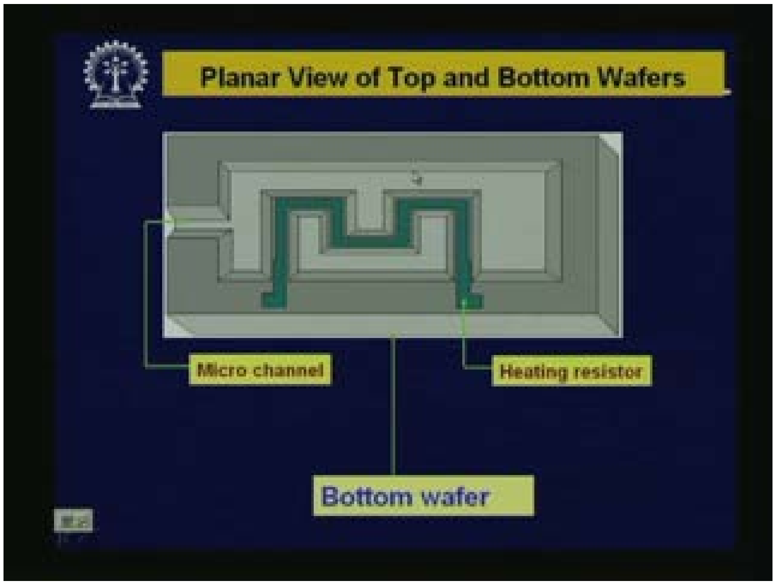

Now if you looked on the bottom wafer, basically one is embedded heater. This is the heater, heating resistance which we made by diffused resistance. Boron diffused resistance of 300 or 250 or 403 different resistance we have used and here is the 1 micro channels. Here through there, so that in that channel, the liquid can propellant can push. This is the heating resistors through the bottom wafer.

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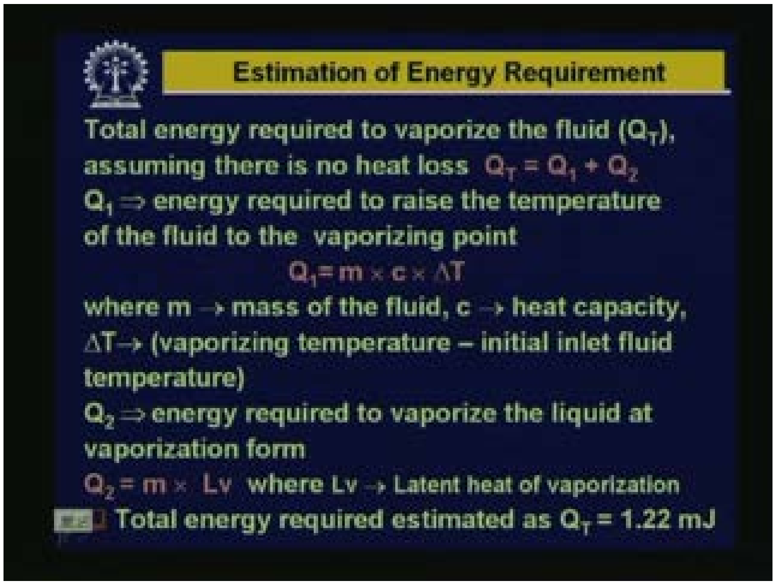

Now total energy required to vaporize the liquid is equal to QT which is this. Some of the Q_2 parameters which is Q_1 and Q_2 where Q_1 is energy require to raise the temperature of the fluid to the vaporizing point. The temperature or energy required to raise that raise to the vaporizing point that is Q_1 and which is basically M into C into Delta T. Where M is the mass of the fluid, C is the head capacity, delta T is the temperature difference from initial and the vaporizing point. And the second term is Q_2 that is the energy required to vaporize the liquid at the vaporizing vaporization form. That is the latent heat nothing else. So M into LV; LV is the latent heat of vaporization, M is the mass. First the room temperature to the vaporization point that is the Q_1 vaporization temperature, to make it wafer you have to have the latent heat amount of energy. So that is Q_2 so total Q_T is equal to Q_1 plus Q_2.

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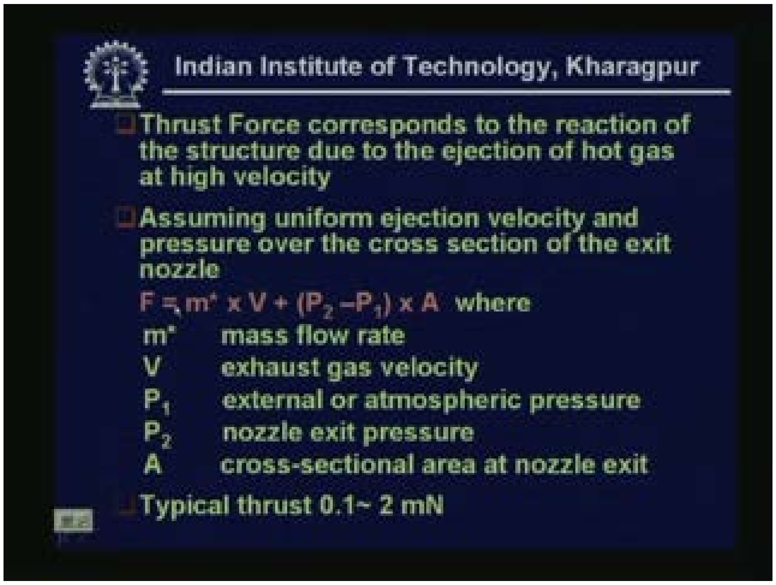

Now thrust force corresponds to the reaction of the structure due to the ejection for hit gas at high velocity. That we have to calculate and that is given by F equal to M star multiplied by V plus P_2 minus P_1 into A. Where M star is mass flow rate, V is exhaust gas velocity and P_1 external or atmospheric pressure, P_2 is nozzle exit pressure and A is construction area at nozzle exit. Typical thrust obtained out of this is 0.1 to 2 mill newton from this micro thruster.

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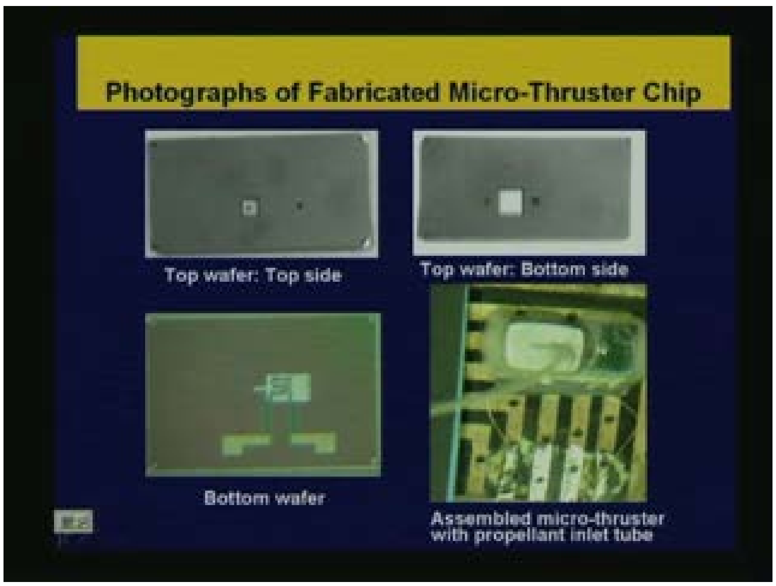

Now this is the fabricated device earlier was diagram and this is the actual photograph of the device is a top wafer-top side, bottom wafer, top wafer-bottom side. This is the embedded heater you can see here in this structure, this is connected through that 2 bonding pads are there and the crowed way we have assemble to test. You can see 1 tube is going there, this is an inlet of the propellant and some exit nozzles are here. If you apply power in a PCB you have made is a crowd device. Then the water propellant we have used and that vaporize and the wafer will come out of the nozzle with a higher speed and we have tested the thrust by some alternate arrangement on the wafer from which the through exit path with vaporize coming. If you put a very thin membrane and on the membrane you put laser beam laser light, so if the membrane to the wafer if it vibrates, so laser will be deflected. So from how much it is deflected from there, if you can calculate how much thrust it is created. In an indirect way, you can just calculate the amount of thrust created by the device when the propellant is coming out of the exit nozzle, so that is in few in earlier slide it is shown is 0.1 to 2 mill newton.

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So now thrust efficiency is one of the important issues. It accounts all the energy losses that do not result it kinetic energy including what is that. Because what is the energy was supplied it must be transmitted to kinetic energy. So that is, if something is loss, so then your efficiency you will be lost. So what are the parameters which can degrade the efficiency waste of electrical power unaffected or improperly activated the propellant that is propellant utilization? Propellant utilizing, propellant is necessary. Loss of thrust resulting from dispersion of the exhaust, heat loss, so all these issues you have to take care to get greater thruster efficiency.

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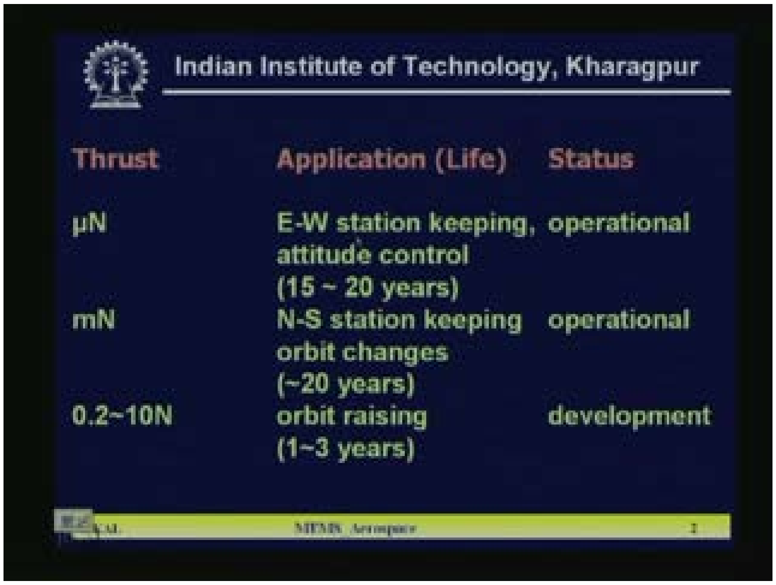

Now the applications of the micro newton, millinewton and newton thrust in different cases. So east-west station keeping attitude control. You need micro newton kind of thrust and strategy is operation is used. Now a day 15 to 20 years its working its life millinewton kind of thrust required for north-south station. Keeping that require for orbit changes, that is also operational, 0.2 to 10 Newton is orbit raising. It is active for 1 to 3 years its development is not a done is under development stage. So micro newton, millinewton and 10 Newton is required for orbit raising. These are the different application.

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Now overcoming translational and rotational perturbations in satellite orbits such as NSSK.

What is the NSSK? NSSK is here North-South Station Keeping that is NSSK and EWSK East-West station keeping. So now overcoming translational and rotational perturbations in satellite orbits such NSSK of satellite in geosynchronize orbits or aligning telescope or antennas in low LEO or medium earth orbits LEO is a low earth orbits and MEO medium earth orbits. For a typical NSSK task in a 35 kilometer orbit a velocity increment of about 50 per second every year or 500 meter per second for 10 year might be needed. So that means it is not instantive, in different time you need it. Potential mission such as interplanetary travel are also candidates for electrical propulsion. For example return to the moon, mission to the mars, require high thrust and power. So lot of R&D is going on in this direction so that these things in miniature form can be produced. So that lot of innovative research can be carried out in the near future using the MEMS devices. So here in this lecture I gave you a small PML of a particular micro thruster which is being used micromachining technology and it is also one of the programs in our county space program. So let me stop here today. Thank you very much.