Jet and Rocket Propulsion
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Lecture - 39

Good morning. So, we are inching towards the end of the course. We have already covered in great detail the chemical rockets, rocket propulsion, and the basic principles. Now, only the last topic remaining to be discussed in this course is electric rocket propulsion. So, in the next couple of lectures, we are going to talk about electric propulsion for rockets.

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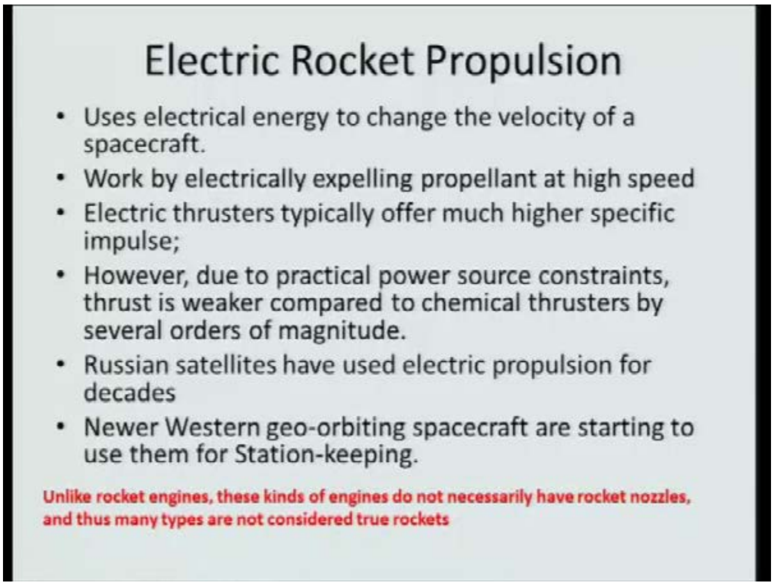

Now, first of all what is electric rocket propulsion? Electric rocket propulsion uses electrical energy to change the velocity of a space craft. That is the basic remains of electric propulsion. Now, the work is done in these systems electrically expelling the propellant at a very high speed. In the chemical rocket essentially is the conversion of the potent, the chemical energy into kinetic energy, but here in this case the conversion to kinetic energy is done electrically.

So, electric energy is converted into kinetic energy, and the electric thrusters typically offers much higher electric impulse compared to chemical rockets. Reason being that the mass the velocity produced by these devices are much higher compared to the chemical systems. So, because of that the specific impulse is much higher. However, the limitation is the practical availability of power, how much power is available to the system and due to this practical limitation or the power source, constrained thrust is typically much weaker compared to chemical thrusters by several orders of manager. For instance, typical chemical thrusters of rocket will produce tens and thousands of Newton's of thrust, whereas electric system typically will be less than 1 Newton. As we go along, we will see that the thrusters produced one say in the range of milli Newton or micro Newton or at the most to a Newton.

So, that is the major limitation that the magnitude of thrust produced by device. These devices are much less compared to the chemical rockets. However, these devices have their own advantage and own specific use. For example, Russians satellites have used electric propulsion for decades starting from 1960's. They have been using electric propulsion systems in their satellites for various applications. I will explain what those applications are in which typically the electric propulsion systems are used, where the chemical propulsion systems are not very effective. Now, newer western geo orbiting spacecraft are the space craft designed for deep space. Applications are starting to use particularly first station cubic for maintaining the satellite within its course. These small electric propulsion devices are now being used extensively unlike rocket engines. Many of these types of electric propulsion system do not have rocket nozzles.

So, therefore, in the strictly speaking sense, they cannot be considered as rockets. However, some of them do have nozzles. We will talk about them. There is a special category of electric propulsion systems which do have nozzles, but many of them do not have their nozzles. So, therefore, it is not that through the nozzles, you are accelerating it to a high velocity. Essentially the acceleration is primarily because of electric forces or magnetic forces and not because of the fluid mechanic acceleration. So, that is why in classical sense, probably some of them cannot be classified under rockets, but in general sense they are using electrical energy for the production of thrust. All of them are classified under electric propulsion systems.

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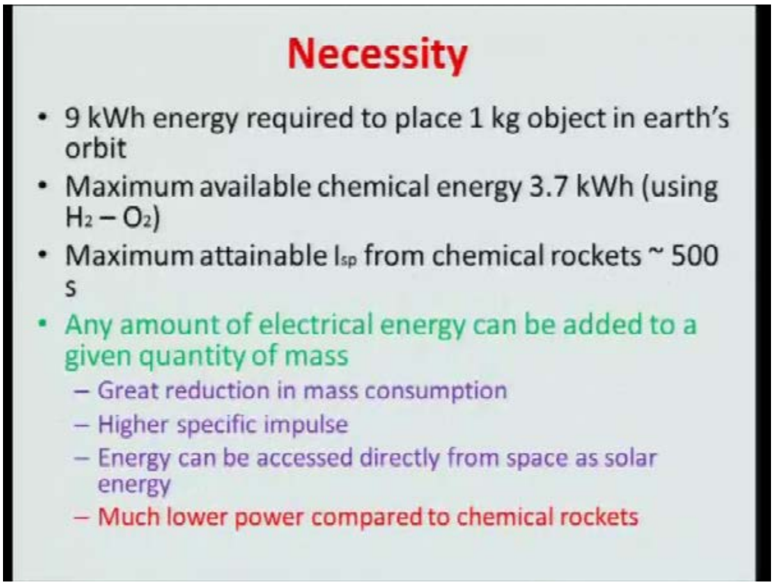

So, with this background, let us see first why do we need electric propulsion system? Typically, it has been now acknowledged over the world that in order to place 1 kilogram of object in earth's orbit, you need 9 kilo watt hour of energy to produce to place 1 kg of object in earth's orbit.

Now, the maximum available chemical energy which is if you say burning tragic propellant hydrogen and oxygen is 3.7 kilo watt hour per kg of propellant, only 3.7 kilo watt hour of energy is available from the maximum possible by burning hydrogen and oxygen. So, you can straight away see that about 2.5 kg close to about 3 kg of propellant is required to place 1 kg of object in the earth's orbit or may be more because there will be other systems also. So, therefore, this proves a limitation that if you have to put a certain thing in an orbit, how much propellant you are allowed to use. Because of this limitation, the maximum attainable specific impulse is limited to about 500 seconds for about 480 to 500 for chemical rockets burning hydrogen and oxygen as propellants.

So, as this limitation is primarily because of how much velocity increment you can get because that depends on your nozzle size. Nozzle size is limited because if you make the nozzle bigger, the rocket is going to be heavier or the temperature you can get now, temperature is also limited by the heating value of the fuel. So, you cannot get much higher temperature than what is physically possible. Then, only thing is that you have to expand it more. You have to put a bigger nozzle and that adds to the weight of the structure. So, there is an optimum value which you can choose. Because of that the specific impulse which essentially is the velocity divided by acceleration due to gravity.

So, the velocity increment you can get from a practical chemical system is limited and because of that, at the most about 500 second of specific impulse you get. However, if you are using electrical energy, the chemical energy has a limitation because to a 1 kg of burning 1 kg of propellant, you can produce only a fixed amount of chemical energy. Depending on the heating value of that, you cannot produce more than that no matter what you do whereas, any amount of electrical energy can be added to any given quantity of mass because electrical energy is not related to the amount or mass you are using. So, to a particular unit mass, any amount of electrical energy can be imparted.

Now, if that is the case, there is a great reduction in mass consumption. You can take a very small amount of mass and energize it to very high level. So, therefore, the amount of mass requirement is much less and it is energized much higher level. So, it will be moving at higher velocity. So, specific impulse will be more. So, because of this we can use very small amount of mass and accelerate it to a very high speed. A high specific impulse is attainable and this energy, the electrical energy. Another advantage of electric propulsion system is that it can be accessed directly from space as solar energy because solar says which can absorb solar radiation and produce solar energy, which can be then used for the propulsion.

So, we do not have to separately carry energy source or fuel. Only thing what you need is something to drop this energy and then, use it in the way that we will discuss to produce thrust. So, there will be a conversion of this electrical energy to thrust power, but that is much economical compared to chemical energy and not limited by this velocity factors. However, the problem is the amount of power produced by will be much less compared to chemical rockets. Why we will discuss that? Why the amount of power produced is less? It is because typically the efficiency of the systems is much lower compared to chemical. The efficiency mean the energy conversion efficiency is much lower compared to the chemical rockets.

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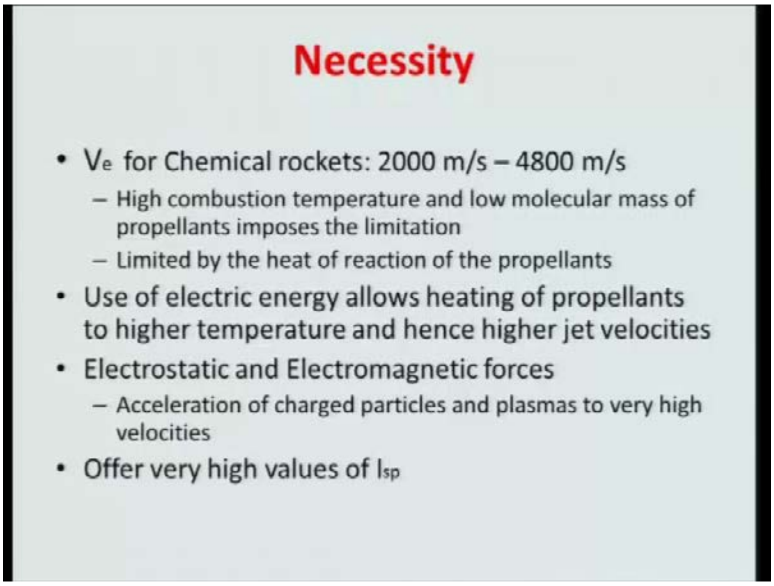

So, this kind of brings out the necessity of electric propulsion system. To continue with this, the exact velocity attainable by a chemical rocket is limited to about 2000 meter per second to about 4000-8000 meter per second. So, now, what limits this thing? First of all, the high combustion temperature if you go to very high temperature as I have discussed earlier, the molecules start to dissociate and dissociation reactions are endothermic. So, therefore, the available energy goes down. So, as the temperature goes up, the available energy reduces.

So, therefore, there is a limit to the velocity increment. We can go in an attempt by going to higher combustion temperature. At the same time, we go higher temperature, the heat losses will be more. So, that also reduces the available energy at the same time. So, first the high combustion temperature and also, the low molecular mass of propellant imposes the limitation on the velocity increment that we can get. So, as I have mentioned previously, it is limited by the heat of reaction of the propellant. So, every propellant combination has a specific heat of reaction. It cannot get more than that. Now, use of electrical energy on the other hand allows heating of propellant to higher temperature. There is a class of electrical propulsion system I will discuss which actually directly heats the propellant. Others may not heat the propellant, but one class directly heats the propellant and there we can go to a very high temperature. It can be close to 20000-30000 Kelvin. Very high temperature can be attained by electrical heating and hence, if you can get higher velocity temperature, you can get higher jet velocities.

So, by electrical heating or by providing electrical energy, we can go to very high jet velocities. This is one of the major advantages of electrical propulsion system on other thing. Instead of heating, we can also use electrostatic or electromagnetic forces to accelerate the propellants, but in this case, they need to be charged. So, we will talk about them. So, electrostatic forces can be used or electromagnetic forces can be used to accelerate charge particles and plasmas to very high velocities and because of this, we get always very high values of specific impulse. Bottom line is the electric propulsion system. The velocity of exhaust jet is much higher. Order of magnitude is higher than what is attainable from chemical rockets. So, that is one of the major advantages of electric propulsion systems which provides us cc with higher specific impulse.

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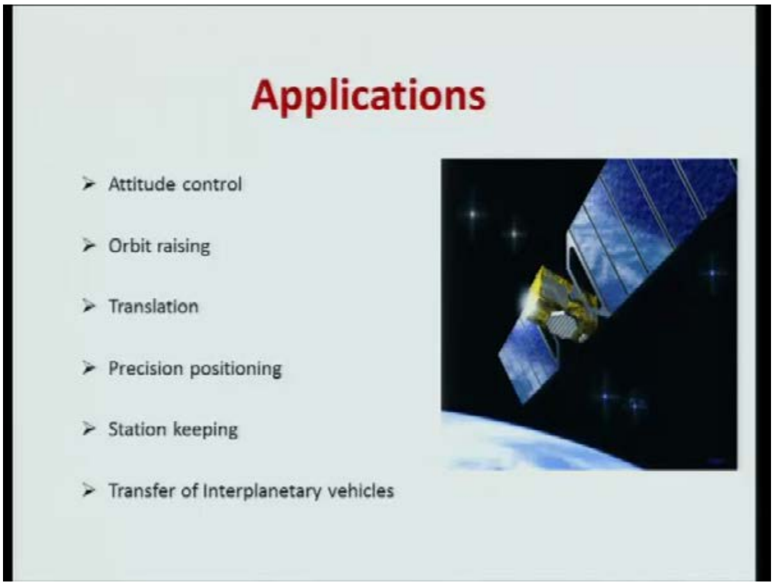

Now, let us look at some of the applications of electric propulsion systems. First and foremost is attitude control in outer space, where satellite is moving or vehicle is moving this, typically not much of drag. So, whenever it goes out of the particular attitude, you require very small amount of thrust to bring it back. So, that can be done very effectively by these electric propulsion devices.

So, one of them is attitude control. Secondly, orbit tracing where in any machine actually you go in steps. You go to one orbit and from there you go to another orbit, from there you go another orbit. Similarly, when you are de orbiting, it comes from higher orbit to lower orbit like that. So, this orbit transfer mechanisms or other processes, the vehicle itself is moving with a very high speed as a small push is good enough to take it out of the orbit and take it to a new orbit. So, again small amount of thrust is good enough. So, this electric propulsion devices are very effectively can be used for orbit tracing. Similarly, translation going from one place to another precision positioning particularly will let us have, we have to precisely dock vehicle into a space station or something like that. Precise positioning is very important.

So, very small precise amount of thrust is required and that can be provided by these thrusters in a very good controlled manner. Then, station keeping essentially requires attitude control precision positioning transition. Everything is station keeping where you maintain the satellite in a certain particular orbit, so that again requires small amount of thrust which can be provided by this electric propulsion system, and transfer of interplanetary vehicles. Typically if you are going for large distance, say mission to mars or towards the edge of the solar system, very large distances, in that case many times electric propulsion systems become very handy because the mass consumption rate is very small and because of that a small amount of propellant will go a long way.

So, the life of the life expectancy of these vehicles will be much longer because these missions for interplanetary vehicles essentially are long terminations. So, that in order to continue with the mission, you need some propulsion systems and that has to work for years. Chemical propellants once they start burning, they will burn out very fast and their required flow rate is also much higher, but these systems, as we will go along, we will see that the mass requirement is very less and because of that a small amount of propellant can last for a long duration. So, therefore, for this long time of ages, this is a preferred system for propulsion.

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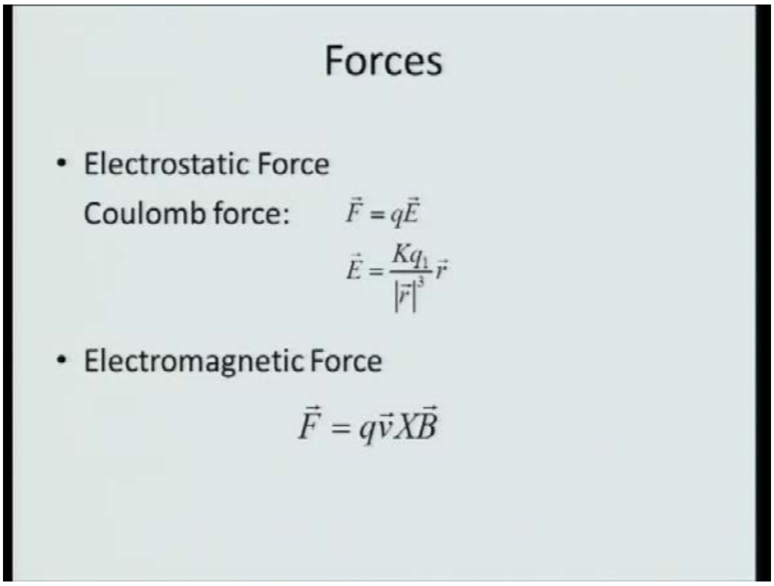

Now, let us look at what are the different forces. Electric forces are electromagnetic forces that actually take part in electric propulsion. There are primarily two types of forces. One is electrostatic force which is also called coulomb force which is given by this expression F equal to q times E, where E is the electric field which is given by K which is a constant q 1 is a charge of that particular point and r is the distance between the two, the one by the two charge particles. So, E is the electric produced by a charge particle located at a particular location and q is the charge of the particle. So, therefore, this is Coulomb force that is produced because of the presence of two charge particles close to each other.

Now, depending on this Coulomb force, one particle, the lighter particle will move. So, if you produce this force, we can move particles. Another type of force is electromagnetic force also called Lorentz force which is given by F q v XB, where v is the potential field, B is the magnetic field and q is the charge. So, electric field and magnetic field and the charge q is the charge of that particle that produces another force on this particle given by this F, Lorentz force. So, again a charge particle is subjected to this force field. It will start to move with a particular. Now, this particle is to see q. These are sub atomic particles, very small particles as we will see there will be photons. So, sub atomic particles, the mass is very less, right. So, even if a small force will produce very high acceleration because force is mass times acceleration. So, mass of the particles are very less. A small force will produce lot of acceleration. So, the particles will be moving at a very high speed and that is primary idea of any electric propulsion system taking small particles moving them at very high speed.

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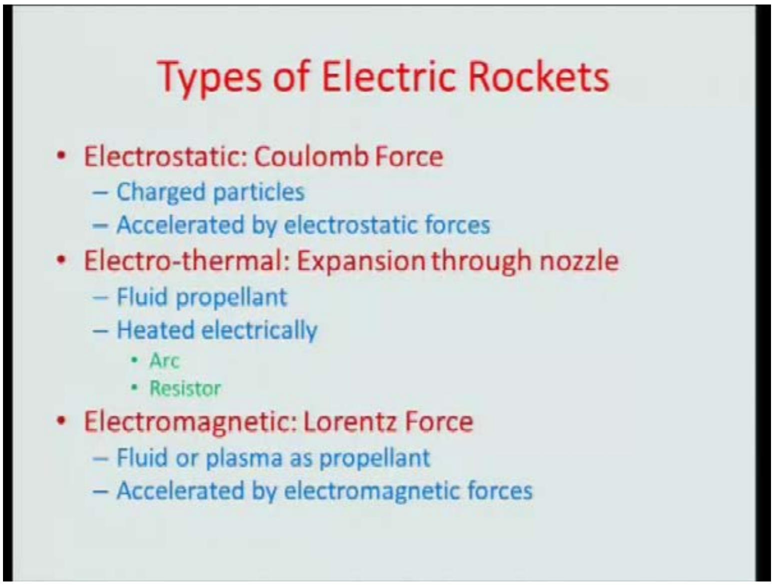

So, next let us talk about what are different types of electric rockets. They can be classified under three broad categories. One is electrostatic propulsion systems which essentially are governed by Coulomb force as I have just discussed where we produced charge particles. By some means, we will produce charge particles. Typically the propellants are treated in such a way that charge particles are produced and then, these charge particles are accelerated by electrostatic forces. So, that is usually at the back of all electrostatic propulsion systems. The other category is electro thermal. In electro thermal systems, we have a fluid propellant which is heated by electric energy and because of this typically the propellant will be mostly in liquid phase. Because of this heating, they get converted into gas and heated to a very high temperature. So, you have a heated gas at a very high temperature. Then, it is expanded to a conventional and converging diverging nozzle and because of that very high velocities are produced at the exit. So, since you do not have the limitation of chemical energy, you can heat it to a very high temperature.

So, typically they can be heated by producing an electric arc which is very strong temperature, very high temperature zones or resistive heating. By this means, you can heat it to a very high temperature and then, allow the heated gas to expand through a nozzle. So, this is typically electro thermal propulsion system and the third category is electromagnetic propulsion system, where the primary force is the Lorentz force. As I have just discussed few minutes back, here once again we have fluid or plasma as propellant and these are charged and then, an electromagnetic force is created around it and the acceleration is produced by the electromagnetic force field.

So, in the electrostatic, you need only electric field whereas, in the electromagnetic, you need electromagnetic field that is the electric field and a magnetic field. So, essentially some time the electric field itself produces the magnetic field and some time, you have separate magnetic field produced. So, these are the various types of reactive rockets. Now, what we are going to do is, we will discuss each type of these rockets and within each of these categories, there are various versions depending on various methods of energisation. So, we will discuss various types of this. So, today what first we will do is, we will focus on electrostatic. So, all our discussion today will be essentially focusing on electrostatic propulsion system which uses full force to accelerate particles. In the next lecture, we will talk about electro thermal and electromagnetic, and that will then cover the entire domain of electric propulsion system.

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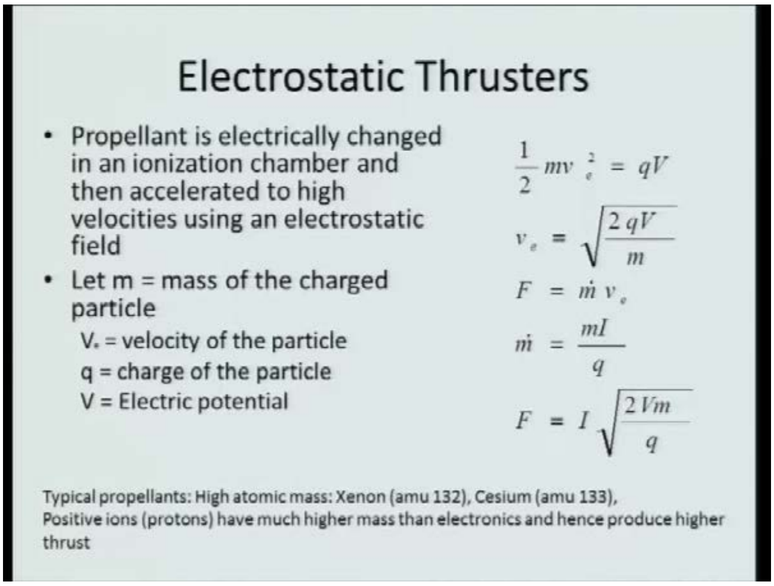

So, to start with the electric electrostatic propulsion systems or electrostatic rockets, let us see what exactly happens in electric thruster, electro static thrusters. The basic principle is that the propellant is electrically charged in an ionization chamber, and these charged particles are then accelerated to high velocities using an electrostatic field. That is the basic principle of operation. So, let us consider that the mass of the charged particle is m, the velocity of the particle which is attained after the acceleration of the electrostatic field is V. V sub e q is the charge of the particle and capital V is the electric potential. Then, if I look at this equation, the kinetic energy attained by this charge particle because of the presence of electric field is half m V e square, where V e is the final velocity, m is mass and q is the charge of the particle, V is electric potential. So, therefore, this product gives us the total potential energy, electric potential energy. So, this is the burning equation. From this equation, we can simply have simplified and get an expression for the exit, the velocity of the charge particle V. So, that is given by this expression.

Now, the force acting on this particle is rate of change of momentum at. So, essentially the force is mass ferrate times exit velocity in the classical rocket equation. So, here the mass ferrate m dot essentially is nothing but m which is the mass of single particle times the current divided by charge at. So, current charge divided by current is the dimensions of the time, right. So, this becomes rate of change of mass. So, therefore, m dot is m I by q, where I is the current and q is the charge. So, if I combine all these equations, I get an expression for the force which is the coulomb force produced when a charge particle is subjected to a electrostatic force. This is given by f equal to I square root of 2 v m by q, where m is the mass of this charge particle, q is the charge of the particle, V is the velocity potential field and I is the current.

Now, if I look at this expression, then what I can see is that the force that will be produced will be proportional to current, right. So, higher the current, I get higher force or it will be square root of the velocity potential. Sorry, the electric potential or the voltage across the two cathodes that I will be using. So, if I go to higher voltage, I will get higher force, but voltage and current product is the power. So, power is limited, right. Any of them we increase, the power requirement is increasing. So, is limited by power m is the mass of the particle. So, if I use a heavier particle, I get more thrust and q is the charge. So, lesser charge is better to produce more force. So, this is the expression that we will be working with. Now, as I just mentioned that higher the mass, we get higher thrust or higher force or higher thrust produced, so therefore typically the propellants which are used for this type of propulsion system have high atomic mass. For example, typically xenon which has atomic mass unit of 132 gram or cesium with a m u of 133 are used. These are quite heavy. At the same time, we use positive ions and not electrons because electrons are very small mass, right.

So, therefore, the thrust produced will be much less if you are trying to accelerate electrons. So, we use protons which are miserably higher mass. So, because of that we use the charge particles which we want to accelerate will be the protons. So, we accelerate these protons to a high velocity and that is what the principle of operation of electro static thrusters are. So, in that case, what do we need then to make an electric propulsion system based on electro static thrusters? First, because all these molecules xenon cesium, they will be equally equilibrium. So, first we have to energize them and we want to use the protons. So, we have to somehow strip the details electrons out of them which can be done by bombarding with electrons, right. So, you can bombard this proton, these molecules with electrons. This will take away some of the electrons out. You will be left with charged, positively charged protons of these heavier molecules.

Then, we create an electrostatic force. Within this electrostatic force, this will move, right and then, they will come out, but there is a problem. If these charge atoms come out, it will create its own electric field around it. That will have some implication in the space craft applications because it will be a charged field completely. It may interfere with your communications and all. So, you need to neutralize it also. So, these positive ions atom which are coming out, we need to neutralize it. So, we need again some electrons to neutralize it, so that the exhaust finally becomes neutralized. So, that is the basic principle on which this will be working.

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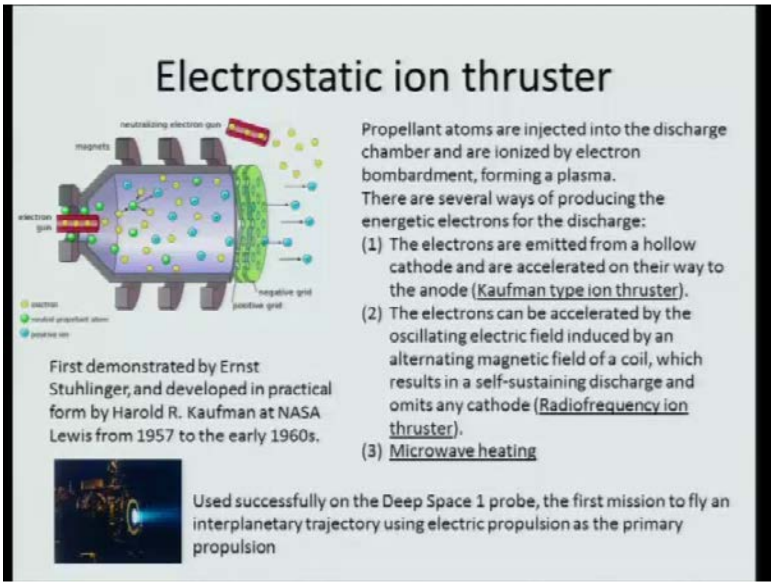

So, let us see now the different types of thrusters. One thruster is electrostatic ion thruster. So, here ions are produced which are accelerated. So, this concept was first demonstrated by Ernst Stuhlinger and developed in practice by Kaufmann at Nasa Lewis. The concept is exactly what I discussed, right. Now, here is the schematic of it. You can see that this is the chamber; this is an electrically insulated chamber. Propellant atoms are injected into this chamber. As you can see, these green ones are the neutral propellant atoms which are injected into these chambers and these are then we have an electron gun in between these electron gun fires. Electrons into it, these electrons collide with these neutral atoms and strip the electrons away leaving the protons which are positively charged outside.

So, therefore, typically what we are having is that the propellant atoms are injected in the discharged chamber, and these are ionized by electron bombardment fall forming plasma. Now, this method can be carried out in several ways. One method I have shown here is electron gun. It can be done in various ways. For example, the electrons are emitted from a hollow cathode which is electron gun and accelerated on their way to the anode. This is the anode, positive anode. So, the first grid you can see here is the anode. I will come to that again in detail or they can be accelerated by an oscillating electric field induced by a magnetic field. You can have magnets which will induce their electric field. So, that will also allow a directional move. Directed movement of these charged particles and typically the radio frequency ion thrusters use this type of thing, where radio frequency waves are created which will essentially a magnet over a magnetic coil which results in a self-sustaining discharge and omits any cathode requirement. That is also possible or you can have microwave heating which will also strip the electrons and produce protons.

So, essentially the basic idea is to produce these protons first. Second is to accelerate these protons. So, by the way, this device which was electrostatic ion thruster was successfully used in deep space. One probes the first mission to fly an interplanetary trajectory using electric propulsion as the primary propulsion device. So, it has been successful tried also. So, this is the schematic as we see here. Now, let us see how it works in practice.

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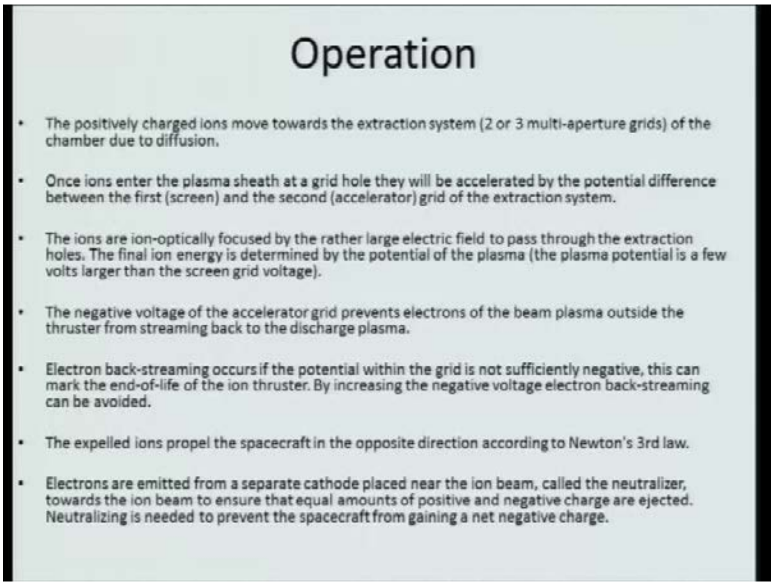

So, this is the operation. The positively charged ions move towards the extraction system essentially which are the two grids, two or three grids. This you can see here. These are the grids. One of them is positively charged, other is the negative grid. One is positive grid, other is negative grid and we have holes in between. Now, once the ions enter the plasma sheath through these grid holes, it will pass through. So, we have a positively charged ion. It passes through the positively charged, it just further accelerated and after this acceleration. So, after that the second screen is considered this is a negative grid.

So, there is a potential difference between the two. So, this charged ion now gets accelerated because of this potential difference based on the Coulomb force we have just discussed. So, there is an electric potential that is created. Because of that there is a massive acceleration of these particles. So, once they pass through this electric field, they get accelerated to a very high velocity and the negative voltage f, the accelerated grids prevents the electrons of the beam plasma outside the thruster to come back in because if the negative at the exit, so it will not work like a valve. It will not allow the things to come from outside to inside and now, this entire thing, the particles are coming out are charged positively. So, there is a separate cathode space outside as you can see here. This one, this one is a separately placed cathode which sends electrons to neutralize this ion beam.

So, the ion beam is coming out which is positively charged. It is neutralized based on by this electron coming out of this electron gun or cathode, and this is called neutralizers. Finally, what we have is a neutral exhaust. So, this is the entire operation as it consists fairly simple, but it has its own limitations. First of all, it is limited by the power that you can produce and secondly, these electrons are the light emitting devices always because they get contaminated, they get burned etcetera and because of the high potential difference that we are creating. Also, the thrust produced is not very large, but in practice they can operate for days and years. This is one of the things that they can operate for long durations without much of problem.

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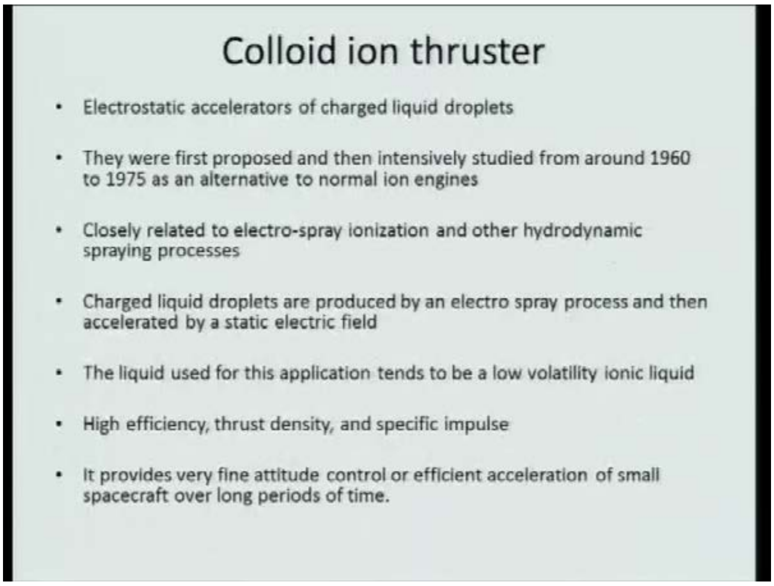

Now, the next type of thruster that I am going to talk about is colloid ion thruster. This is also an ion thruster, but the difference is in the previous start thruster, the propellant was gaseous. In this one, we have liquid as the propellant and liquid droplets are charged. So, what we have is charged liquid droplets.

So, this was first proposed in 1960s and then, alternative to normal ion chargers this is closely related to electro spray ionization and other hydro atomic spraying process where liquid is spread into atmosphere of the high potential field. That liquid gets charged and then, that charge liquid particles or liquid droplets move out of the system. So, charged liquid droplets are produced by an electro spray process and then, these charged droplets are accelerated by a static electric field. The liquid used for this application have low are typically low volatility ionic liquids. These devices have high efficiency, high thrust density and high specific impulse. It provides for very fine attitude control or efficient acceleration of small spacecraft over long periods of time. That is the primary application of these thrusters.

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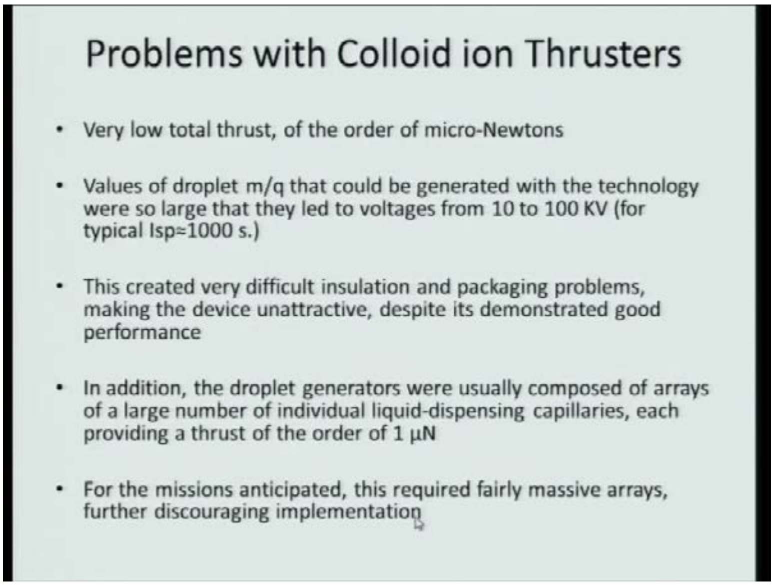

The problem with the colloid ion thrusters is that the thrust produced is very low of the order of micro Newton's and the values of droplet mass per unit charge, that could be generated with the technology that was available in 1960s were so large that they led to voltages of 10 to 100 kilo volt for a typically about 1000 second of specific impulse. So, you can see that the voltage requirement was very high and because of this high voltage requirement, it created a difficult insulation and packaging problems and that is what makes this device quite unattractive. At the same time, the droplet generators were usually composed of arrays of large number of individual capillaries, and each of them will produce thrust in the range of one micro Newton. So, we need many of these devices to produce some appreciable amount of thrust. So, for the mission at which they are supposed to be used, this was not practical. However, at present there is a renewed interest in this technology because of some newer technologies that were emerged already.

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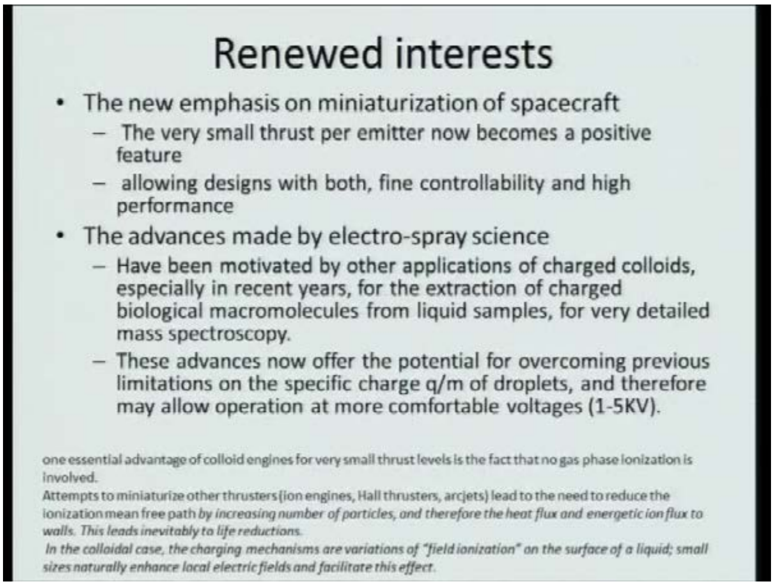

First of all, at present we are thinking about miniaturization of spacecraft, where we are thinking about small satellite clusters. So, we are thinking about producing very small nano satellites or micro satellites and for these small satellites, the very small thrust emitter can become a very useful thing because they are very high efficiency light weight. So, because of this, they will allow design of both fine controllability and high performance.

So, because of this emphasis on the miniature space craft, there is a renewed focus on this type of thruster. At the same time, the electro space ions have made a massive progress in the past few years, past few decades. Rather typically these colloids have been used in the extraction of charged biological macromolecules from liquid samples and these were done electrically and for detail mass spectroscopy. So, there has been a lot of advancement in this. Similarly, there has been advancement in printed technology which sometime uses these essentially electric spray devices and because of that, the technology has matured enough to produce good quality droplets charged particles. That is why there is now a renewed interest because it is now possible to operate these devices between 1 to 5 kilo volts. That is within our durable range. So, therefore, now there is a renewed interest in this type of thruster.

Now, one essential advantage of these colloid engines for small thrust level is that there is no gas phase ionization. This is a big improvement. You do not have to ionize a gas and the problem is that because of this ionization requirement, if you have to make smaller thrusters from the conventional gas phase electro static thrusters, the charge density becomes so much that it becomes very difficult to handle. So, because of that, not only charged density, the heat fluxes will be very high. So, because of that there is a size limitation. We cannot make the conventional electric thrusters smaller than a particular size because of the other issues whereas, this device works best in the smaller size.

So, that is why is the best choice for the smaller space craft and in this colloidal case, the charging mechanisms essentially variation of field ionization on the surface of a liquid. So, small size typically enhances the efficiency of this system, where small size reduces the efficiency of other systems. For this type of this system, the small size enhances the efficiency. That is a major advantage. So, therefore, they will be the choice for the future electric propulsion systems for smaller spacecraft’s.

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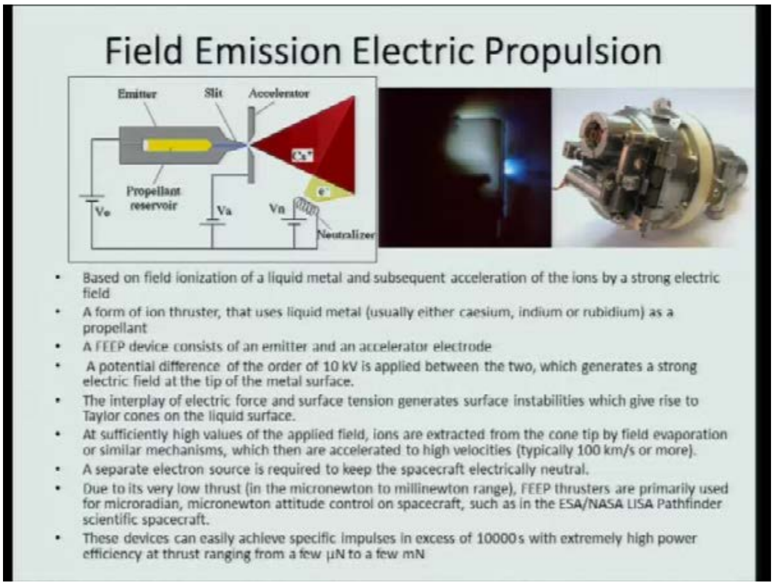

Now, I just mentioned one thing about the field ionization. So, there is a new concept field emission electric propulsion system which is actually based on field ionization of liquid metal. So, here in this system, this is the schematic given here. We have emitter electric field is provided here is through a small silt. Liquid metal is passed through and this is the accelerator. So, these two will be maintained at a potential difference as you can see and because of this electromagnetic field, this will move at a high speed. That is a very simple process.

So, we have charged metal accelerated by a electrostatic field. So, based on field ionization of liquid metal, subsequent acceleration of ions by a strong electric field, this also is a form of a ion thruster, but it is using liquid metal either cesium or idium, indium or rubidium as a propellant. Again, this consists of an emitter and an accelerator electrode very much like an ion thruster. Only thing is that the propellant is different. The potential difference between the two cathodes are two electrodes which will be in the range of about 10 kilo volt, and this generates a strong electric field at the tip of the metal surface, and this interplay of the electric force and the surface tension generates surface instabilities which give rise to Taylor cones on the liquid surface, and at sufficiently high values of the applied field ions get extracted from the cone by the field evaporation which are accelerated then to very high velocities. Typically, the velocity can be in the range of about 100 kilometers per second or more.

So, you can see that it is order of higher than what a chemical rocket will produce. So, there is another problem here. You will also need a neutralizer because this will be charged. So, you need a neutralizer to neutralize the charge particles. So, separate neutralize is used. However, the thrust produced is very low due to its very small thrust are primarily used for micro radian or micro Newton attitude control on spacecraft. Typically the thrust produced will be in the micro Newton or milli Newton range. The specific impulse which can be achieved by these devices close to 10000 seconds with extremely high power efficiency while thrust will be ranging from 1 kilo few micro Newton to few milli Newton, but this is a major advantage specific impulse is so high. So, this is again a device which is now being tried out for various applications.

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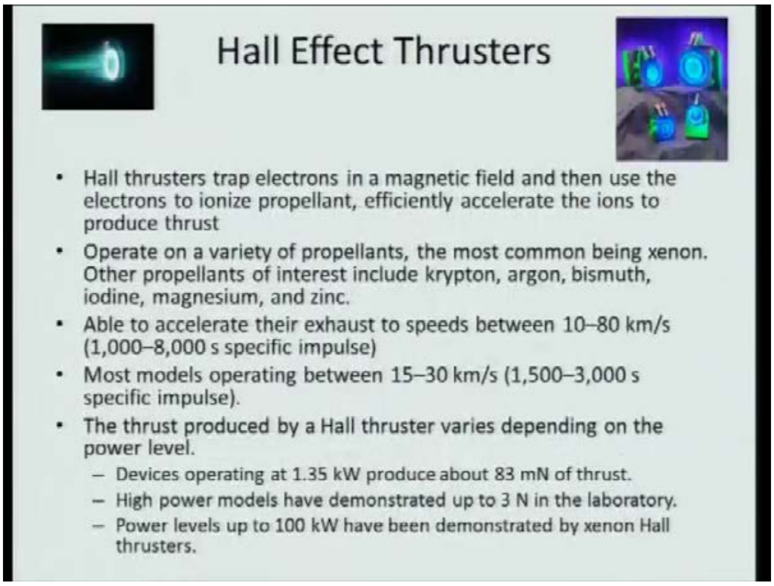

So, now with this we come to the most widely used electrostatic propulsion system which is Hall Effect thrusters. This is the hall thrusters. Again, the principle is same. We produce some electrons and then, accelerate them. So, hall thrusters trap not electrons ions are the charge particles. That means, so thruster also require some charge particles and then, accelerate them. So, hall thrusters trap electrons in a magnetic field and then, use the electrons to ionize the propellant which is then efficiently accelerate the ions to produce thrust unlike an ion thruster, where the propellant is bombarded by electrons to produce the charge. Here the electrons are trapped by a magnetic field and then, that is used to analyze the propellant. So, there is a basic difference between it. This operates on variety of propellants. The most common propellants are xenon. Other propellants of interest are krypton, argon, bismuth, iodine, magnesium and zinc.

These devices can accelerate their exhaust to speed between 10 to 80 kilometers per second. So, specific impulse up to 8000 seconds can be achieved by these devices, most models. However, available model or working model operates between 15 to 30 kilo meters per second speed range or about 3000 seconds. Specific impulse speed range the thrust produced by hall thruster varies over a range depending on the power level. Typically a device operating at 1.35 kilo watt produces about 83 milli Newton of thrust. High power models are available which can produce up to 3 Newton power levels up to 100 kilowatt have been demonstrated by xenon hall thrusters. So, these are basics one has been achieved by hall thrusters. Let us see how they work.

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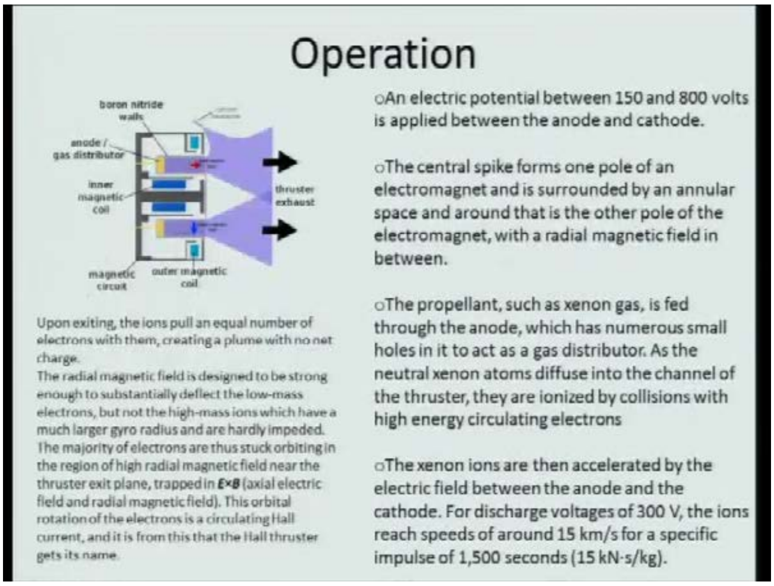

So, as I mentioned that all thrusters are very much similar to ion thrusters. So, here is a schematic of a hall thruster, here this is the anode or the gas distributor where the propellant is stored and charged, and we have a magnetic coil, outer magnetic coil. So, between these two the electric field is created.

So, a electric potential between 150 to 800 volt is applied between the anode and the cathode. The central spike that is here forms one pole of electro magnet, and we have an annular surrounding it, annular space around it. In the other pole of the electro magnet is the other pole of the electromagnet with a radial magnetic field in between. So, we have a magnetic field in between these two propellants which is like a xenon gas as is shown here is fed through the anode which has numerous small holes in it to act as the gas distributor. So, it is like a spray. So, anode has very many small holes through which the spray gas is coming out as the neutral xenon atom diffuse in to the channel of the thruster. They are ionized by the collision with high energy circulating electrons in the anode. Now, the xenon ions are then accelerated by this electric field between the anode and the cathode as is shown here, and for then because of this electric field, they move at a high speed for discharge voltage of 300 volts. The ions will reach speed of about 15 kilo meters per second.

So, this is typically what they do. However, after coming out of this as you can see here, after coming out of this thruster, the ions pool an equal number of electrons with them. So, we have a cathode neutralizer, the ions pool these electrons and then, neutralize it here. So, finally, what we get? The thrust exhaust is neutralized by the electrons produced pooled by the cathode from the cathode. This is typically what Hall Effect is. Thruster is the radial magnetic field is designed to be strong enough to substantially deflect the low mass electrons, but not the high mass protons. So, the electric magnetic field should just take away the electrons, not the protons.

So, that is how it has to be designed and the majority of electrons are thus stuck orbiting in the region of high magnetic field. So, the electrons essentially keep on orbiting this field and because of these orbiting electrons, an electromagnetic field is created, right. This is given by E cross B. So, because of these orbiting electrons here, electromagnetic field is created and this electromagnetic field actually produces the acceleration. This effect is called Hall Effect. That is why these thrusters are called hall thruster. So, this is how as you can see the radial magnetic field as an accelerated electric field and because of that finally the particles will be out.

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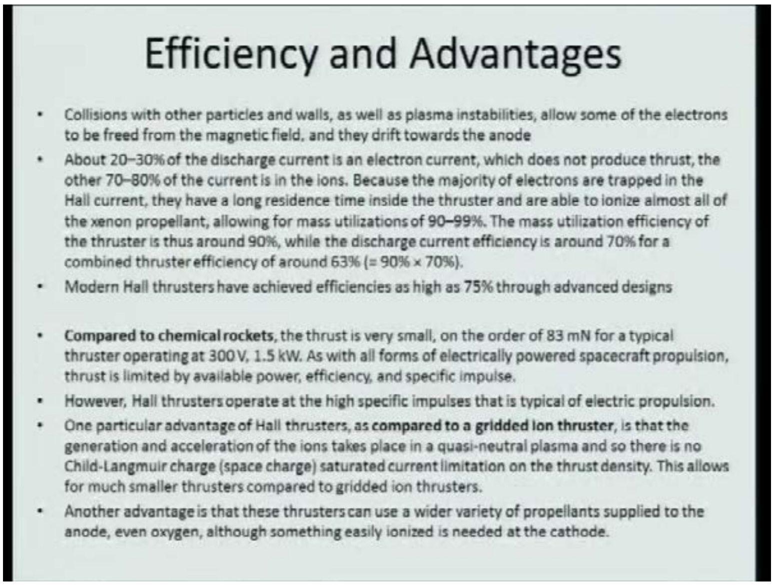

So, hall thrusters as I have just mentioned, they are very efficient. First of all, the collisions with other particles and walls as well as plasma instabilities allow some of the electrons to leave the magnetic field and drift toward the anode that reduces some of the efficiencies. So, about 20 to 30 percent of the discharge current is electron current which does not produce any thrust. Other 70 to 80 percent as per the high number of the current is in the ions because of this. The thrust efficiency is very high. Let us just look at this paragraph here because the majority of electrons are trapped in the hall current. They have a long residence time because they are circular rotating. Remember rotating in the radial direction.

So, they are present a lot of time within that because of the long residence time inside the thruster. They are able to ionize almost all the propellants. So, therefore, the mass utilization of propellants xenon is 90 to 99 percent. That is a very high ionization and because of the high mass efficiency, the mass utilization efficiency of the thruster is about 90 percent. The discharge current efficiency is about 70 percent. So, overall thruster efficiency will be about 63 percent. Thus, pretty high efficiency 63 percent thruster efficiency. So, even with improved design efficiencies as high as 75 percent has been achieved by these thrusters compared to chemical rockets. The thrust is very small as just as have been saying because the particle mass is as small, very small. The order of about 83 milli Newton for a typical 300 volt system, 1 kilo watt system, but it can be increased, but they are limited by the power available with on board air craft or on board space craft, and because of the availability of power, the thrust produced is limited, efficiency is limited, the specific impulse is limited. However, they operate at high specific impulse as we have just mentioned one particular advantage of the hall thruster as compared grid ion thruster. We had discussed that the generation and acceleration of ion takes place in quasi neutral plasma.

So, there is no space charged, that is saturation current limitation on the thrust density. This allows much smaller thrusters compared to the gridded ion thruster because in the gridded ion thruster, let me go back. This is a gridded ion thruster. The charge is created here. So, if you make a small, the charge density becomes so much that the losses will be much higher whereas, that problem is not there in this device. So, because this is continuously flowing out as you can see is continuously flowing out. So, because of this advantage, there is not lost much smaller thruster compared to the grid ion thruster. Another advantage is that this thruster can use a wider variety of propellant. Even oxygen can be used, xenon wider variety of propellants can be used although something which is easily ionized needed at the cathode, but in the anode, even higher lot of propellant, different types of propellants can be used. So, these are the different types of advantages of hall thrusters.

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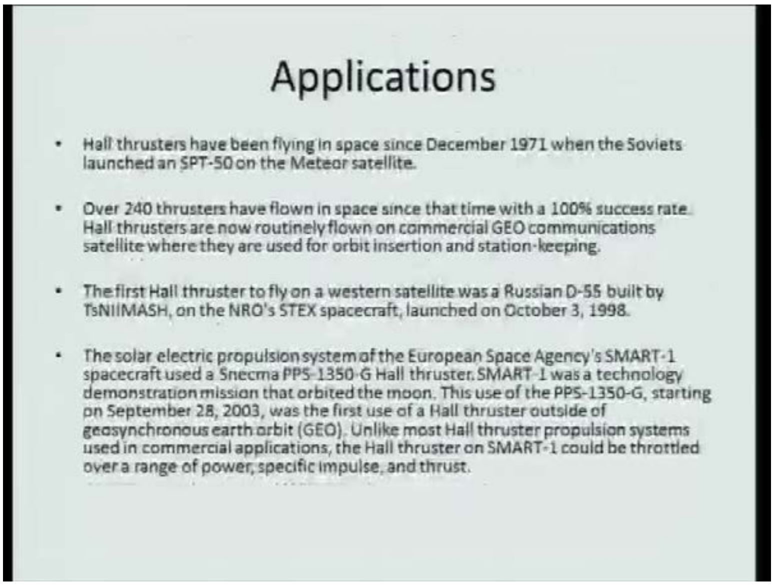

Now, some of the applications I will have listed out about the hall thruster. They have been flying in space since December 1971 when the Soviet launched SPT-50 on the

Meteor satellite. Then, over 240 thrusters have flown in space since that time with 100 percent success rate. So, perhaps the most widely used electric propulsion system is hall thruster. They are now routinely flown on commercial geo communication satellites, where they are used for orbit insertion and station-keeping. The first hall thruster to fly on a western satellite was a Russian D-55 built by TsNIIMASH, on the NRO’s STEX spacecraft which was launched in October 1998. The solar electric propulsion system of European space agency SMART-1 space craft uses a hall thruster which is a Snecma PPS-1350-G Hall thruster. This was a technology demonstration mission that orbited the moon. This use of the thruster starting on September 2003 was the first use of hall thruster outside of geo synchronous earth’s orbit, so that it has gone to moon unlike most hall thruster propulsion systems used in commercial application. The hall thruster on SMART-1 could be throttled over a range of power specific impulse and thrust.

So, that is at the present as I have just mentioned that the hall thrusters are most widely used electric propulsion systems particularly in geo synchronous orbit satellites, where typically used for station-keeping or orbit insertion over has been used for a while now and will be used in future as well. So, with that I come to an end on the discussion on electrostatic propulsion systems.

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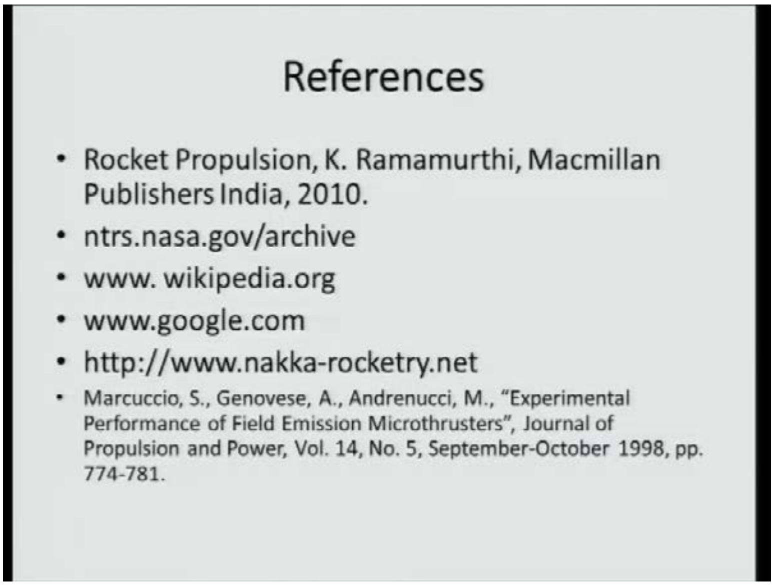

So, I would like to thank the sources from which I have got this material. First of all, the book on rocket propulsion by Professor Ramamurthi, then the NASA website, Wikipedia, Google, then this paper on by “Experimental Performance of Field Emission Microthrusters” from which at least one of the topic has been taken. So, I would like to thank all these references. So, with this I stop the discussion on electrostatic propulsion system. In the next class, we will discuss the electric heating, electro thermal that is electro thermal and electromagnetic propulsion systems.

Thank you.