Rocket Propulsion

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Module 01

Lecture 35

Electrical Thrusters

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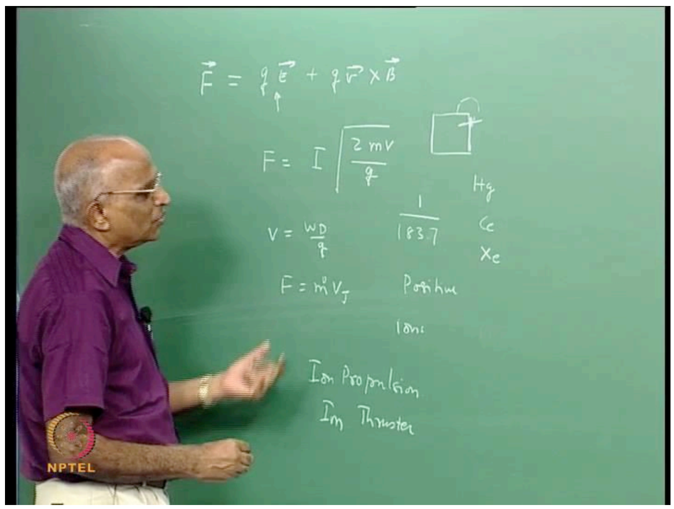

In the last class we talked of electrostatic forces namely we said charge into electric field viz, the voltage gradient which was the electrostatic force and we also said a charge moving in a magnetic field to generates a force, which was the electromagnetic force. This was what we called as Lorentz equation. B is the magnetic field in Tesla, E is the electrical field in voltage per meter and q is the charge is in Coulomb. Force is a vector so also fields E and B. We continued with this and we found that the force that we could get in the case of the electrical field could be written as the current$\times\sqrt{2\,m\times V/q}$; and how did we get this? We got something like the potential difference i.e., voltage was equal to the work done per unit charge.

We were able to write qV for the work and relate the force equal to $m^{\circ} \times VJ$, and we got this particular relation. Force is in Newtons, I is in amperes, voltage V in volts, mass m in kg and the charge q in coulombs.

We found that it is essential for the mass which we are charging to q Coulomb should be substantial so that we get some meaningful force and we said electrons which weigh 1/1837 of a proton are not suited. That means an electron has a mass something like 1/2000 of a proton and therefore it is very difficult to have electrons, which will give sufficient force. Therefore only positive charges or ions are used for generating the forces and we cannot use the electrons because their mass is so small that we do not get any impulse at all.

Therefore these positive charges or what are called as ions are used and therefore such mechanism of using the electric field for generating force is known as ion propulsion. We call it as an ion rocket, but, the type of forces which are generated are quite small; instead of calling it as a ion rocket we call it as ion which generates some thrust or ion thruster. Therefore, when we talk of low thrust rockets we call it as a thruster instead of a rocket. But, anyway you could call it as an ion rocket. It depends on the person who uses it; there is no hard and fast rule that it must be called as a thruster and not rocket or stuff like that. But, generally you find the rocket that produces low value of thrust is known as a thruster and all the electrical rockets like electrostatic rockets generate low thrust and we call it as an ion thruster.

Having said that, we also went one step further and said if I have to use this electrostatic principle and generate an ion rocket; we would also like to have substances or propellants whose molecular mass is larger or whose atomic mass is larger. And therefore, I rather have heavy substances like may be mercury, cesium, xenon. Mercury vapor contaminates the surfaces of spacecraft and is no longer used. If we were to consider let us say a spacecraft; it consist of lot of sensors may be an earth sensor, may be sun sensor, etc., and these sensors have transparent glass surfaces. The optical quality of glass is important to sense the radiation. The mercury vapor exhausted from an ion thruster could form a monolayer on it and it will make it opaque. And therefore mercury contaminates and is generally not used. It was used in earlier spacecrafts but is no longer used. May be cesium was also used, but no longer used because it is a reactive metal. Something that is universally used today is xenon, which is a noble gas.

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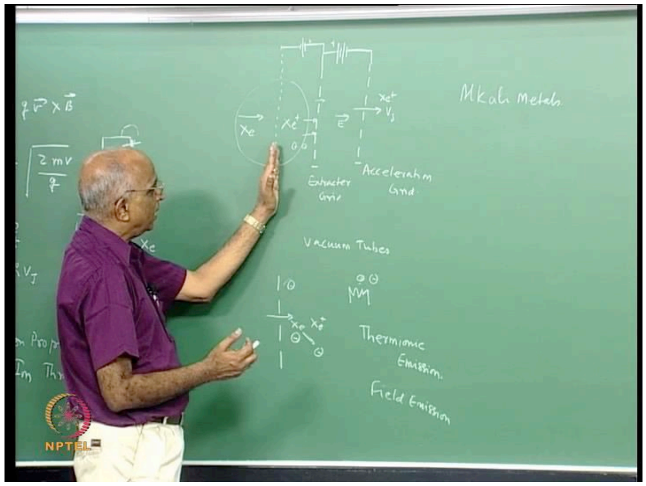

Therefore, how will a construction of an electrostatic rocket look like? Well, I need to supply in this particular xenon gas. We need to generate positive ions of xenon and then we require a negative grid, something like a screen, which is negative such that it will attract the positive ions towards it; another screen over here that is still more negative. That means, we have voltage difference between these two. This is less negative. That means, it is positive compared to this screen. Whatever xenon ion is being generated is attracted by this screen or rather is extracted by the slightly negative potential. we want it to extract the ions and therefore it is called as an extractor grid.

It extracts the positive ions. It attracts and brings it here. This is a more negative screen downstream and therefore, what happens is because I have a field here, electrical field between the extractor screen and the downstream screen, the ions are accelerated and out goes the ions of xenon ions at a high velocity VJ. And therefore, this will be the construction of an ion rocket or ion thruster. Therefore, if I were to put a high voltage source here, this is the positive, this is the negative and I connect it as shown. I connect another power source that will extract the ions and the grid generates the positive ions. I will come back to this generation of ions in a moment.

Well this grid is going to be negative. The grid, which is highly negative is what is known as an acceleration grid. We have assumed that xenon positive ions are created here and how do you create the positive ions? See, you all grew up in a generation wherein we do not have these vacuum tubes. You are in a generation with semiconductors. Previously we did not have these semiconductors and we had what was known as vacuum tubes, which consisted of diodes, triodes, etc. We had a filament preferably of tungsten, which used to generate the electrons on being heated. The work function of tungsten is low. When it is heated it could generate electrons; that means, negative charges.

Therefore if we could have a grid made of tungsten or even molybdenum for that matter and I heat this particular grid; may be electrons are generated from this grid and these negative ions when they hit against the flow of xenon gas which is passing through the grid; the neutral xenon is hit by a negative charge and the electron knocks of one more electron of the xenon and makes the xenon positive. And this is how we could create the xenon ions. The resistor of tungsten or molybdenum on being heated generates electrons and is known thermionic emission. It is not only the thermionic emission, but when we have a gas which is flowing and we generate some ions. We are also knocking of electrons; these electrons are also available in this space and we have lot of these electrons which are going to hit the xenon gas further. And therefore, I have something like a field emission of electrons in addition to thermionic emission. In this particular way I keep on generating more and more ions.

By having a grid, which is a low work function material we generate electrons. And the low work function material could be tungsten or molybdenum or some alkali metals. Alkali metals are metals such as calcium and these also have a low work function such that when it is heated, it releases the electrons. It interacts with the neutral flow of a xenon gas and creates positive ions and by field emission and the xenon ions multiply. These are acquired by the extractor grid and accelerated by the accelerator grid and this is what gives me the thrust.

Therefore we have a grid to generate ions, a grid which is extracting the ions. Once it is attracted the acceleration grid further pulls it at a high velocity VJ and therefore, such type of construction is known as gridded ion thruster.

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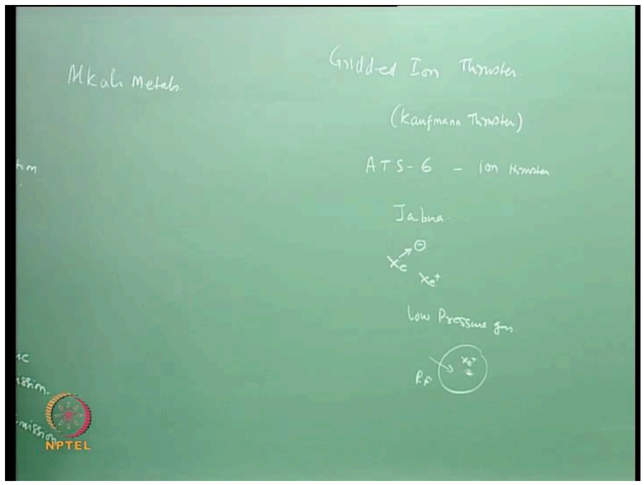

We have 3 grids in the gridded ion thruster. This was started by Kaufmann and therefore, it is also known as Kaufmann thruster. This ion thruster has been used in several missions starting from mid 1970s and in fact in India we used one particular satellite known as Application Technology Satellite made in USA by Hughes Corporation and called as ATS 6. This was used as an experiment before we got into INSAT for communication purposes. In India a substantial part of the population resides in villages and we wanted to assess whether a satellite like INSAT would be useful for the remote villages. Therefore in the period 1975 to 1980 or so, we got a satellite from US which is known as ATS 6. It broadcast programs for the different villages in the country and demonstrated its use in improving let us say the education in villages, may be the health care in villages. We had very backward villages like in MP; places like Jabhu. And we put some power sources and demonstrated that a satellite will be useful in improving the quality of life. This particular satellite ATS 6 also demonstrated the use ion propulsion or an ion thruster.

Therefore, we find a gridded ion thruster can be used, but is this the only method of generating ions? After all I need to generate ions. To generate ions, I can use something like low pressure xenon gas and into this low pressure gas supposing I were to heat the gas and how do I heat the gas? I sort of introduce radio frequencies in it and excite the gas; the xenon tends to form positive ions and electrons. And we use the same attractive force of a grid or otherwise to isolate the ions. In other words, we use radio frequencies to generate positive charges.

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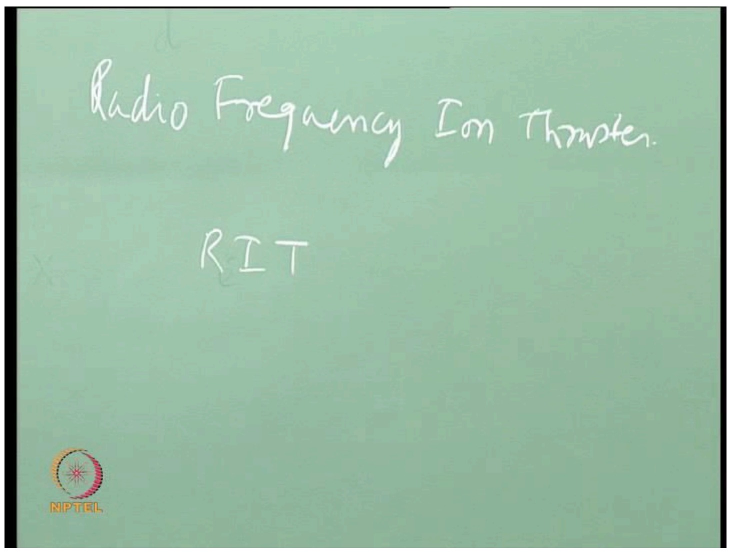

And if we use radio frequencies for generating ions, the thruster is known as radio frequency ion thruster. I write it here; it is known as RIT. It has also been flown. Therefore, we are talking of some of these electrostatic type of thrusters wherein we could use gridded ion thruster, may be radio frequency ion thruster or even we could think of some other configurations.

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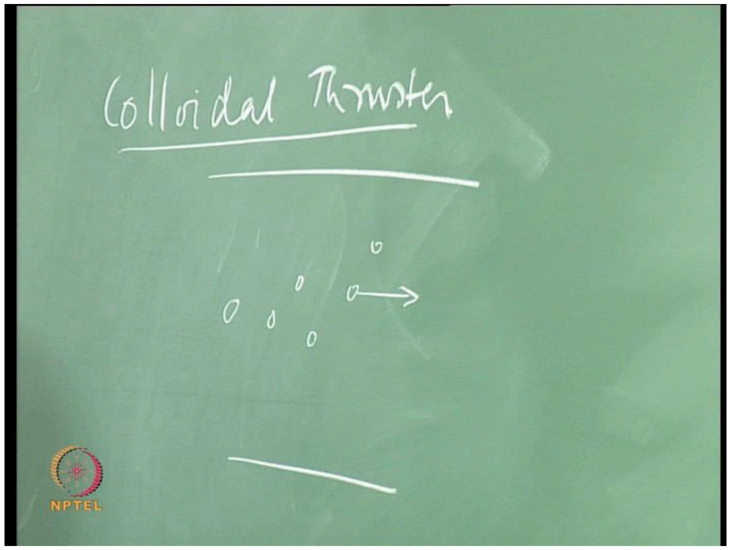

In fact, you would have heard of this rocket pioneer by name Yuri Kondratyuk who developed a colloidal thruster, which again works on the electrostatic principle. You have a colloidal solution. What is a colloid? It is a viscous liquid. You could form something like let us say fine droplets of the colloid and these fine droplets like an aerosol are then positively charged. These charged particles, if in an electrical field could be accelerated and this could be used to provide thrust. Namely, you charge the colloidal solution and these colloid particles once they are charged, you put it in an electrostatic field and you generate thrust. This is what is known as a colloidal thruster.

Using the electrical field, the ions could be accelerated to provide thrust. Well, this is all about electrostatic thrusters, but having studied it, let us see whether there are any specific problems in these thrusters. Is it readily usable and are some improvements required in it? Because we do not see ion propulsion being used as much as some other forms of electrical propulsion. And what could be the problems? You are having these accelerated charges hitting against this particular grid, which is like a sieve with lot of fine openings.

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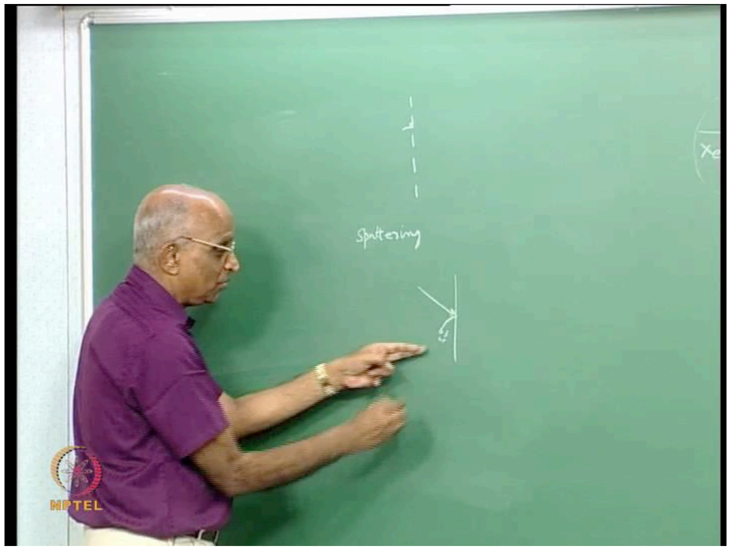

And when these things are hitting against the material of the sieve, it removes or erodes the metal and this is known as sputtering. That means I pass high velocity ions. High velocity charges when it impacts here it corrodes the metal and it is known as sputtering.

I think we must remember this word sputtering because when we talk of nanomaterials; one way of making nanomaterials is we take a material, we allow high velocity charges to strike on it. I generate particulates which are very fine nanoparticles. This sputtering in the case of the gridded ion thruster sort of erodes the grid and the lifetime of the thruster reduces.

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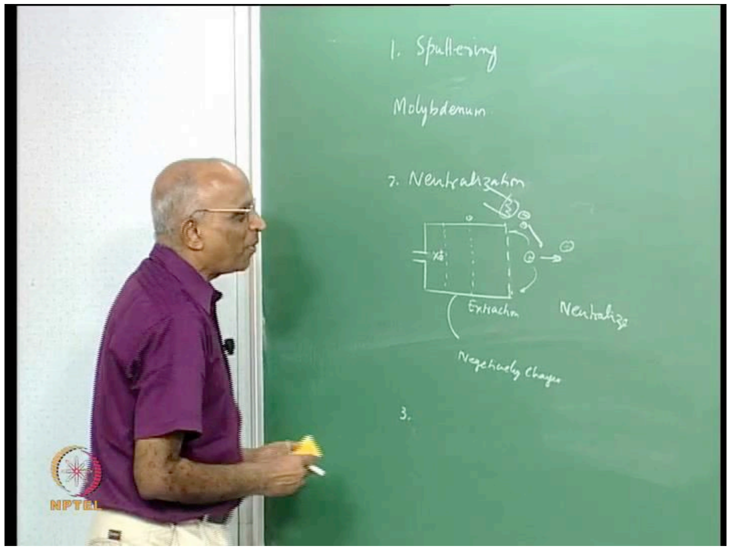

Therefore, one problem I can immediately say is a problem of sputtering. But, how do you correct for sputtering? Maybe I can only reduce it. I use instead of tungsten the metal molybdenum is less susceptible to sputter. We use something like a molybdenum grid.

There is a second problem and this second problem is common to almost all types of electrical thrusters. Supposing, let us say we have this particular container containing the ions. We create the charge over here - xenon positive. We put an extraction grid over here to get the xenon ion out at the end of it and thereafter I have the acceleration grid and we said may be the voltage of this could be something like 1.5 KV with respect to 0 here and this would be negative with respect to this by some 100 volts.

Now, what is going to happen? The positive ions are going out being accelerated at high velocities. All the electrons are getting accumulated within. How are positive ions getting generated? You are removing electrons from the xenon and making the xenon have positive charges. So, therefore, thruster becomes negatively charged because we are getting the positive charges out. The thruster becomes more and more negatively charged.

Even though I am pushing the ions out of the thruster there is a tendency for the ions to get retarded or pulled back by the negatively charged surfaces. The positively charged ions are decelerated and cause it to come back. And therefore, it is necessary for us before we push it out, the ions to be able to neutralize the positive charge. And how do I neutralize the charge? All what I do is, I put a cathode at the exit; a cathode generates negative charges; which means I put another say some thermionic emitter over here and I generate negative charges. Put it into this stream of ions such that the electrons will hit the ions and what results is neutral charges, not positive charges, but neutral. Therefore, the second problem, which is common not only for gridded thruster but all electrical thrusters, is the retardation of ions for which we need to neutralize the exhaust of ions from it. That is neutralization and must be done.

Therefore, an ion thruster should have neutralization of the charges otherwise when negative charge is build up it will not be able to generate thrust.

There is a third problem. Let us visualize it the third problem through this figure.

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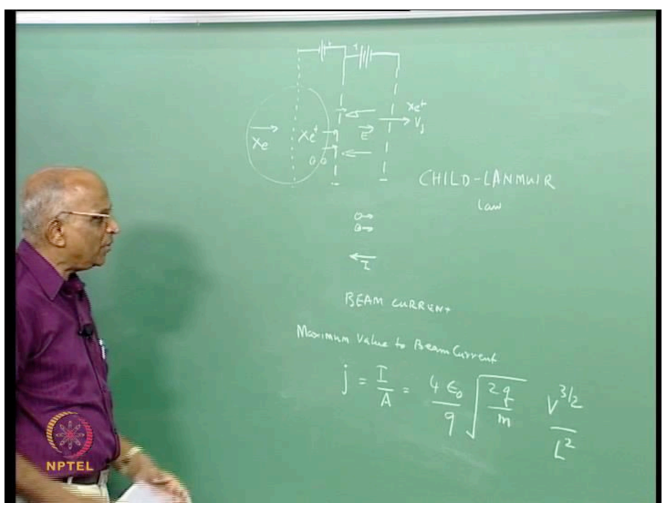

We are pushing the charges, positive charges, accelerating it over here. When positive charges move like this I have something like a current which travels in the opposite direction. What is current? Current is a motion of electrons. Therefore, we have something like a beam current. What is the beam? We have a beam of electrons; a beam current as it were. Let us put it down properly I have a beam current as the positive charges are moving out. I have a beam current in this particular direction and what will this beam current do? Between the accelerator grid and this extractor grid even though this is negative, this beam current will reduce the effective voltage with which the positive charges are being attracted by the accelerator grid. Maybe for a critical value of beam current no more extraction of ions become possible and the thruster will fail. That means, there is a maximum value to the beam current in an ion thruster.

And we will not go into too much details of this. But, we recognize that there is a maximum amount by which we can push it out because as we have more and more of the positive charges are moving out, we get a current in the opposite direction. That current will ensure that we do not have sufficient negative voltage to suck in or extract the positive charges here.

And therefore, there is a threshold value of the beam current and this maximum beam current is given by the current density J which is equal to beam current divided by the area of cross section. The maximum value of beam current is given by a law known as Child Langmuir law. The law can be derived from basics; it states that the maximum value of current density is given by $4 \times \varepsilon_0/9\times\sqrt{2}q/m \times V^{3/2}/L^2$. In other words, there is a limiting value of beam current beyond which it is difficult to extract the ions over here and the thruster will fail. Therefore, the maximum value of current which is possible in ion rocket is now given by I through the maximum value of the current density.

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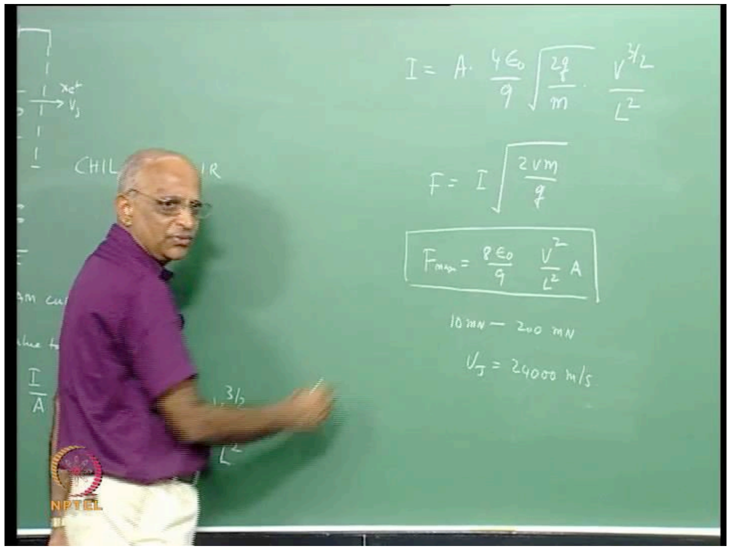

Therefore, the maximum current what we can get in an ion rocket is equal to the cross sectional area of the thruster A into 4 × value of permittivity of free space ε_0 /9. Unit of permittivity we saw as Farads per meter. This is multiplied by $\sqrt{2q/m}\,V^{3/2}/L^2$ to give maximum beam current. But we already know the force equation and the force equation or the thrust developed by a particular ion rocket we derived as $I\sqrt{2Vm/q}$.

And therefore the maximum thrust which an ion rocket can develop can be determined if we substitute the value the maximum value of current in this expression. We get it as $4\times\varepsilon_0\times A/9\sqrt{2q/m}\times V^{3/2}/L^2$ into permittivity divided by 9 into root of 2 q by m. And therefore, this becomes the maximum beam current. The maximum thrust is therefore $8\times\varepsilon_0/9$ × q/m and q/m cancels off × voltage $V^{3/2}/L^2$ which is the maximum thrust. How did I get it? A comes over here, two and two gives me 8, 8 permittivity of free space epsilon into nine over here and we get V which is left here as V square by L square. This is the equation to the maximum thrust which can be developed by an ion thruster and we find that normally the thrust is around let us say 10 milli Newton to about 200 milli Newton. The maximum specific impulse or rather we put in terms of V_J is around 24,000 meters per second.

You know when we talked of chemical rockets; we found that the VJ is around 3,000 meter per second. The ion rockets give around 10 times the performance of chemical rockets, but at a very reduced thrust level. And what is the maximum thrust level; it given by this particular equation? Well this is all about ion thrusters. These are flown in several missions.

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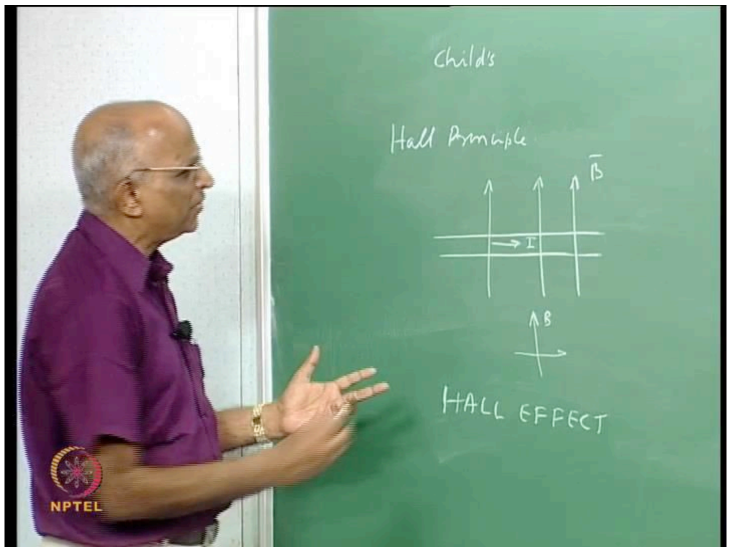

But, a development in ion propulsion by the Russians made it to be much more popular. Let us try to appreciate the principle and see what is involved? We have the Child Langmuir law which we just now wrote saying that there is a limitation on the amount of charge per unit area which can be emitted and therefore the maximum thrust which can be generated by the ion rocket. Now, there is a principle in electrical engineering or in physics known as Hall principle. What does this principle tell?

Supposing we have a conductor. In the conductor we pass a particular current I and this conductor is placed in a magnetic field B which is perpendicular to it. That means, we have so much Tesla of magnetic field normal to the current flow in amperes. Then the Hall principle stays states that when a conductor carrying a current is placed normal to a magnetic field a voltage is generated normal to both the current and the field. In other words if we pass a current like this which is in a field B, we generate a voltage normal to both and this is known as Hall principle or something known as Hall effect.

It is this principle that is made use of in improving the ion thruster. We have a current flow in the thruster. If we were to put a magnetic field normal to it, I could have a voltage generated and this was used by the Russians in the following way to improve the performance of the ion thruster. Because as mentioned earlier in an ion thruster, the thrust is small, but V_J is excellent and we need a strong electric field.

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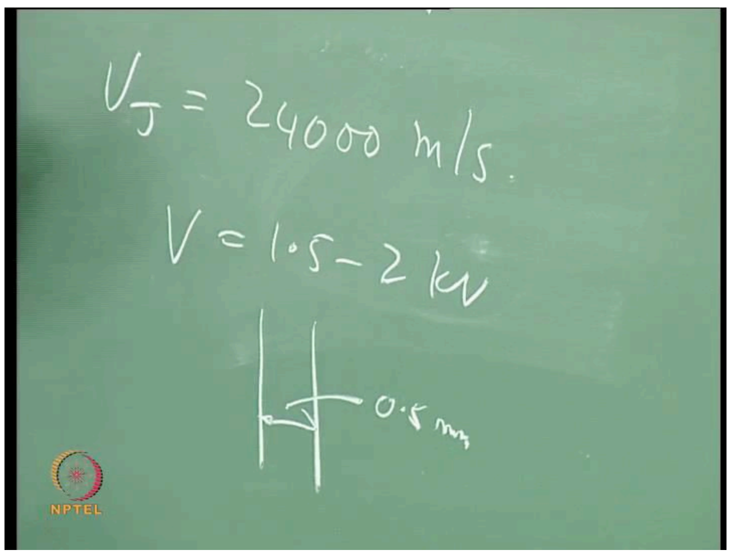

We use a voltage of around 1.5 to 2 KV to be able to accelerate the ions in the ion thruster. In order to get a high value of the electric field, the distance L distance between the acceleration grid and the extracting grid is something like 0.5 mm. Therefore, it is not easy to make these grids for there will be a tendency to short or spark.

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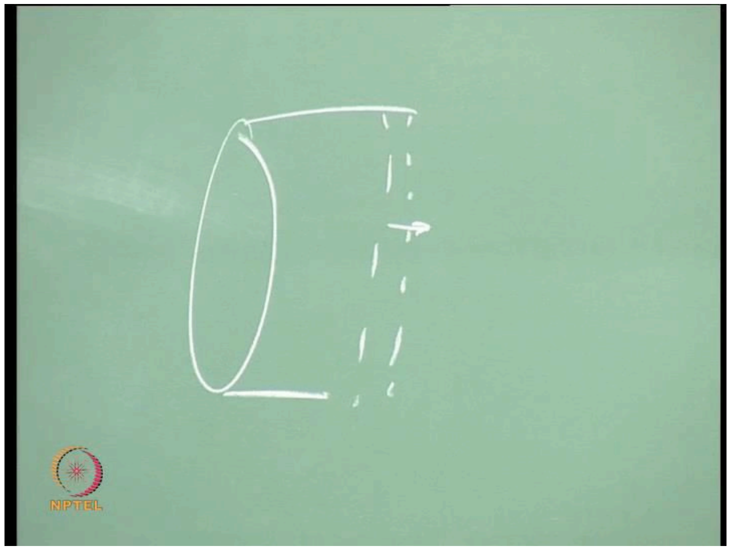

We have an extractor grade and we have an acceleration grid. The distance between them is around 0.5mm, the voltage across something like 1.5 kilovolts and therefore, construction is quite difficult.

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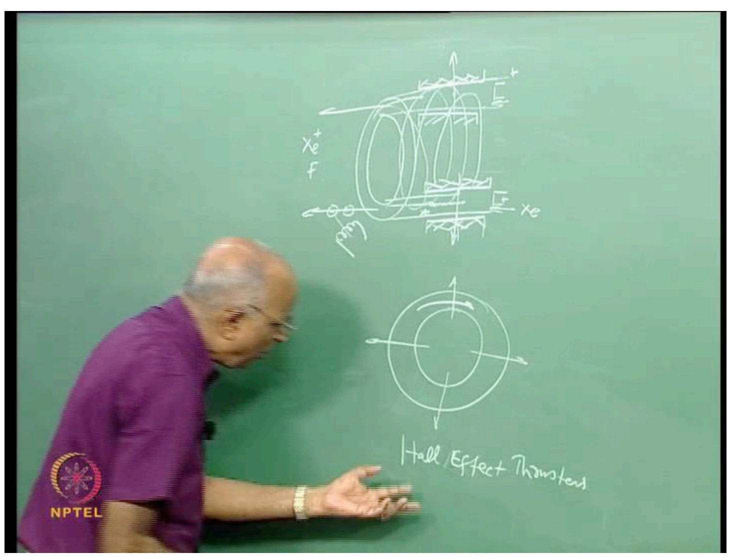

Therefore what is done using the Hall effect? If we were to have something like this over here, we have something like an annulus here. I am talking of something like a cylinder and an annular gap between the inner and outer and supposing we were to introduce a radial magnetic field in this annulus. That means, in the annulus between the inner and outer I have a magnetic field. Let me take a section over here. In this I put magnets over the inner and outer part of the annulus to generate a radial magnetic field.

We have a magnetic field in the radial direction. And now I put let us say an anode at one end of the annulus. That means I have a positive voltage here. I place a cathode upstream of the annulus over here and the cathode generates electrons. We heat the cathode and the work function being small it generates electrons. The positive anode is going to attract the electrons it in this direction through the annulus; as the electrons travel along the length of the annulus, it is equivalent to a current flow. However, we have the magnetic field is in this radial direction. Therefore, now I get tangential voltage from the Hall effect. Instead of the electrons moving along the length of the annulus, the Hall voltage causes the electrons to move in a path which is spiraling as shown.

When the electrons are spiraling in the annulus, what we do is through the annulus we admit the xenon gas from the anode. The xenon gas when it comes into this spiraling mass of electrons is going to collide and generate positive charges and these positive charges will be pushed by this positive anode and we get a net flow of xenon positive ions being pushed by the anode and this gives the thrust. Therefore, we use Hall effect effectively to improve the performance of the ion thruster and this is known as Hall Effect thruster. The Hall voltage deflects the electrons being lighter whereas the flow of the heavier ions is not influenced. These thrusters have been flown by the Russians and in several other countries. In India also we are working on these Hall Effect Thrusters for satellites. It was supposed to be flown in the last GSLV, but as you are aware the last GSLV mission was not successful.

Therefore, all what we will say is Hall effect thrusters make use of these spiraling effect of the electrons which essentially collide with the propellant flow and since the spiraling effect is used we do not have a limit to the beam current is that. Essentially it is a plasma consisting a lot of neutral gases in the annulus. We do not have the problem of any sputtering here.

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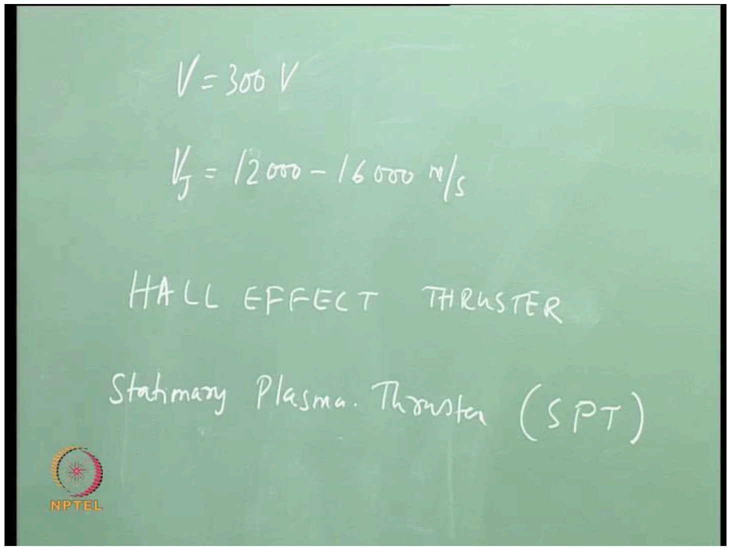

And we can use a low voltage of around 300 volts and there is no question of a small gap between grids. The associated V_J what we get is somewhat lower; of the order of let us say 16,000 compared to 24,000 meters per second what we get in the ion thrusters. Maybe let us say 12,000 to 16,000 meters per second, but even though we get a smaller value of V_J, we use much lower voltages. This is known as a Hall effect thruster.

Since we have plasma instead of ions in the annulus, which is stationary, it is also known as Stationary Plasma Thruster (SPT). Therefore, we have talked in terms of the electrostatic principle and in the electrostatic principle we talked of ion rockets, maybe radio frequency ion rockets, stationary plasma thruster, maybe we could have a colloidal thruster and these come out of this principle of force in an electric field with charges.

Let us go back to the next part namely the electromagnetic principle. In the electromagnetic principle the thrust is small and normal to the magnetic field. We are not looking at the description of a thruster, but want to understand the mechanism of operation.

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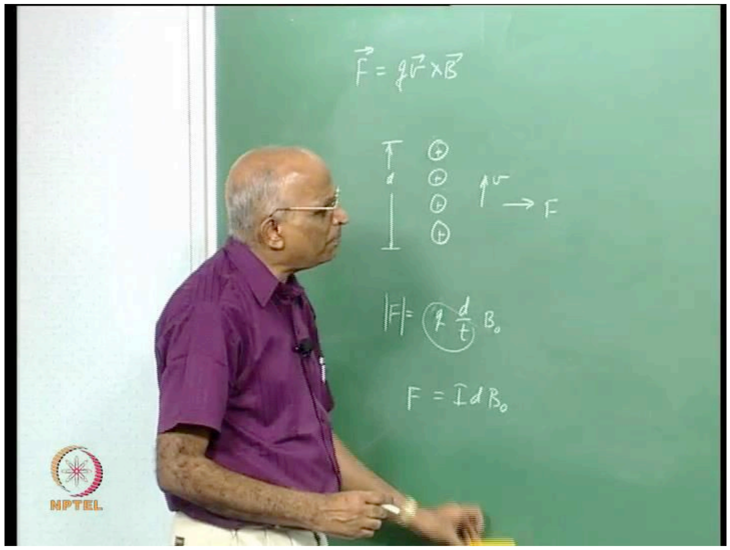

We said a force can be generated in a magnetic field when a charge moves at a given value of velocity. This is the force which is generated and we called this equation $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$ as Lorentz equation. Therefore, now if we have a magnetic field let us say which goes into the board and in this maybe we move a charge q with velocity v. A positive charge is better because electrons do not have much of mass and we want a force to be generated. I have a charge moving with a velocity v.

And therefore, if this charge is moving from bottom to top as shown, we should get a force in this particular direction, which is normal to the magnetic field and the motion of the charge. Let us calculate the magnitude of the force from the particular equation. We have the charge q moving the velocity v. Well, let us say I have a distance d over the field over here and I am interested in velocity. Therefore, for velocity we can write as d / time taken for the body to experience a force in this particular direction or rather let me say I move it in this particular direction such that I get a force normal to both in this particular direction.

Therefore, we say d/t is the velocity. The magnetic field is B Tesla. We say the value of the field in Tesla is **B** and we have to differentiate the vector from the scalar quantity which is denoted by B_0. Therefore, we have the charge q and this is the time over which it moves in the electrical field at velocity d/t in B_0 naught and therefore the force is q

$\times d/t \times B_0$. However, q/t is current I and the force can be written as current into $d \times B_0$. This is the force. Therefore, we find in a magnetic field if we have a current I and the depth of the magnetic field is d, we get a force F.

If we were to write force as equal to mass into acceleration where m is the mass of the charge, we get $m \times dv/dt = I \times d \times B_0$. B_0 is the magnitude of the magnetic field or rather we get $dv/dt = I \times d \times B_0 / m$. Supposing at the initial state, the velocity of the charge $v = v_0$ at time $t = 0$; I can straight away integrate the velocity as equal to $I \times d \times B_0 \times t / m$ from which we can get the value of the distance x at time t. Again $x = 0$ at time $t = 0$. Therefore the value of x at time t becomes I into d into $B_0 \times t^2 / 2$ m.

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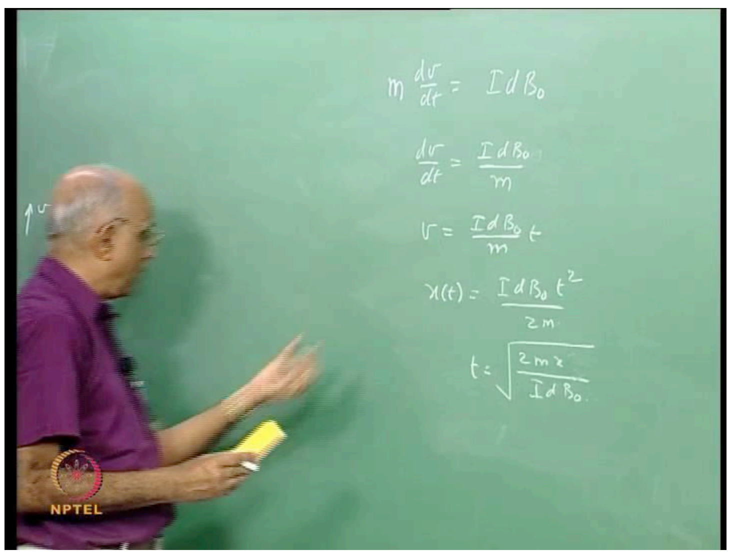

I can go ahead and then simplify if we want the velocity. From the above expression, we get t as under root of $\sqrt{2}$ m $\times$ x at the time t / I d B_0 and therefore, we can get the value of velocity which is required to give us the particular force. These are the set of equations, which are applicable for a thruster, which makes use of the magnetic principle. But, in case of a magnetic thruster, we must have the charge to be provided with a given velocity.

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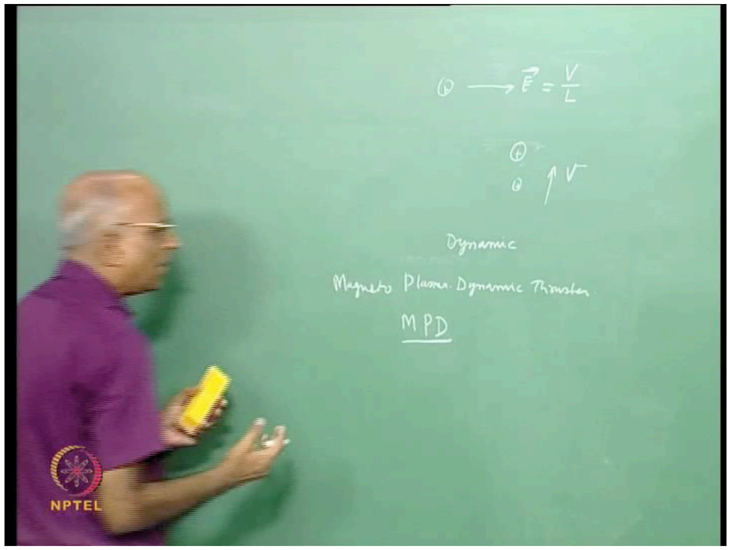

What is the difference between electrostatic and electromagnetic thrusters? In the case of electrostatic thruster, we have a charge, which is accelerated by the field E and what was the acceleration? V is the voltage between the acceleration grid and the extractor grid. The distance between them is L and the value of the field was V the voltage divided by

L. In the case of a magnetic or electromagnetic thruster we have a field which is available and into this field I have to move the charge with a given velocity. In other words we are talking of a dynamic situation and therefore, electromagnetic thrusters or magnetic thrusters are known as dynamic thrusters because you need to have a velocity to begin with. And therefore, if we have plasma; it is known as plasma dynamic thruster. But, most of the plasma is in the magnetic field and it is known as magneto plasma dynamic thruster or MPD. This is about the magnetic thrusters.

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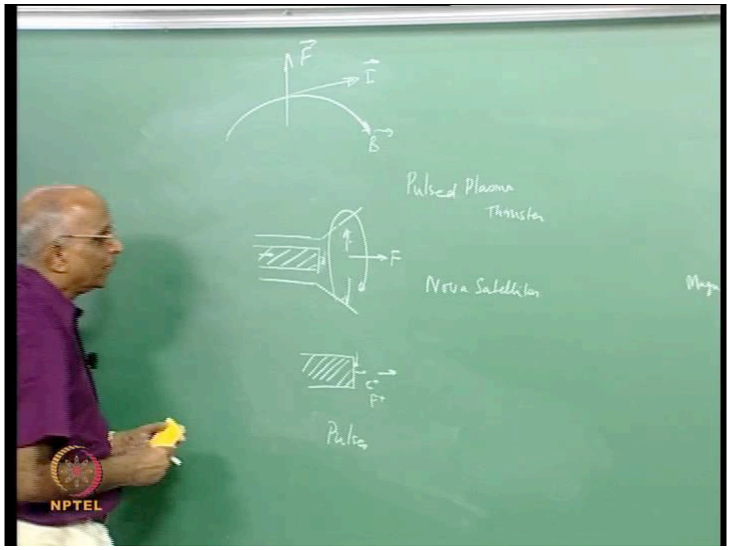

And let us make a sketch of the electromagnetic thruster. We now know the principle let us observe a sketch of how it must be. Well we could have a magnetic field in a tangential direction, maybe I could have in the orthogonal direction to the field a current I and therefore, we will have a thrust normal to it. This is the direction of the force. Let us see the construction of it. Well we have a chamber into which we pass the gas containing the charge. We have a construction with a magnetic field in a particular direction. We allow the charge the flow normal to the magnetic field. Let us say a voltage is present across the two sides and causes a current flow in this particular direction. We get a force in this particular direction and this is how a magnetic or electromagnetic thruster operates. We call it as a dynamic thruster or we say magneto plasma dynamic thruster because you have a plasma of ions and electrons. Current goes in the radial direction and therefore, the force you get in this particular direction.

Well, these are about electromagnetic thrusters. IIT Kanpur is working on a pulsed plasma thruster. In this you have something like Teflon and we put an electrical spark over its surface and generate plasma. In a material like Teflon, which is essentially carbon, chlorine and fluorine, we generate carbon charges. We generate the charges by depositing energy from an electric spark. The charges move in a magnetic field and generate thrust. Whenever a spark is given, a flow of plasma results from the surface and it creates a thrust in a magnetic field. That means, we generate thrust in pulses. Whenever we initiate a spark, we generate the plasma and we generate the thrust; these are known as pulsed plasma thruster. See you can keep on evolving and that is the beauty of propulsion; in propulsion all what we want is some field to generate a force.

The Pulsed Plasma Thrusters have been flown by the by France in one of their Nova satellites. Well, I think it is time to take stock of whatever we have learnt so far in electrical propulsion. We tell that the electrical rockets could be either electrostatic or it could be electromagnetic; in electrostatic we had the ion rockets and Hall thrusters or stationary plasma thruster. We had the dynamic thrusters using the electromagnetic principle.

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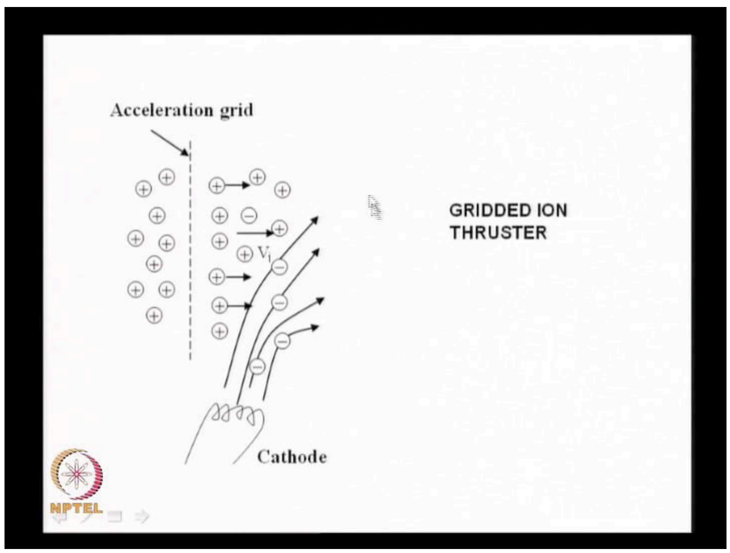

Therefore, let us quickly go through the electrostatic thrusters. You need an acceleration grid, you need a neutralizer and we introduce electrons in the exhaust such that what comes out is neutral.

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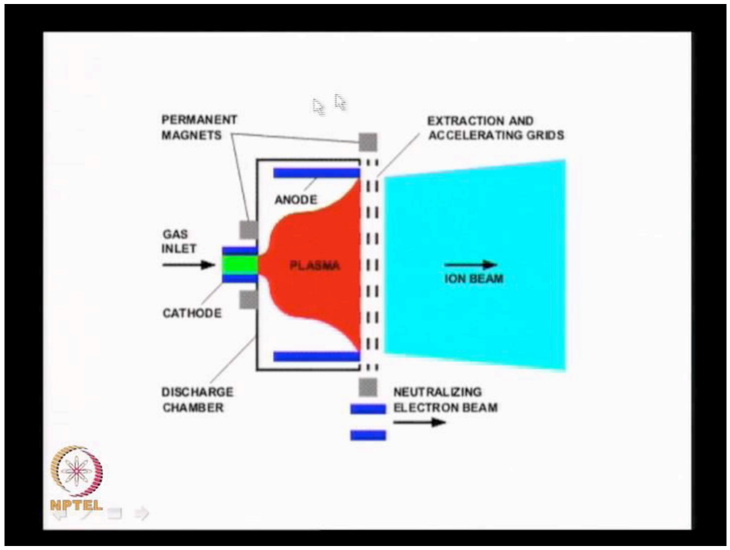

This is how an ion rocket looks like. We admit xenon gas over here. This is the chamber in which we make the positive ions and this is something like an extractor grid, this is something like an acceleration grid, the spacing between them is around half a mm and the voltage is around 1.5 kV. That means, we have an intense field and the ions are accelerated in this electric field. We inject the electrons into the exhaust for neutralization. We have magnets; why do we have magnets in this case of electrostatic propulsion? This is done to have controlled plasma of ions. Mind you it is not like an electromagnetic thruster.

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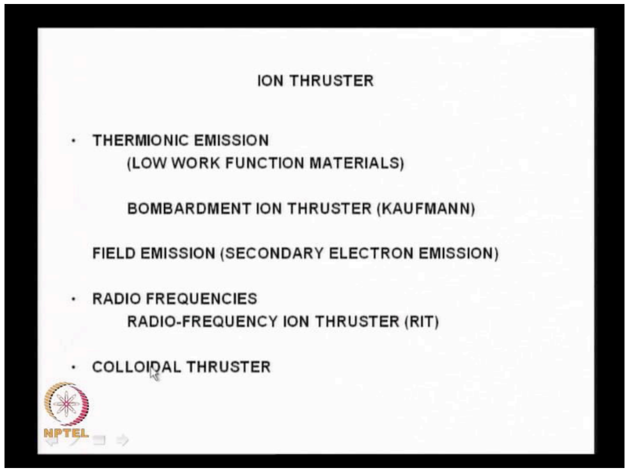

We talked in terms of thermionic emission or bombardment ion thruster because we bombard the gas with the electrons and by bombardment we get ions and this is what we had in the gridded ion thruster also known as Kaufmann thruster. We could have field emission wherein bombardment takes place and secondary electron emission also constitutes to generate more electrons and therefore positive charges. We talked in terms of radio frequency thruster. I talked in terms of some substances which could be charged like colloids or even water droplets and used for generating thrust.

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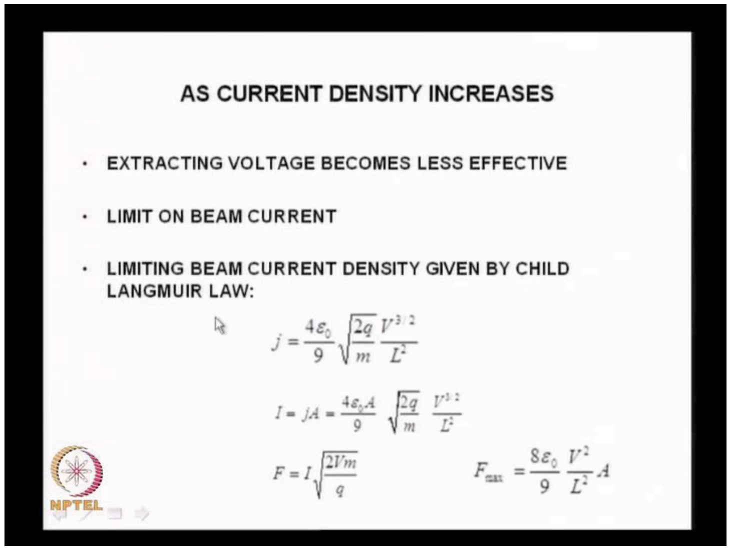

As current density increases we had the three following problems; the extracting voltage becomes less. Therefore, the Child Langmuir law came into the picture. We have limitation on beam current and we found out how to get the maximum value of thrust.

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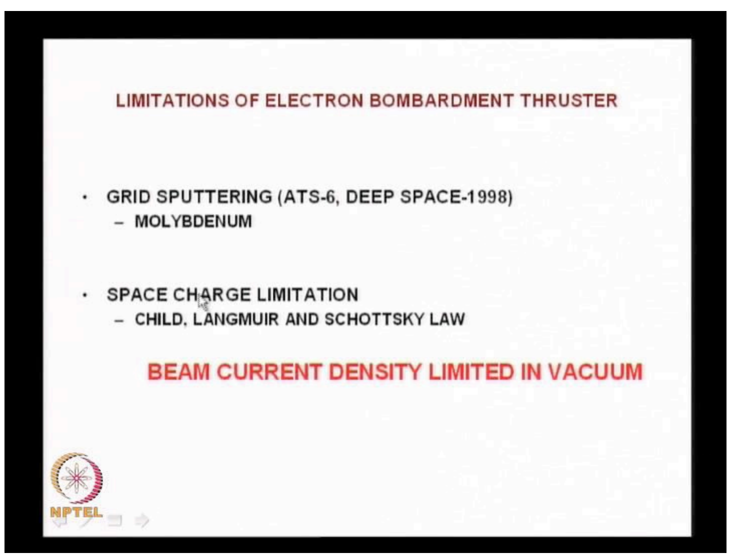

And as I said these gridded thrusters even though there are limitations; it was used in the

ATS 6 satellite for the India. It has been used in some missions like for deep space, which leaves our solar system and gets into distant space. To prevent sputtering we use for grids the material molybdenum. However, for the space charge limitations, the tendency is to make use of the Hall effect thrusters wherein you allow the electrons to be attracted in the annular propellant flowpassage. The electrons spiral and generate the positive charges and are pushed out to provide thrust.

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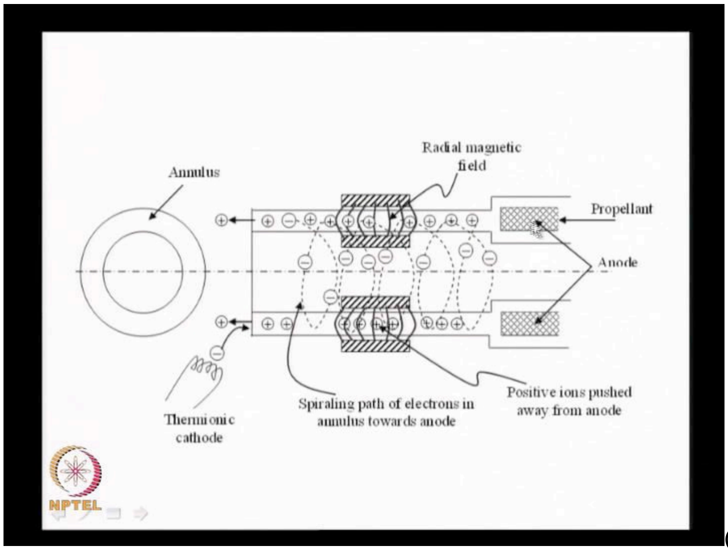

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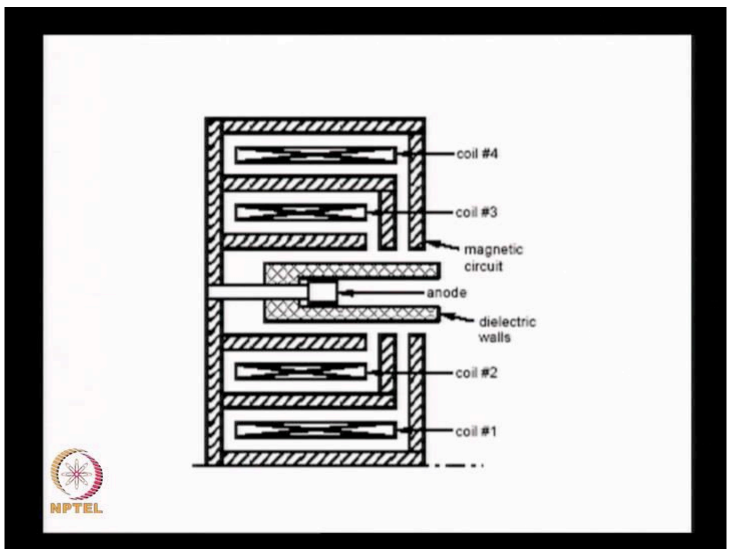

But we did not specifically tell about disadvantages of the Hall thruster. Let us look at the construction. This is the center line, we have magnet between the is the annulus. We have a set of magnets here and have a strong magnetic field. The strength of the magnetic field in the Hall thruster compared to the Earth's magnetic field of 0.4×10^{-4} Tesla is around 0.1 to 0.3 Tesla.

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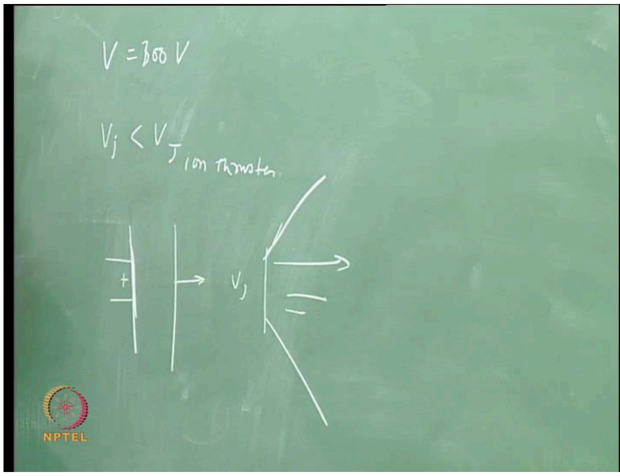

The voltage is around 300 volts and you can generate slightly higher thrust compared to the ion rocket. But, as we said the VJ is less than what you get in the ion thruster.

But there is one problem, which we can immediately foresee. You have the anode, that is positive and it is pushing out the charges with some velocity. Therefore, the velocity being lower, you know it does not really go as a free stream. It tends to diverge a little bit and when it diverges you know it goes and contaminates the other bodies on the surface of a spacecraft. To be able to prevent it, people talk in terms of whether we could reduce the length of the thruster such that the positive anode is more effective? And that is what I also show after a couple of slides.

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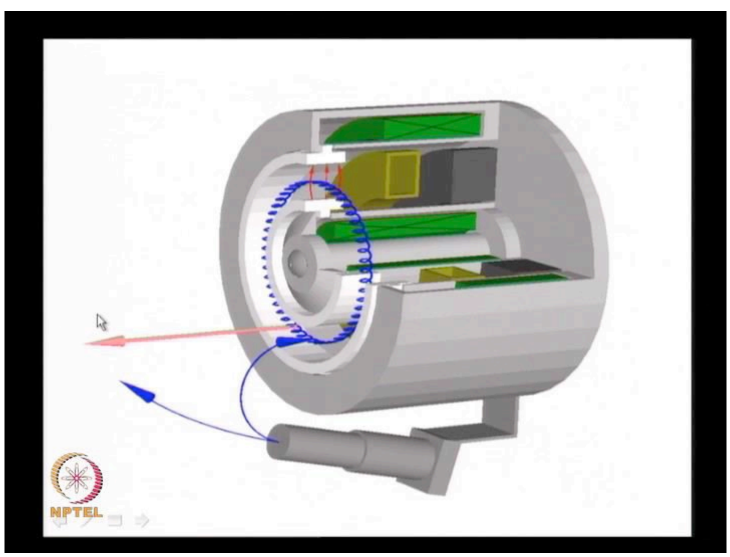

Let us take a look at the construction of the Hall Effect Thruster. This is where the electrons are generated using a cathode. It enters the annular gap over here. There is a strong magnetic field in this particular gap over here and therefore, the electrons spiral you have an anode here which pushes the ions out and you get the thrust

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This is the face view in the annular gap through which the xenon comes out and you get the thrust. This is the sort of the cathode which generates the electrons.

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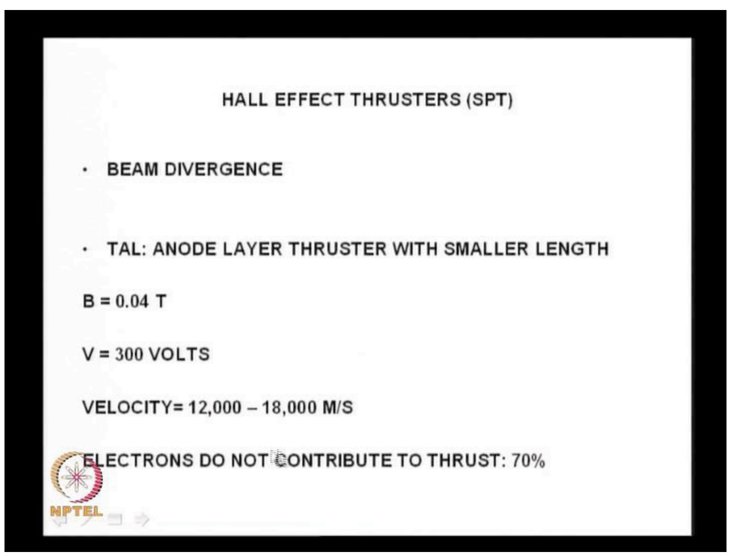

To prevent the divergence which leads to contamination; a small length is to be preferred and this small length thruster is known as the anode layer thruster or rather TAL. Well we have considered this earlier; the magnetic field is around point 0. 4 Tesla and the voltage around 300 volts. We get around 15,000 meters per second as the jet velocity and we said since the electrons are just spiraling and they do not contribute to thrust. The efficiency is low around seventy percent.

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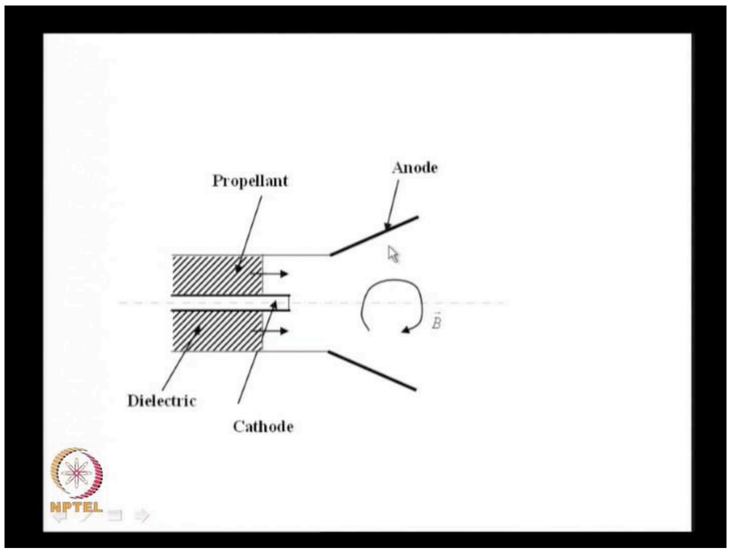

Well, we considered the electromagnetic thrusters and this is an electromagnetic thruster. You have a tangential field into which the charge is moved. We have a voltage difference between the two sides. Therefore the charge travels in the radial direction and I get a thrust in the axial direction.

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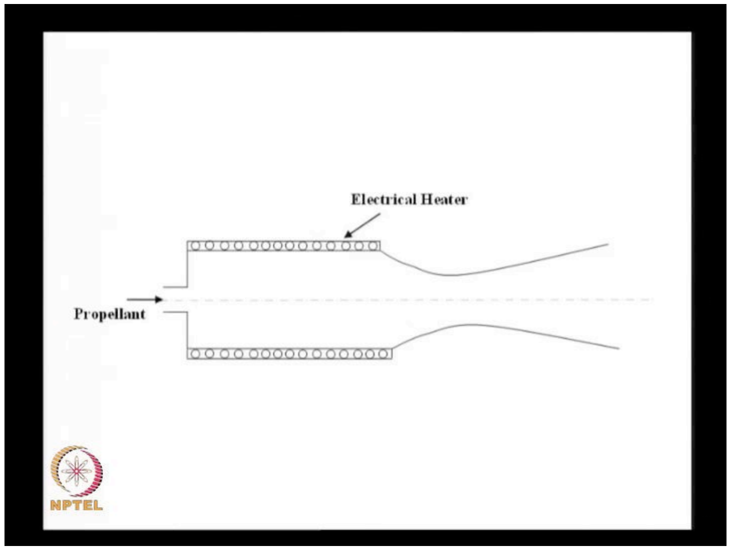

Well this is all about electrostatic and electromagnetic thrusters. But, something you know which we missed out when we talked in terms of electrical rockets.

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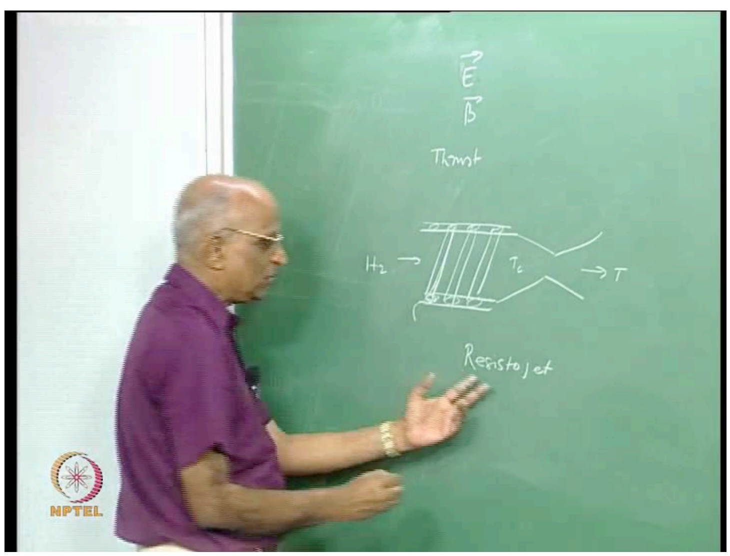

In the electrical rockets, we essentially went into the principle of electrostatics and electromagnetics and how to generate thrust? But, something which was very apparent which we did not do was supposing we have a gas flow and we use may be a series of electrical resistances here; We put a resistance coil on the wall and we pass current through them; Well, we can always heat this chamber and I could have a regular nozzle in which the hot gases are expanded.

That means we heat the gas using resistance wire and these are known as Resisto jets. But this is not very practical though. We heat the gas either by the resistance wire in the gas or we heat the wall using some resistance wire. That is just the same way as we have a geyser at home wherein we heat the water. I heat the gas and the hot gas to a temperature Tc. I could admit hydrogen, which has a low molecular mass. Well, I can get a thrust. This is known as a resisto jet and why a resisto jet? We use electrical resistance for heating.

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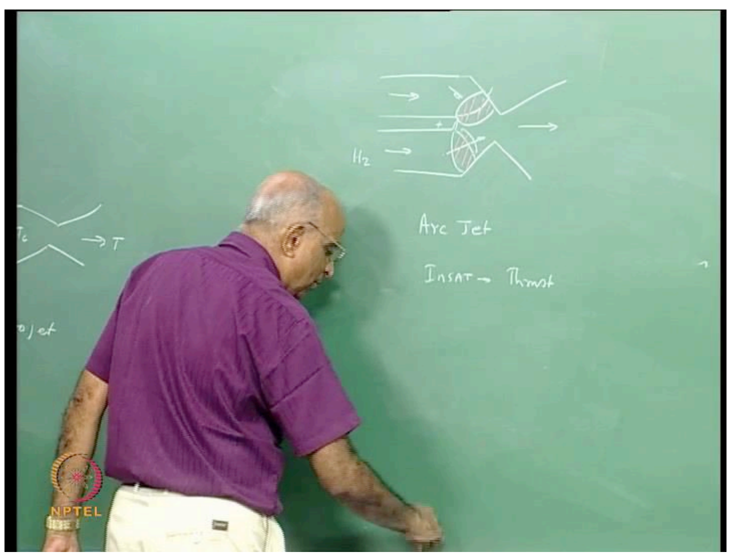

We can also use a similar principle and we can create an electrical discharge or an arc in a chamber. We pass a gas, a low molecular mass gas let us say hydrogen in the chamber and generate an arc discharge to heat the gas.

We have a high voltage at one end and a neutral at the other. We form an arc discharge and when the gas flows through the arc; it becomes heated and highly ionized. We have very high temperature and we could expand this out as a high temperature gas and this is known as an arc jet. In other words, instead of using resistance for heating, we use electrical arc for heating and the zone of the arc we show here. It is highly non equilibrium. We have dissociation taking place, We have lot of excited species being formed and these excited species will not recombine and release their energy and will reduce the efficiency. But we can get high temperature and we can get a good thrust also. Therefore these are arc jet thrusters, but, you know they have some problems because of dissociation and the arc which tends to create electrical disturbances can influence the spacecraft also.

In fact, when we first wanted to have a propulsion system for the Indian National Satellite INSAT, we thought we will use ammonia as a gas with an arc discharge and use it to generate thrust. Therefore, to conclude the present discussions on electrical rockets:

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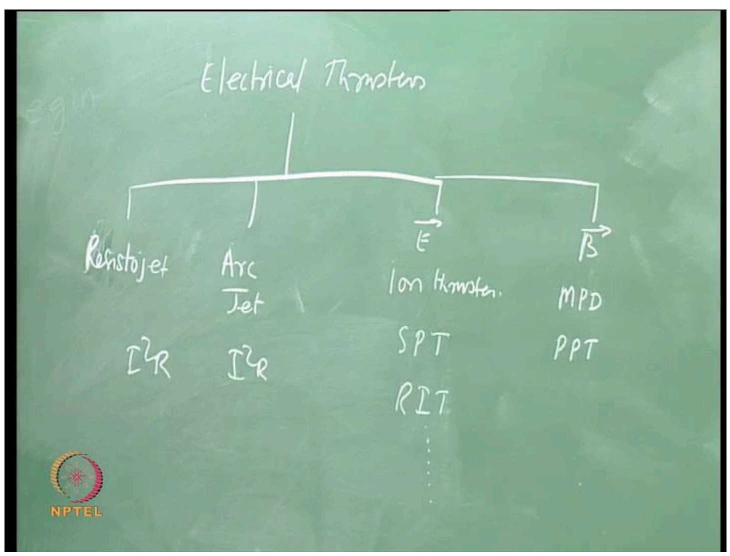

We can say the electrical rockets; we call them as electrical thrusters since they generally can be used only for low thrust. It could be something like a resisto jet using electrical resistance heating. It could be an arc jet. Then it could also use the electrostatic principle in which case it could be an ion thruster. It could also be an improvement as a stationary plasma thruster or Hall effect thruster. We could have a radio frequency ion thruster or may be a colloid thruster and so on. We could also use the magnetic principle namely the magnetic field for the MPD, magneto plasma dynamic thruster or we could also have pulsed plasma thruster. We could keep on deriving further. Well, this is all about the electrical thruster.

The heating in the resisto jet and arc jet goes as I^2R. Though the resisto jet is easy to visualize and the Arc jet is little more complicated, it is instructive to see how arc discharge can be started in space. In vacuum of space, we have a gap d between the electrode and the neutral. When there is vacuum we cannot strike an arc. When we start supplying the gas, the vacuum level comes down and if the vacuum level drops to a level where in we get the product of pressure into the distance as a critical threshold value, we get an arc discharge by which we can heat the gas and we can get the thrust. The striking of the arc is therefore done automatically.

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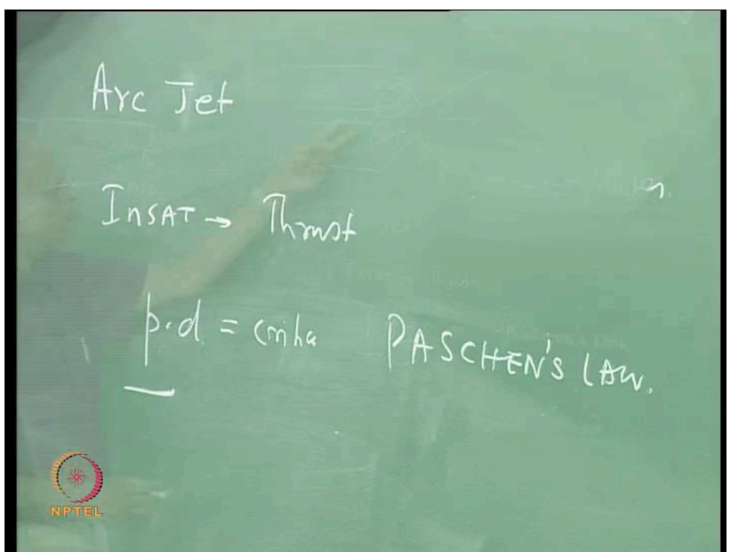

The product of pressure and distance defines when an electrical arc can be formed and the critical value comes from Paschen's law. While some designs use this threshold value for initiating the arc discharge in vacuum, there are others who mount the electrodes in a gear train and adjust the gap for initiating the arc discharge. An arc discharge is formed at a small distance between the electrodes and then it is brought to an equilibrium value.

And therefore, this is how an arc jet works.

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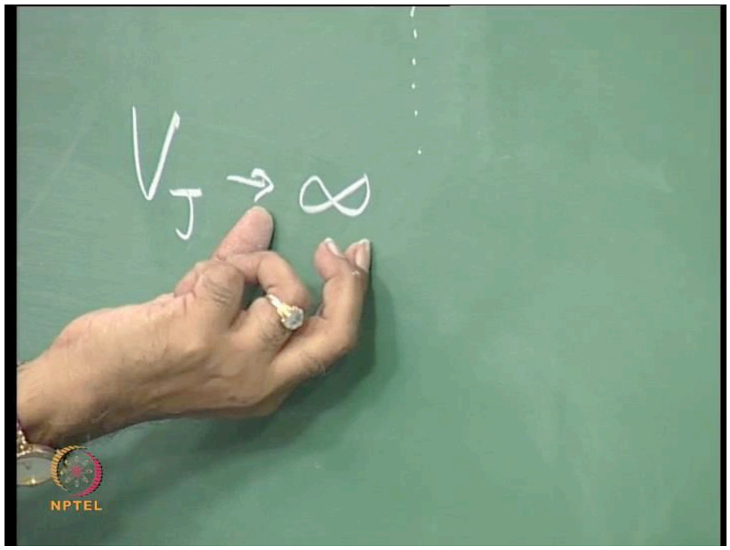

In the next class, we will wrap up whatever we have learnt in this course; but we will also see if V_J can be infinity? In fact, one of the goals of Robert Goddard was to have extremely high values of V_J. But, is it really possible or is there some limitation on V_J, which influences the performance? And this is what we study see in the next class.