Rocket Propulsion

Prof. K. Ramamurthi
Department of Mechanical Engineering.

Indian Institute of Technology, Madras

Lecture No. # 36

Electrical and Nuclear Rockets; Advanced Propulsion

This will be the concluding lecture of this course and what we do in this class are the following:

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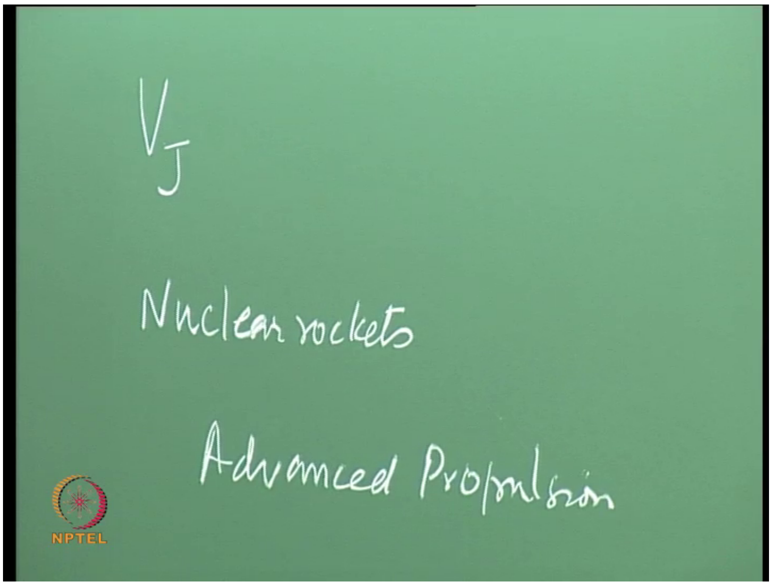

We said V_J must be high and let us see whether there are some limitations to the value of V_J especially for electrical propulsion. After looking at this, we will try to see whether there are other possibilities of using let say nuclear forces for generating thrust like nuclear rockets; we can use the light like photons or rather some of the newer developments like zero point energy as advanced propulsion. The question of advanced is always relative because compared to chemical propulsion, the electrical rockets are relatively recent and more advanced. But, anyway let us see whether anything more than electrical propulsion, something like newer types of propulsion is possible in the years to come. And I think all of us must concentrate on this because may be all you all will have a chance to develop some new propulsion system which is innovative.

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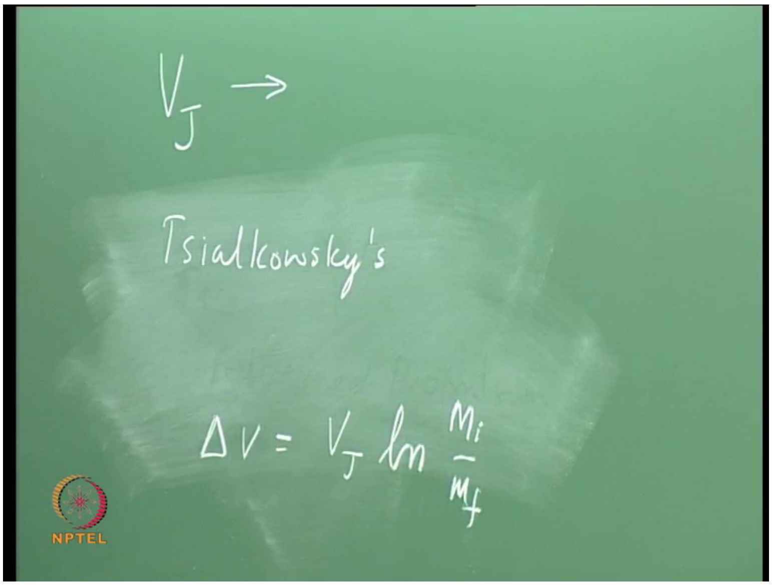

Having said this let us take look at V_J. Should V_J be extremely large? I have been telling this a couple of times. Tsialkowsky formulated the rocket equation and in today's class we will go back to the equation because we would like to conclude about V_J. What was the rocket equation? We said that the incremental velocity delta V which a rocket gives not only comes from its exhaust jet velocity like Isp or V_J but also the logarithm of the initial mass to the final mass. If we have to get a high V_J such as with electrons which can be pulled in a magnetic field and we could get very high V_J; but it so happens that electrons have very low mass and therefore, it does not give you force.

Well after Tsialkowsky and another ten years maybe twenty years or thirty years later something like in 1930's and 1940's, people were interested in using electrons itself for propulsion. Can we get the electrons to go at the speed of light and therefore get a high value of V_J? Or are there some limitations? There could be no limitations in getting a high V_J but does the basic equations what we consider suggest some limit to V_J which is possible? And that is what we will try to do in the next five or ten minutes.

Let us now take a realistic picture of the electrical rockets that we discussed in the last class.

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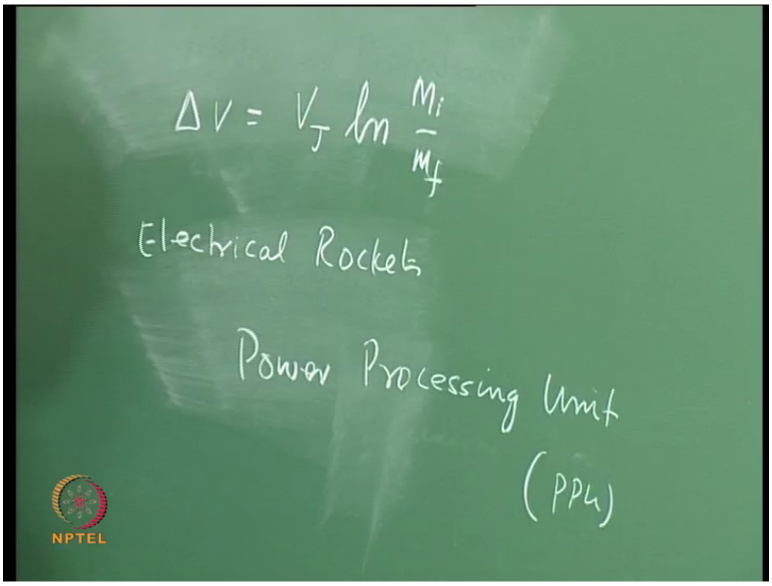

What we needed in in the electric propulsion unit was something more than the thrust generating device. We needed propellant and propellant was let us say xenon. We also said that we need the electrical field in case of ion rocket. W need a voltage of something like 1.5 kV. For the Hall thruster we needed about 300 Volts. That means I need something like a power unit. Even if I had solar power, we convert it into electricity in the spacecraft. I still have to recondition the power to give me a high voltage that means we have something like a power processing unit. It has to process according to the voltage and current requirements. We call it as PPU, power processing unit.

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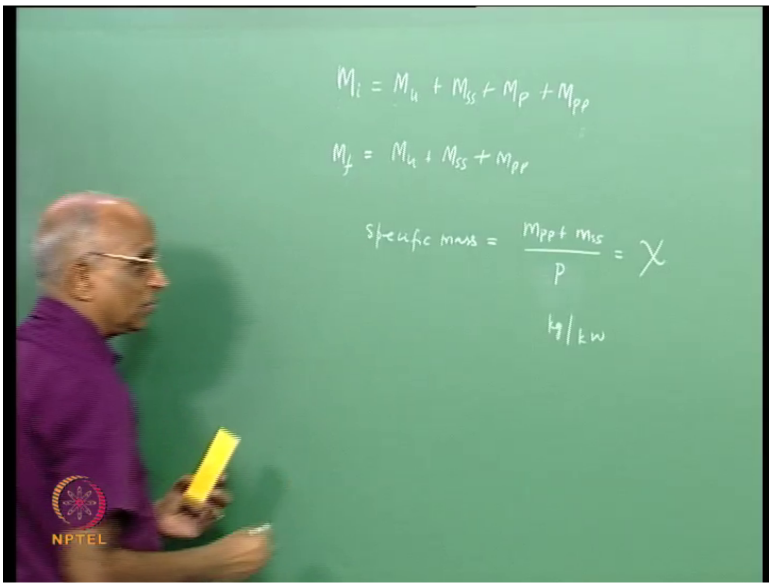

Now, if I have a battery; it is going to be heavy. That means in addition to the usual structural mass in a chemical rocket, there are other mass which are to be included in the initial mass of hardware. Let us go back to the Tsialkowsky's equation or the rocket equation.

It had the structural mass; it had the propellant mass. Now what is it that we are saying? Now, we have a power processing unit which has some mass and therefore we should add something like M_{PP} in addition to propellant mass, in addition to structural mass. But, the structural mass will also go up because this has some weight and must have a structure to support it. Therefore, the initial mass in the case of electrical rocket will consist of useful mass plus structural mass and this power plant mass and the propellant mass. And what is going to be the final mass? Final mass is going to be the useful mass, the propellant has burnt out and I have structural mass plus the mass of the power plant. Therefore, I find I am unnecessarily carrying this power plant, which has certain inert mass and also the structural mass associated with the power plant.

We can define the specific mass of the power unit as mass of the power plant plus mass of the structure associated with the power plant divided by power that is generated by the power plant. This is denoted by χ and its unit is kilogram per kilowatt.

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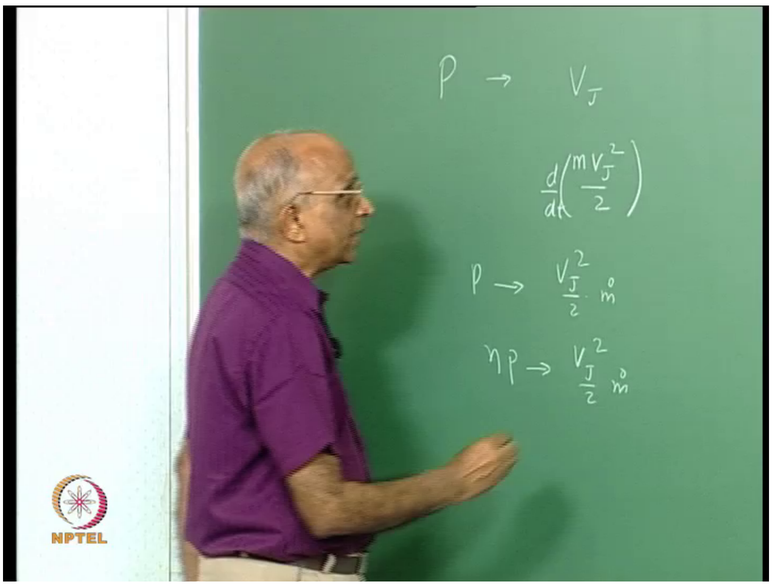

When we supply power P and use this power to enhance the velocity V_J, what we are essentially doing is the rate of the energy or work namely power gets converted to the kinetic energy and what is kinetic energy? Mass m into V_J squared divided by two; but we are talking of energy here whereas it is power that is rate of energy that is supplied. Therefore you have something like d by dt of the kinetic energy. Therefore, power gets converted into let us say V_J through rate of kinetic energy. I take V_J squared divided by two into m dot or rather power get converted into the rate of kinetic energy.($\frac{1}{2} m^\circ V_J^2$)

Whenever some conversion takes place there is some loss and efficiency of conversion. We put in electrical power convert it into something like kinetic energy over here and therefore have an efficiency of conversion. If the efficiency of conversion is say η, then we have η_P which gets multiplied by power to give $\frac{1}{2} m^\circ V_J^2$. We can write that power is equal to $\frac{1}{2} m^\circ V_J^2 / \eta_P$.

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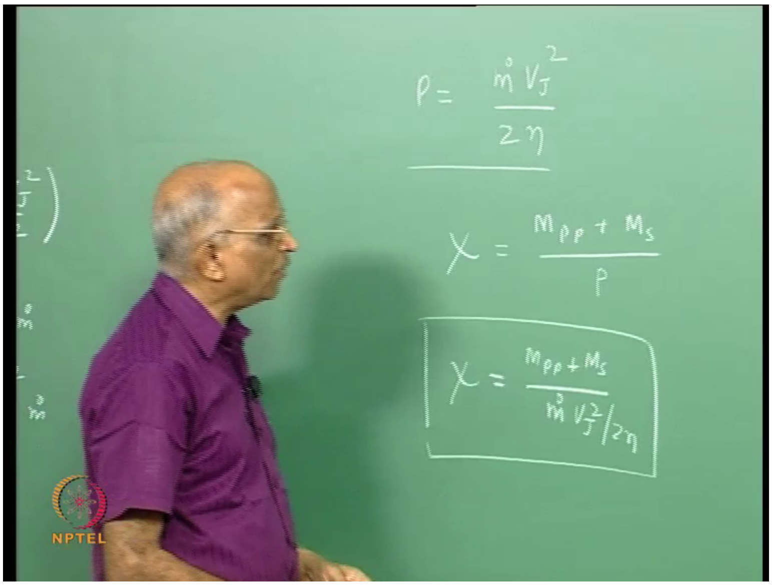

Thus gives us the power as a function of the useful kinetic energy. If the efficiency is low or efficiency is poor that means we need a higher power to get the same jet velocity. Having said this let me now work the specific mass what we defined as equal to χ was equal to M_{PP}, mass of the power plant plus you have the mass of the structure divided by power. The specific mass of the power source is the total mass of the power unit and the structure associated with it divided by the power. Now, if I can use this value of power to be substituted over here, we get $\chi = (M_{PP} + M_S)/m^\circ V_J^2/2\eta_P$.

Why is it we are deriving this? The reason is we were looking at the rocket equation; when I get a higher jet velocity I must also get a better useful mass or useful payload.

But, if we have a higher value of jet velocity, my power goes up. If my power goes up, well my mass also goes up and it quite possible that the useful mass decreases. Let us plot these values.

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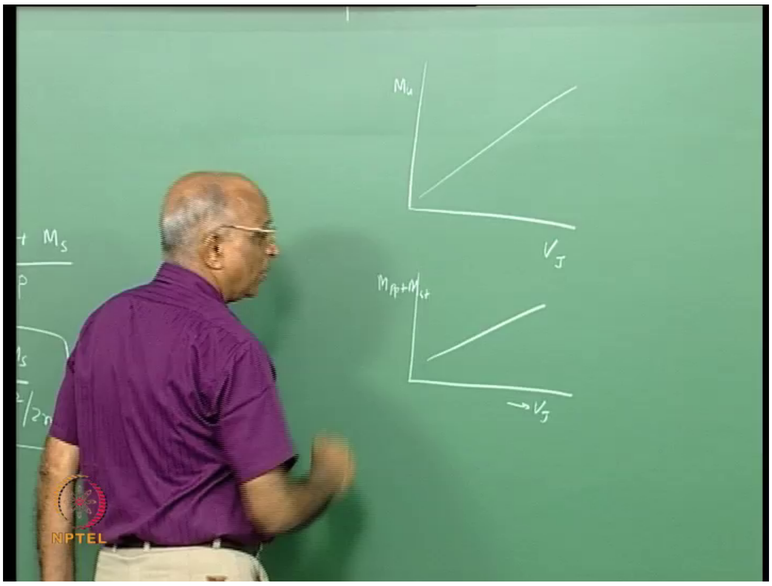

I say, well the payload mass, the useful mass M_U is a function of V_J. If I look at V_J alone may be as V_J increases, the useful payload will go up. This is because we have a higher jet velocity. But, a higher jet velocity results in a higher power and therefore, the power that means the values of M_{PP} plus M_S also increases as V_J increases.

It will adversely affect my value of the useful pay load and this is what I want to work out. Therefore, to able to do this, we write the Tsialkowsky equation for the incremental velocity as the incremental velocity $\Delta V = V_J \ln($ initial mass / the final mass).

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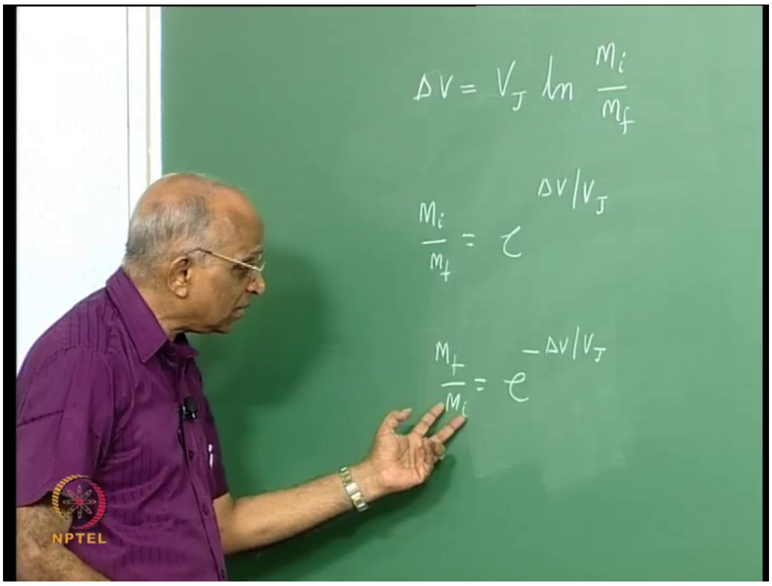

Rather this particular equation I can again write as initial mass to the final mass viz., $m_i/m_f = e^{\Delta V/V_J}$. If we invert it and say we are interested in the final mass divided by the initial mass, we have $m_f/m_i = e^{-\Delta V/V_J}$. Now what is it that we find? As V_J increases, the final mass for given the initial mass will go up. But, then we are also telling that the unproductive mass also goes up. Therefore let us try to build an equation which will give us the useful pay load mass. Let us write it over here.

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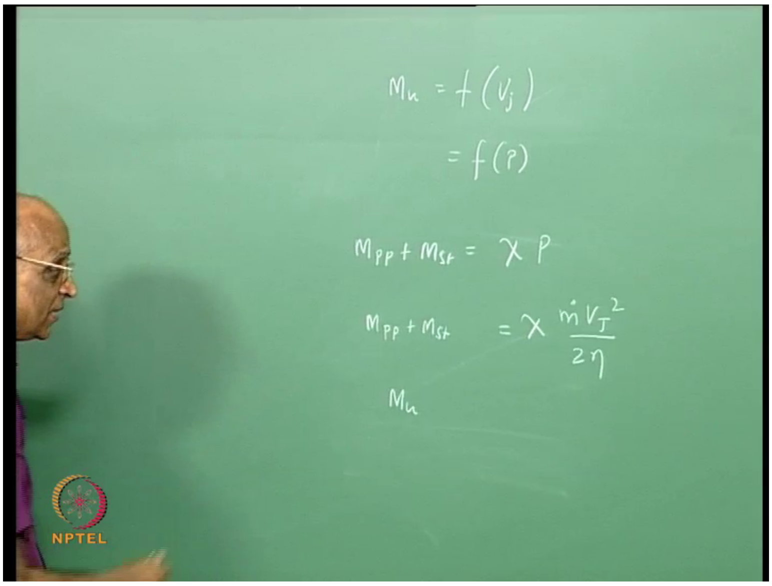

The value of the useful payload is a function of V_J, which is also a function power and this is what I am searching for. Therefore, if we come back to the equation, we have final mass divided by initial mass mf/mi = $e^{-\Delta V / VJ}$. We can write the whole thing as mass of the power plant plus mass of the structure over here from this particular expression and write it as equal to χ of the power. Well the power, we again write it from an expression as equal to $m°V_J^2/2\eta_P$ and we get the value of the mass of power plant plus the mass of the structure $(M_{PP} + M_S) = m°V_J^2/2 \chi \eta_P$. Somehow we want to bring in the value of useful mass over here and therefore, I look at this expression again and want to express the value of useful mass as a function of initial mass and as a function of V_J. So let us return to the masses again.

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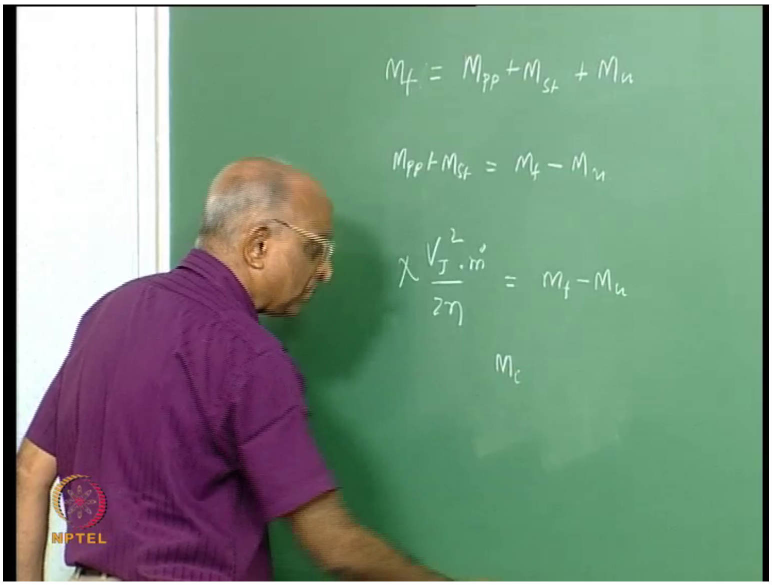

We can now write the final mass: what we get in a rocket is equal to the mass of the structure and the power plant which is left behind as $M_{PP} + M_S$ + the value of useful part M_U. Now, we can write it as $M_{PP} + M_S = M_f - M_u$. We now substitute the value of the power plant mass and this structural mass through this particular expression and this becomes equal to $\chi m°V_J^2/2\eta_P = M_f - M_u$ or $M_f = M_u + \chi m°V_J^2/2\eta_P$. We would like the initial mass also to come in the equation.

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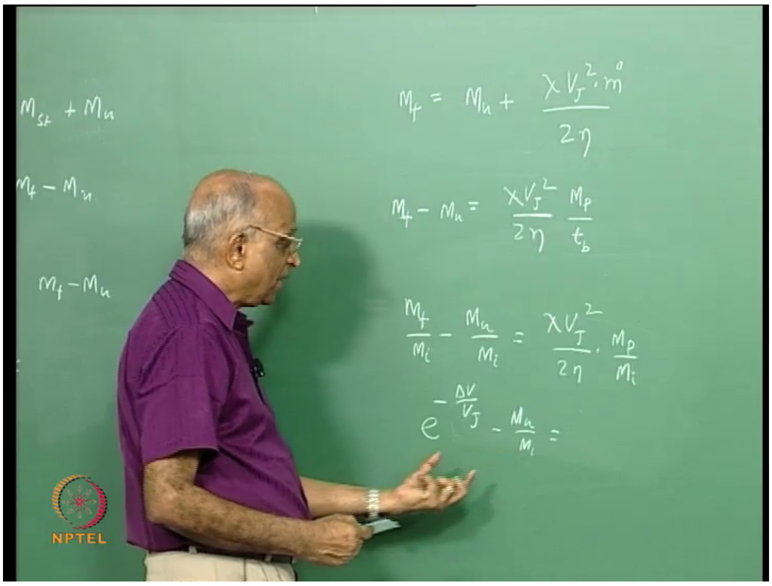

And therefore, I can write this expression as M_f minus M_u in terms of M_i also and for this we simplify the expression. We write $M_f = Mu + \chi m°V_J^2/2\eta_P$. We find that as the efficiency decreases; that is the efficiency of conversion of the power into velocity decreases, well this factor goes up. The final mass and therefore the value of M_u will decrease with decrease of efficiency and is what we should really expect. Because the efficiency of conversion of the power into the velocity decreases, I will have a less useful payload.

Having said this, let us try to again arrange the expression in some particular form. I will write it again as $M_f - M_u = \chi m°V_J^2/2\eta_P$. What is that rate at which the mass is getting depleted? It is the total propellant mass is M_P and this divided by the duration of burning say t_b is m°. We assume the propellant flow rate m° to be a constant. Therefore, we get the value of M_f minus M_u as equal to this expression $M_f - M_u = \chi V_J^2\ M_P/2\eta_P t_b$. The duration of burning also affects the useful payload.

We would like to arrange the above as $M_f/M_i - M_u/M_i = \chi V_J^2/2\eta_P \times M_P/M_i$. We further simplify and express it as M_f by M_i, and we already known = $e^{-\Delta V/VJ}$ and M_U by M_i is what we are interested in. The value of M_u by M_i can therefore be put together through the following expression. $M_U/M_i = e^{-\Delta V/VJ} - \chi V_J^2/2\eta_P \times M_P/M_{i.}$ We know the mass of the propellant and what is the mass of the propellant? Again it is equal to the final mass minus the initial mass and therefore, I can again put it in terms of the value of e to the power of minus delta V by V_J and therefore, the final expression is given in the following slide:

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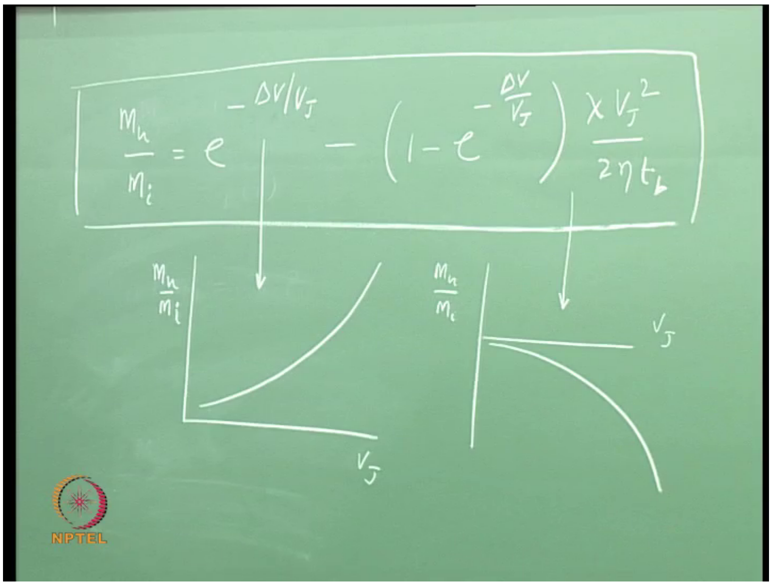

As $M_u/M_i = e^{-\Delta V/VJ}$ and $M_P = M_i - M_f$ when divided by $M_i = M_f/M_i$. We substitute $M_f/M_i = e^{-\Delta V/VJ}$ and we get $(1- e^{-\Delta V/VJ})\chi V_J^2/2\eta t_b$. Hence the expression for the useful mass.

Let me simplify this a little bit and try to point out the dependence what we get. We can write this particular expression as the useful to the initial mass. This expression tells us that the value of M_U by Mi as a function of V_J. As V_J increases, the negative exponent decreases and therefore, it goes like this. Whereas as we are subtracting some quantity over here. Therefore, this is my zero over here. As V_J increases this quantity decreases but then V_J^2 decreases and the value of M_U by M_i goes up. Rather we find M_u/M_i contribution from the first term on the right hand side increases like this as shown while the second term decreases and the net of the two put together shows an increase followed by a decrease with increase of V_J.

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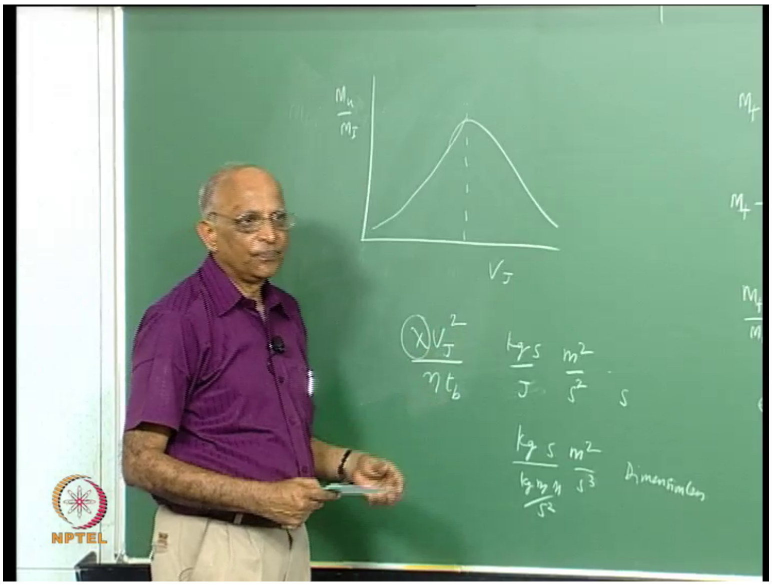

The value of M_U by M_i initially increases when the initial value of V_J is small. When this value of the second term catches up with the first term, well it will decrease and we have a decrease in the useful payload followed by an increase. In other words, there is the value of V_J beyond which the useful mass comes down rather than going up and that is why I cannot really operate the electrical rocket under high power conditions or under high values of V_J.

Now, one last point when I am with this particular expression. If we look at the value of this particular value of $\chi V_J^2/\eta t_b$, what is it that I observe? If I look at the dimensions, it is a specific mass so much kilogram per watt and what is watt? Watt is Joule per second. V_J squared is meter squared by second squared, eta is efficiency does not have unit, t_b has units of second and now if I were to the put the units again, the units of Joules is again Newton meter, Newton is kilogram into meter per second^2 and meter here and therefore this net expression becomes a dimensionless number. We will now take a look at the parameter χ by η and how the useful mass could be expressed as a function of V_J.

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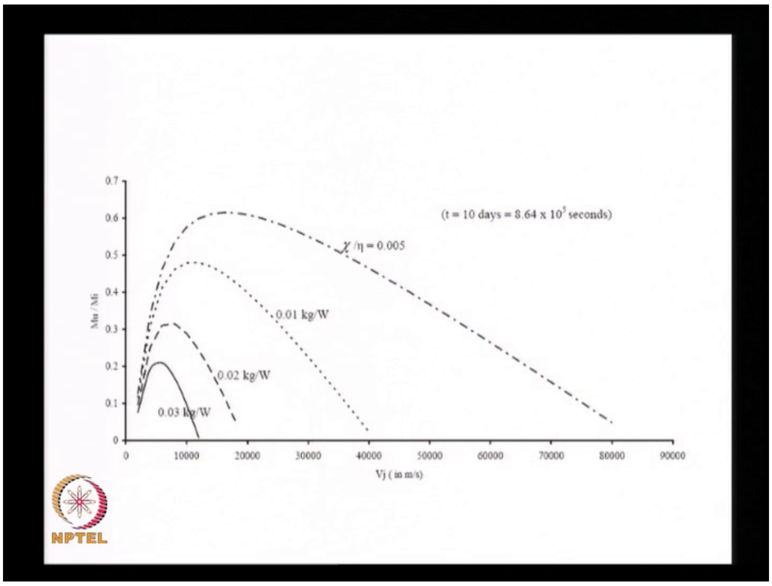

And this is this is what I show here the value of χ by η which I keep changing, the value of V_J is shown on the X axis and the value of M_U by M_i on the Y axis. This is for a particular mission, which takes ten days and it gives a ΔV of 2 km/second. We find that the optimum depends on the specific mass of the system and for a higher specific mass there is no point in me having a velocity V_J greater than some limit. Therefore there is a limit on the velocity V_J. This is all I want to illustrate using this slide. In other words, the effect of increasing the power is to increase the specific mass or increase the mass of the system and it does not really help anyway.

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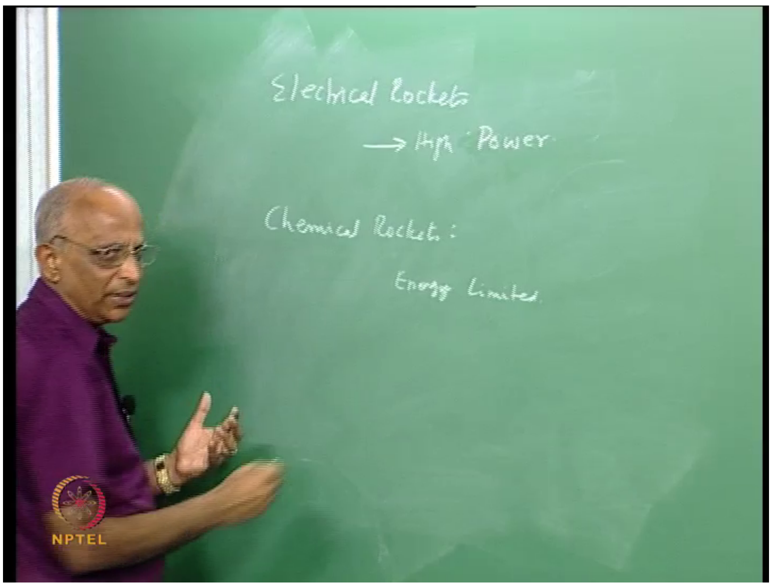
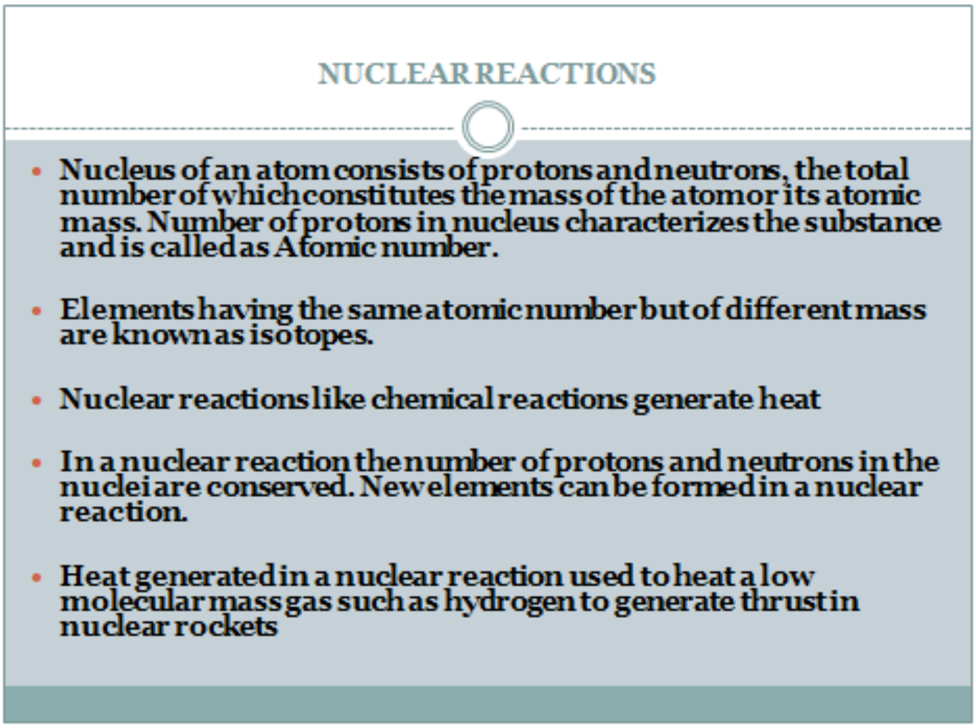


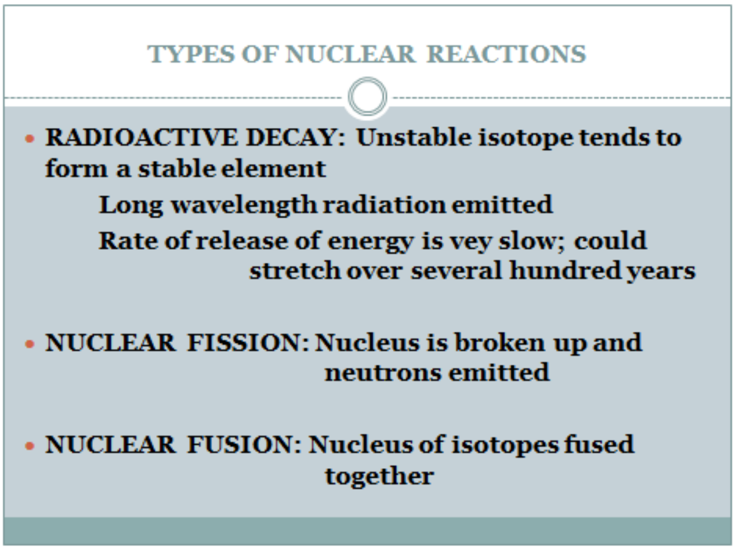
And therefore, we say electrical rockets cannot be operated for very high power levels. That means there is a power limitation. A given value of power beyond a threshold value is not useful any more. Why is this? This is because as power increases, V_J increases and a large value of V_J is detrimental. But, when we talk of chemical rockets; were there any limitations? Can you immediately recall any limitation we had? We had a limitation in temperature because the combustion chamber could not take very high temperatures. That means the energetic of the rockets or we say energy of the propellant have a limitation. That means chemical rockets are energy limited whereas the electrical rockets are power limited. I think we need to keep this in mind and with this we sort of conclude our discussion on electrical rockets.

But, let us see whether we can really have rockets, which are different. Why not have something like electromagnetic radiation or light, which can give you some pressure or may be something like nuclear reactions and we talked in terms of tri propellant rockets. Are there other mechanisms to generate the thrust? And that is what will be doing in the next few minutes.

Let us consider nuclear reaction. After all nuclear reaction also generates heat and power. In a nuclear reaction, the nucleus of the atom participates in the reaction. The nucleus of an atom consists of neutrons and protons and the number of protons in the nucleus characterizes the particular substance. It is known as the atomic number. We have isotopes of a substance and these have the same atomic number but have different mass i.e., the number of neutron in them are different though the number of protons are the same. Most of the isotopes are not very stable.

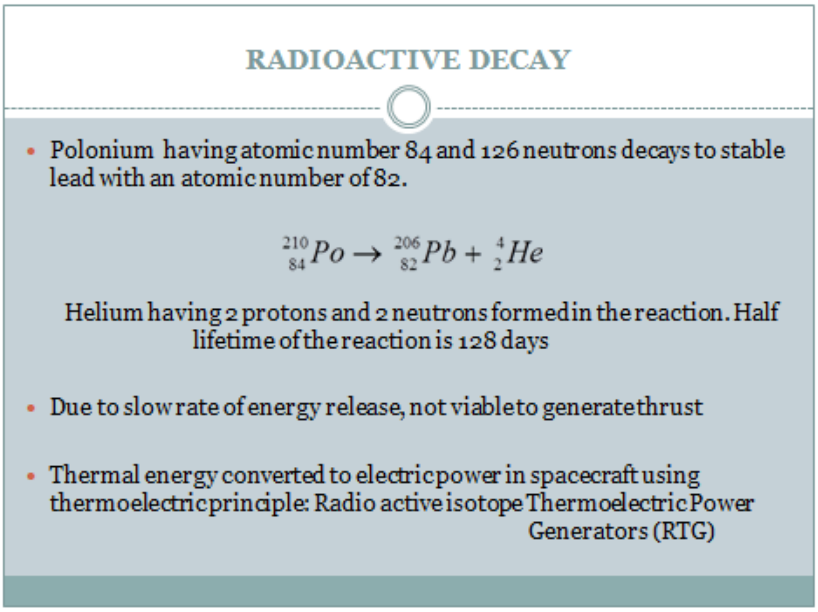


Let us consider a nuclear reaction. Compared to a chemical reaction in which the atoms are conserved, in a nuclear reaction the number of protons and neutrons in the nucleus are conserved and new elements can be formed. The heat generated can be used to increase the temperature of a low molecular gas such as hydrogen and thus generate thrust. This is the principle of nuclear rockets.



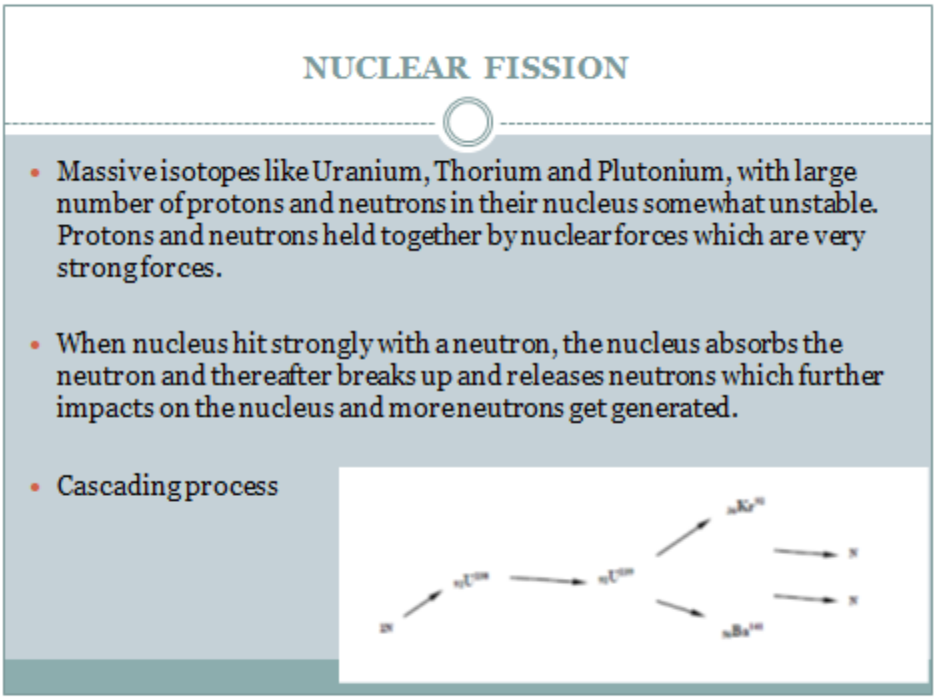
There are three types of nuclear reactions. When the relatively unstable isotope of an element tends to form a stable element i.e., it tends towards a state of equilibrium, it emits energy. This is spoken of as radioactive decay since long wavelength radiation corresponding to radio frequencies is generated. However, the release of energy is very slow. The second type of nuclear reaction is the fission. The nucleus is broken up and neutrons are released. The third type of nuclear reaction is fusing of neutrons in a given nucleus and is known as fusion.

The radioactive decay process is very slow and in some cases takes place over several hundred years. You may recall radiation from the monazite sands in Kerala. Let us consider the case of radioactive decay of Polonium, first discovered by Madam Curie.

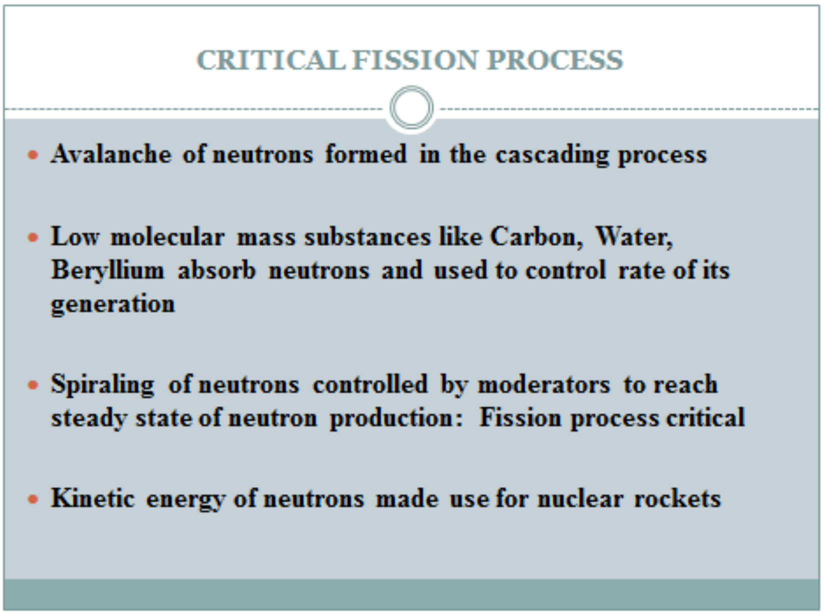


Polonium has 84 protons and 126 neutrons and gradually decays to lead having 82 protons and 124 neutrons in its nucleus. Helium is formed in the reaction and is associated with alpha radiation. The alpha emission from helium gives thermal energy. However, the release is very slow and half lifetime of the reaction is 128 days. The slow release of energy is not favorable for use in a rocket. However, it is converted to electric power for use in spacecraft by the thermoelectric principle. The process is known as radioactive isotope thermoelectric power generator and is abbreviated as RTG. In addition to Polonium, Thorium and Uranium are also used for power generation with RTG.

Isotopes like Uranium, Thorium and Plutonium have large number of protons and neutrons in their nucleus. When the isotope is impacted with a neutron, the nucleus absorbs the neutron and thereafter breaks up and releases further neutrons. In this way a large number of neutrons get generated.



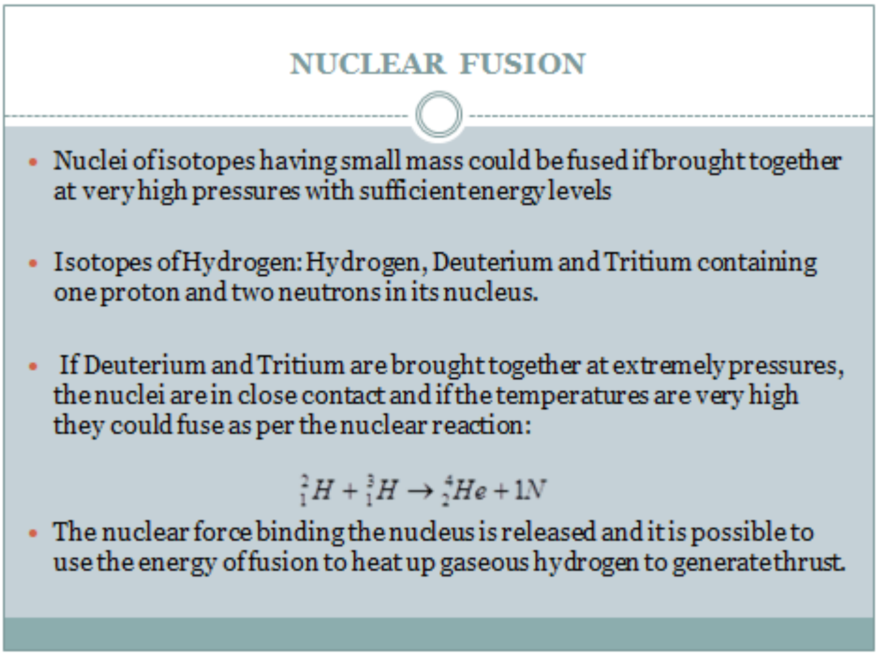
Isotope Uranium with 92 protons and 147 neutrons absorbs a neutron to form an isotope with 148 neutrons. This releases neutrons to form Barium and Krypton. The neutrons further get generated. It can be written as ${}_{92}{}^{239}U$ giving ${}_{56}{}^{141}Ba$ and ${}_{35}{}^{92}Kr$. An ever increasing avalanche of neutrons is formed and this continues as long as the supply of uranium is available.



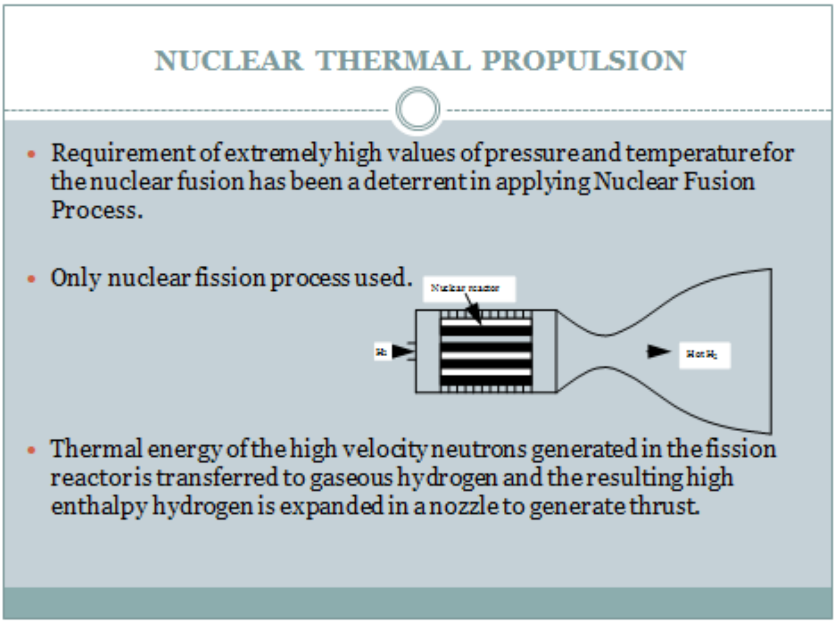
Low molecular mass substances like carbon, water or beryllium can absorb the neutrons and thereby control the rate of generation of the neutrons. In a fission process, therefore, carbon or beryllium are introduced as moderators to control the rate of release of neutrons. By suitably absorbing the neutrons and reflecting it back into the fission scheme, it is possible to have a steady state generation of neutrons. When the fission process is made to go at a steady state, it is said to be critical.

The neutrons have kinetic energy which can be converted into thermal energy for heating a low molecular mass gas such as hydrogen. This principle can be used for making nuclear rockets.

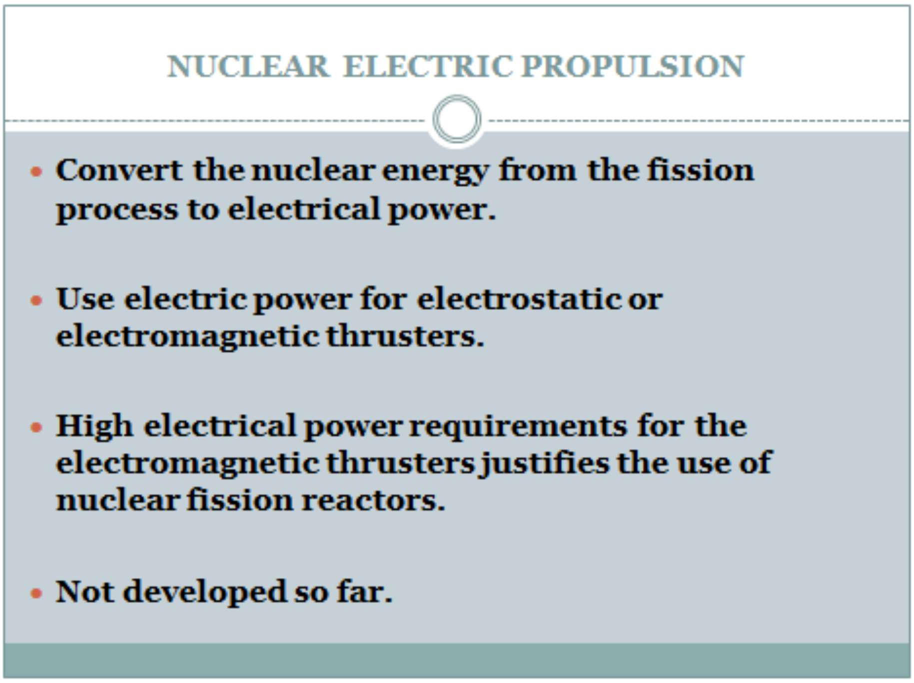
The fusion process involves isotopes having small mass like hydrogen, deuterium and tritium. Hydrogen has one proton, while its isotope deuterium has one proton and one neutron while the other isotope of hydrogen viz., tritium has one proton and two neutrons.



If the nucleus of deuterium and tritium can be fused together at very high pressure and temperatures, helium is formed and a neutron is released. The force binding the nucleus is released and the energy can be used to heat a low molecular gas for generating thrust. However, the requirements of very high pressures and temperatures make the fusion process difficult to apply for nuclear rockets. Only nuclear fission process has been applied so far for nuclear rockets. The thermal energy of the high velocity neutrons in the fission process is used for heating hydrogen gas and the heated hydrogen is expanded in a convergent divergent nozzle for generating thrust.

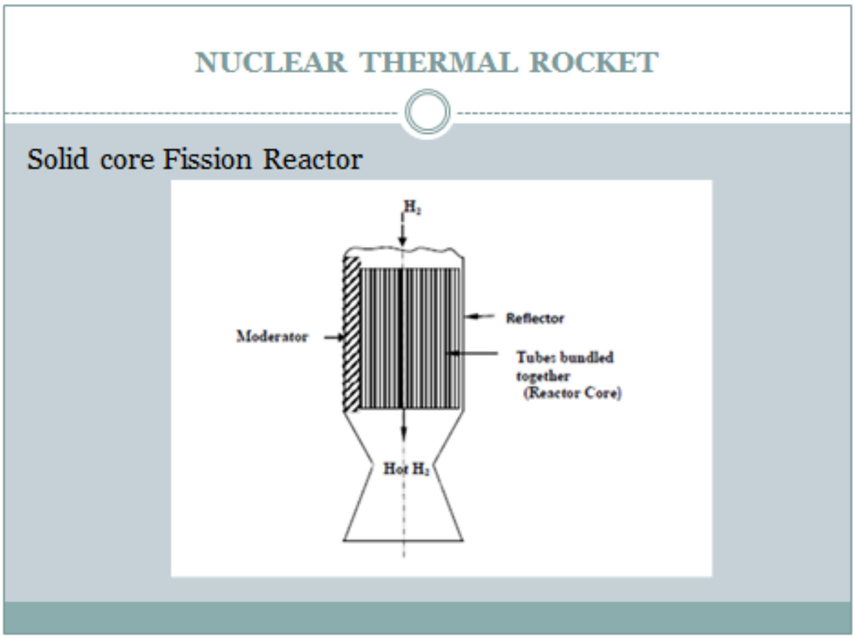


When the thermal energy of the fission process is directly used, as illustrated in this slide, we call it as nuclear thermal propulsion (NTR). It is also possible to convert the nuclear energy into electrical power and use the electrical power in electrostatic and electromagnetic rockets. The use of electrical power from nuclear reactions for propulsion is spoken of as nuclear electric propulsion (NEP).



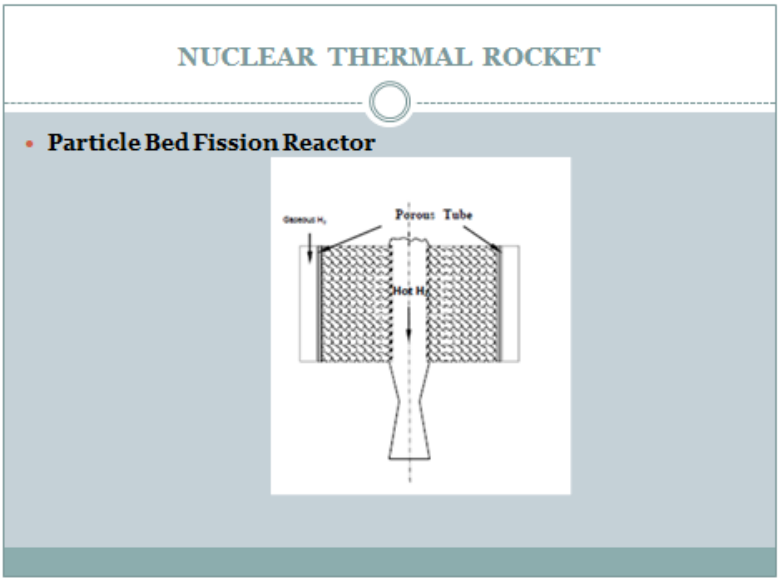
The demands of high power requirements in electro-magnetic propulsion makes Nuclear Electric Propulsion attractive and such propulsion systems have been studied. A typical example is the Vasimr rocket system; but these are yet to be demonstrated. Only the nuclear thermal rocket has been developed as Nuclear Energy for Rocket vehicle Applications (NERVA) in USA.

In the nuclear thermal rocket, a solid core fission reactor has been used. Here pellets of uranium are contained in tubes and a series of such tubes are bundled together to form a cluster. Several such clusters are assembled together to form a solid core.

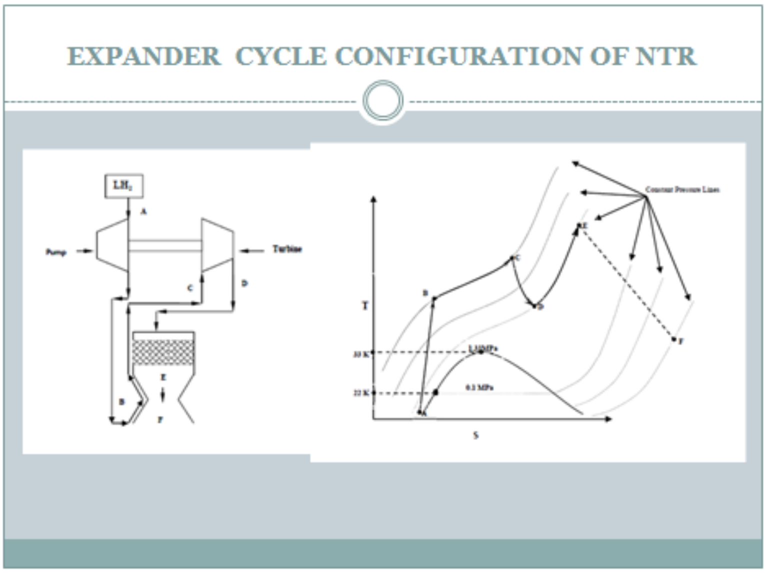


The fission of uranium is initiated by sending in neutrons from an auxiliary chamber. The core, as shown, is surrounded by moderators and reflectors to control the rate of generation of the neutrons. Hydrogen gas is admitted through holes in the reactor and it gets heated by impact with the neutrons. Since the residence time of hydrogen in the reactor is not significant, the efficiency of heating is not high.

A particle bed fission reactor has been proposed for heating of the hydrogen gas. This is shown in the following slide. Here the hydrogen is admitted radially and is in better contact with very significant increase in the residence time. However, since the hydrogen gas could take the path of least resistance, some local overheating and thermal instability could occur.

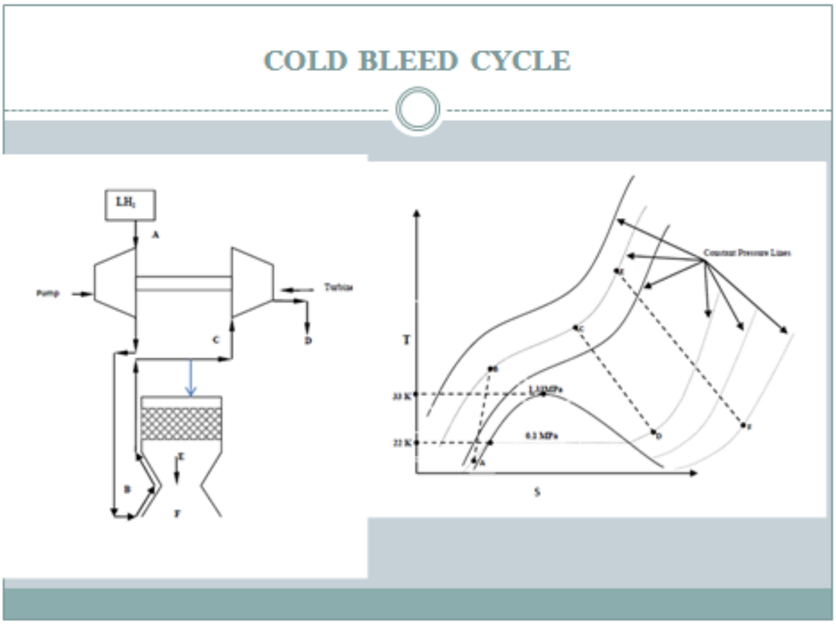


The hydrogen used in the nuclear rocket is stored as liquid hydrogen in tanks and since the thrust in these nuclear rockets would be large, a pump fed system is necessary. The feed system is similar to those used in liquid propellant rockets. The expander cycle of the feed system is used. The liquid hydrogen cools the hot reactor and the gasified hydrogen runs the turbine. The work from the turbine runs the pump. The processes are shown in the Temperature –Entropy diagram. AB shows the increase of pressure in the pump, BC is the heating of liquid hydrogen in the regenerative cooling passage, CD is expansion process in the turbine and DE is the heating of hydrogen gas in the reactor. EF is the expansion process in the nozzle.

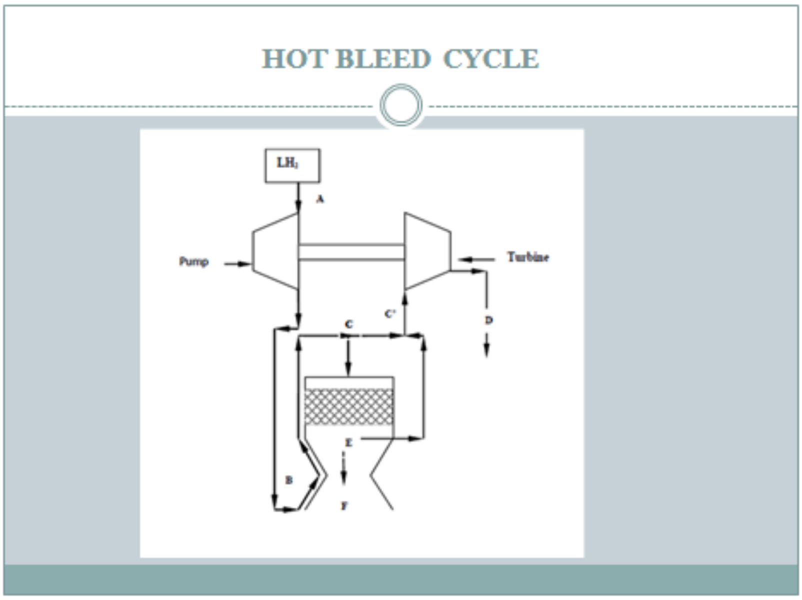


The jet velocity V_J is given by root of two into specific enthalpy drop from E to F.

The liquid hydrogen also cools the reflector materials in addition to the chamber.



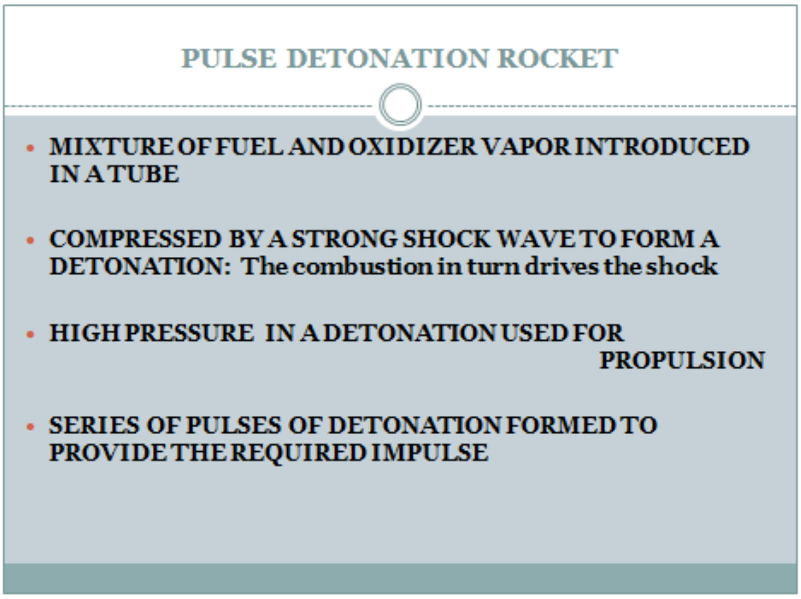
There are different versions of the feed cycle such as a cold bleed cycle in which the cold hydrogen is injected into the chamber and the exhaust from the turbine is let out through an auxiliary nozzle. It is similar to a gas generator cycle. It is also possible to have a hot bleed cycle in which the hot gases from the chamber are bled and mixed with cold hydrogen to drive the turbine.



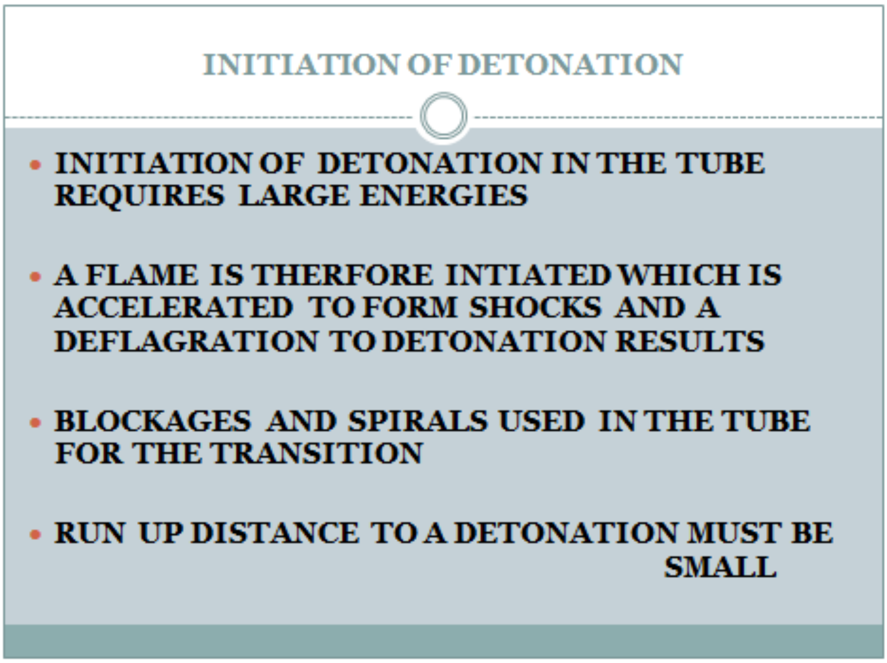
This is the way a nuclear reactor is used for rockets. As such the performance will be very high since hydrogen has a low molecular mass and it can be heated to extremely high temperatures in the reactor core. The development has been stalled because of safety issues; however, it has applications for interplanetary and missions to other galaxies.

The radiation is a major drawback in the use of nuclear rockets. Even the case of radioactive decay for generating power in spacecraft has been a cause of concern. If a spacecraft carrying a nuclear reactor crashes on Earth, as it happened with the reconnaissance satellite Cosmos-954 in 1978 over Canada, the concern of radiation affecting people is worrisome.

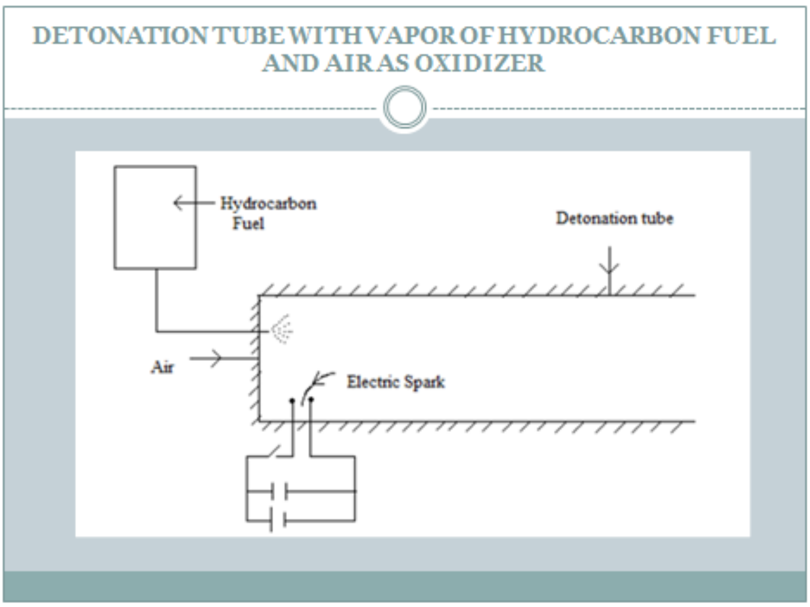
Nuclear energy in a pulsed form has also been suggested for propulsion. A set of directed nuclear explosions if impacted on a base plate attached to the spacecraft would generate an impulse and propel the spacecraft. Suitable mechanism must be evolved to absorb the shock loads of the explosion. These are essentially bombs exploded about the spacecraft. It is known as Pulsed Nuclear Propulsion or as bomb propulsion.



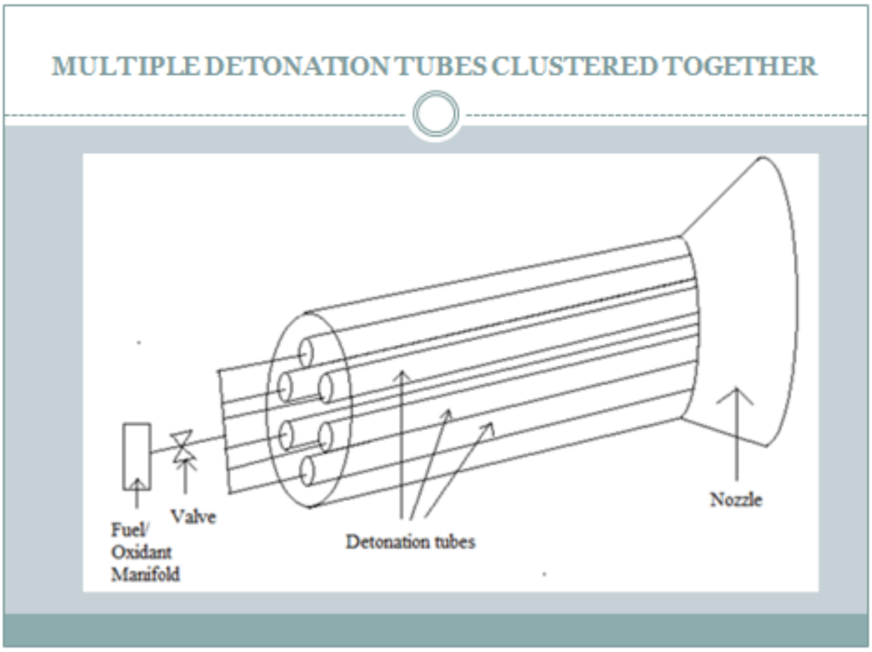
While dealing with propulsion with a series of pulses, it is relevant to consider the Pulsed Detonation Rocket (PDR). Here a series of pulses of detonation are used to generate thrust. A detonation consists of a shock wave which is driven by the chemical energy release behind it. The high pressure behind the detonation contributes to form the thrust. The construction of this pulse detonation is quite simple and consists of tubes bundled together. The tubes are known as detonation tubes. A mixture of the fuel and oxidizer vapor is introduced in the tubes through a feed system and the mixture is detonated. For detonating it, we need a strong shock wave to compress it and heat it to a high temperature and to generate such strong shock requires immense energies. Hence a detonation is not directly initiated but rather a flame is initiated in the mixture in the tube. The flame is accelerated in the tube using blockages and spirals placed along its walls. This results in the formation of shocks ahead of the flame and this shock wave initiates the detonation in the mixture.



A schematic of a detonation tube and is shown in the slide.

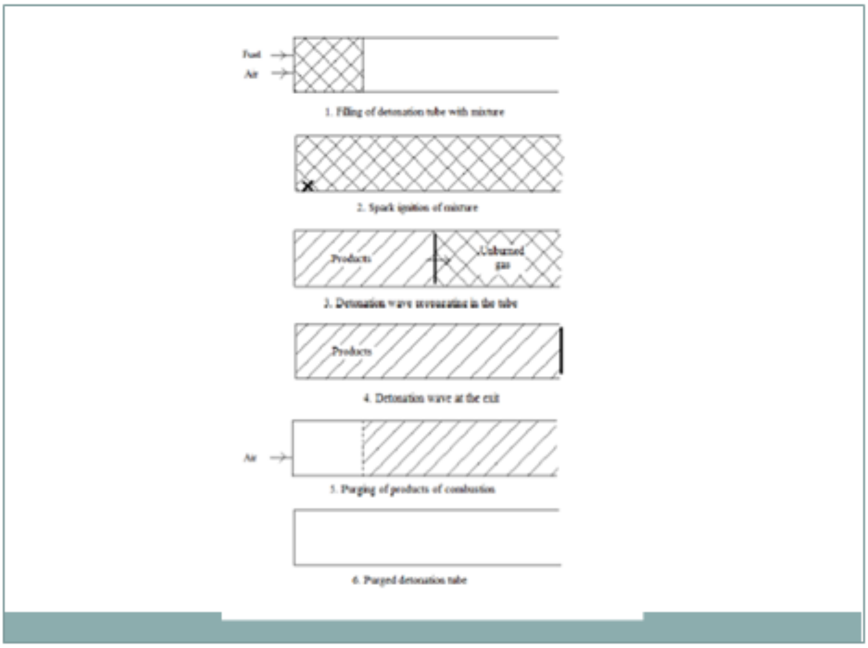


The detonation tubes used in practice are a few centimeters in diameter. The maximum frequency at which a single detonation tube can be fired is a few tens of cycles per second. This depends on the time required for filling the tube with the mixture, the travel of the flame and detonation in the tube and the time taken for purging the tube of the combustion products. If a number of the detonation tubes can be clustered together as

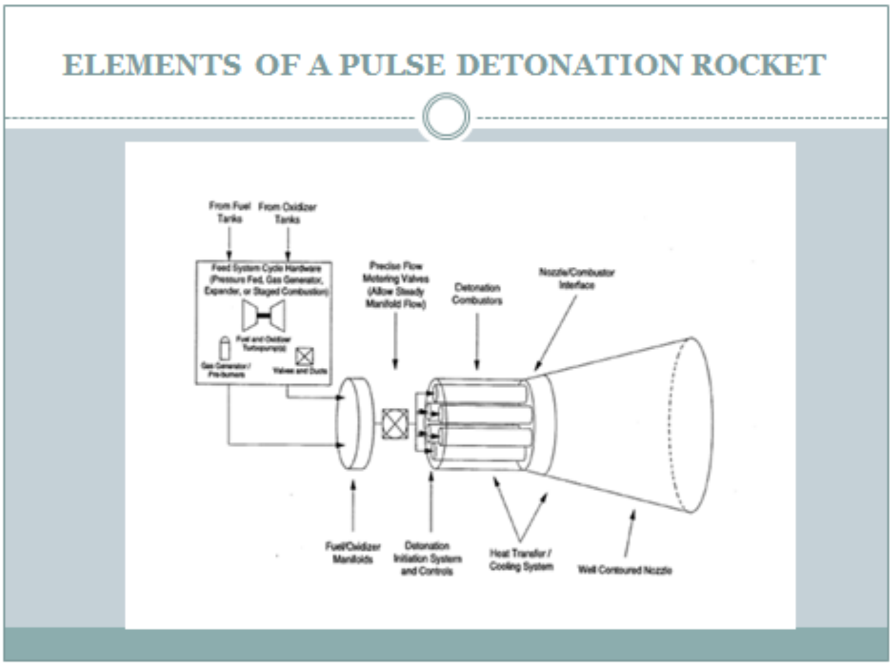


shown in the slide, the number of pulses of thrust generated per unit time can be significantly increased. This is done by operating the tubes successively one after the other. A common mixture preparation chamber feeds the different tubes. However, each of the tubes has its own ignition source. With a large number of detonation tubes, the thrust generated becomes almost continuous rather than being in discrete pulses. A divergent nozzle is provided to enhance the thrust.

The sequence of operation of a single detonation tube is shown in the slide. It consists of filling the tube with the mixture of fuel and oxidizer, spark ignition of the mixture, formation of a flame followed by a detonation, the detonation reaching the exit of the tube and purging of the tube.

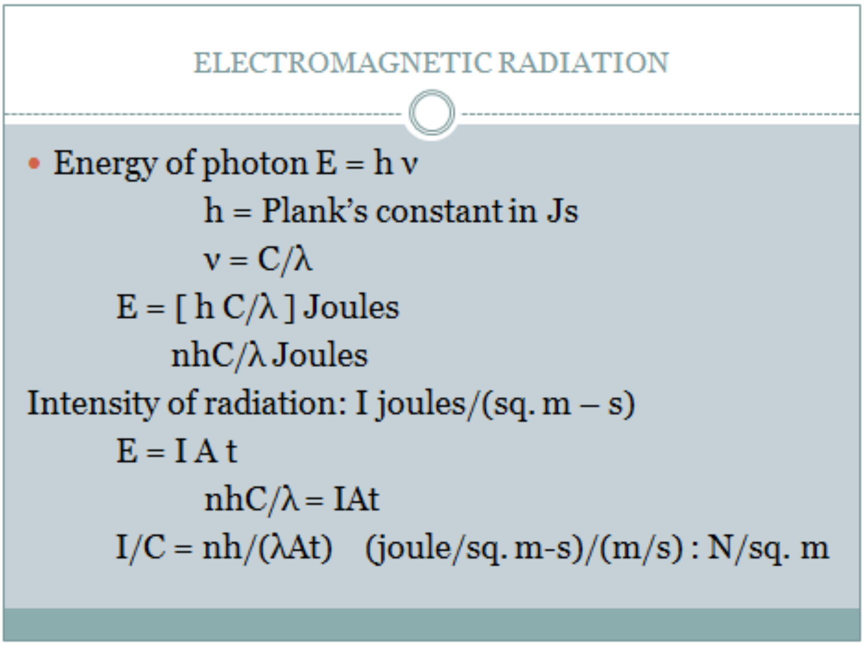


A high pressure fuel pump, as in the liquid propellant rockets is not required since the fuel oxidizer mixture is fed at the low pressures into the detonation tube.



The elements of the pulse detonation engine comprise of propellant tanks, inlet valves, detonation tubes with electric spark system and blockages in the tube for transition of the flame formed by the spark to a detonation. The construction is simple. However, the formation of detonation in the small diameter detonation tubes is difficult and a large value in the run up distance at which the detonation is formed leads to significant loss of thrust. The placement of blockages in the detonation tubes to ensure the formation of a detonation also leads pressure losses and decrease of thrust. The filling of the fuel and oxidant vapors over the length of the tube in a limited time to a mixture ratio well within the limits of detonability and its purging after the detonation is over calls for further developments.

Let us now proceed with other methods of generating thrust. When we talk of electromagnetic radiation or say radiation from the Sun, the energy associated with a photon is given by E joules equal to the plank's constant h into the frequency ν. But the frequency of radiation is the speed of the electromagnetic radiation which equals to the speed of light C divided by the wavelength λ of the radiation. The Plank's constant is 6.624×10^{-34} joule sec. For n photons the energy is nhC/λ joules. The intensity of radiation is given in units of joule per m^2 second and the energy in terms of intensity is I× Area A × time t. The pressure on a surface from an intensity I of radiation is I /C and this can be readily verified by the units joule/m^2 s divided by m/s which gives N/m^2.

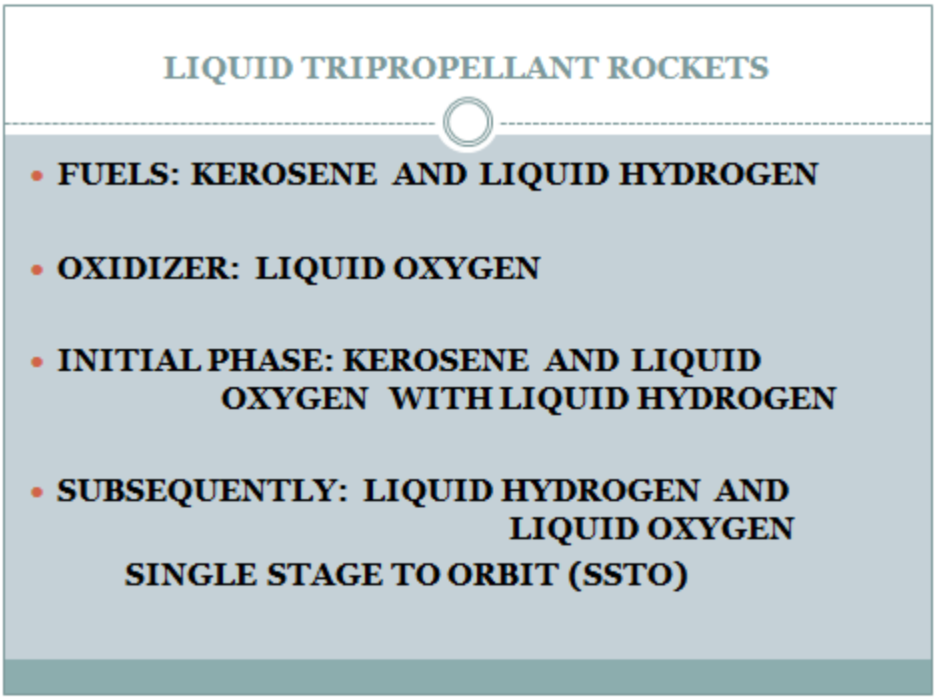


If the radiation is transmitted through the surface on which it falls, the pressure is I/C whereas if all the radiation is reflected, the pressure on the surface is 2 into I/C. The electromagnetic radiation incident over surfaces therefore creates pressure but considering the very small value of Plank’s constant and the small magnitude of quanta of radiation, the pressures are negligibly small. However, if we can unfurl a large surface area up in space of let us say the size of a football ground, we can obtain some force or thrust.

This method of obtaining thrust from electromagnetic radiation is often spoken of as Sail propulsion. The effect of the photons impinging on the surfaces and producing thrust is similar to the sail which is pushed by the wind.

When we talk of dark matter in space which is essentially at zero degree Kelvin, it is associated with zero point energy. There is no movement or wave motion and frequency is zero. However, this zero point energy is available for producing thrust as in electromagnetic radiation.

Well! There are various methods of generating thrust. We studied about mono propellant rockets, bi propellant rockets and we also mentioned about tri propellant rockets? In the tri propellant rocket we had three propellants; liquid hydrogen, kerosene and liquid oxygen. Initially I could inject kerosene and hydrogen along with liquid oxygen in the chamber. I could have both the fuels and the oxidizer burning. The hydrogen is fast burning and it stabilizes the combustion process. Once the rocket goes up we remove kerosene since we do not require the high thrust and use liquid hydrogen and liquid oxygen to give higher performance.



This tri-propellant rocket may reduce the number of stages required to orbit and we could as well have a single stage to orbit (SSTO). It was very much talked of about ten years ago but the interest in it seems to have waned. Perhaps better materials of construction could possibly result in a single stage to orbit vehicle.

We therefore see the subject of rocket propulsion to be endless with a myriad of possibilities and we must learn to dream a little about pushing in space. It was a pleasure to go through the different aspects of rocket propulsion in these classes and thank you for your time and interest.