Fundamentals of Aerospace Propulsion
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Lecture - 38

Let us discuss about chemical propellants and question arise what do you mean by propellant, propellant basically it will be consisting of fuel and oxidizer, but apart from that there will be some additives.

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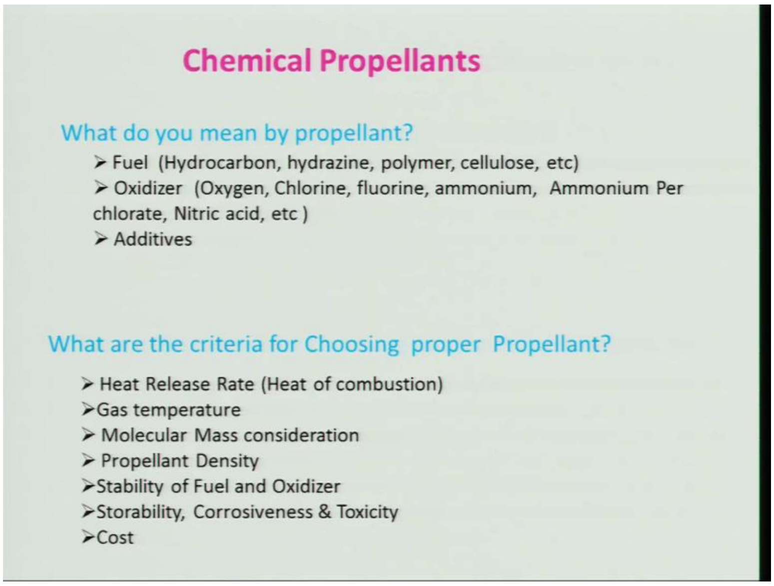

Now, why we need to add additives and other things as you go along will see, but if when you talk about fuel, fuel can be of course, it can be solid, it can be liquid, it can be gaseous as well we have seen. And similarly, oxidizer also can be both any phase as a matter of fact, we can use combination of that also, sometimes liquid and solid and gas.

Like, if you look at the fuels I have given some examples, but as you go along we will learn more about it, that is basically if we look at like hydro carbon, hydrazine and polymer and cellulose, cellulose we use, like in your food and other things, like can it be used as a fuel. And oxidizer like oxygen of course, like which is there in air, we use for combustion purposes in the I think, but it can be used in as a chemical propellant, chlorine, fluorine, ammonium, ammonium per chlorate nitric acid, several of them we can use as a oxidizer.

As, I told you earlier that oxidizer can be like act as a fuel, in some places see if we remember in the beginning I have told, whenever you use fluorine, any other things will be become a fuel, even oxidizer itself will be a fuel for the fluorine, and additives. But, before really getting into these all constituents and what are the additives and why will use additives, let us look at the properties of the propellant which will help us to chose.

If you look at we will be discussing about solid and liquid propellant, but keep in mind that each propellant will be having certain specific characteristics properties, which we would not be discussing now, but as you go along I will be telling sometime. But, what we will be looking at is the common properties, of course sometimes I will be specifying, for example a propellant must have a higher heat of combustion or to get the high heat release rate, because that is very important.

And you keep in mind that the amount of heat being released per unit volume, in case of rocket engine is much higher as compared to your burner, even gas burner engine. So, therefore, it is very important to have a high calorific value, such that you can have a higher heat release rate, and also it must have a higher gas temperature, because after it is getting burnt the chamber temperature must be much higher.

Why, because then we can have a higher characteristic velocity, we have already derived the relationship for characteristic velocity, which will be give you the specific impulse, higher specific impulse is a mandate, it is a requirement for a better performance of the rocket engine. And beside this molecular mass, basically the molecular mass or the molecular weight must be lower, we have seen in the expression of thrust co efficient, it comes as a inversely proportional to the molecular.

That means, if the molecular weight being lower than average molecular weight of the gas which will be expanding in the nozzle, then you will get a higher specific thrust, of course for the same time pressure and as a level. And the another very important thing, what is that we always have you know high lower specific gravity, and to reduce this what we call average molecular weight of the gas, generally hydrogen, oxygen is being preferred, and which will give the higher specific impulse.

And propellant density will be much be higher, so that it will be compact, it may be valid for your what we call liquid fuel and solid fuel, particularly for the solid fuel, because the storage space is very important. The density will be higher; that means, it will be compact in the same you know volume, like a mass will be higher, so that you can have kind of things, and your chamber volume of the liquid propellant will be reduced if you are using a higher density propellant.

So, therefore, it is very important, stability of the fuel and oxidized is very important, for example you have kept some propellant, and when you are firing it is becoming unstable, whether a solid or the liquid. For example, sometimes we are trying to add some aluminum particle to the kerosene what we use, but you that the particles what we are using basically to augment combustion characteristics of the fuel.

Now, if it is separated out, if it is not really settling down in the liquid, then naturally you will be in deep trouble, so, therefore the stability of the fuel and oxidizer is very important, like people keep this propellant for ages together, to ((Refer Time: 06:05)). They will be storing the solid propellant, and suppose by the time they fire, it is not fired it is unstable then it will be a problem, and beside this storability is very important, whether you could store or not properly, whether leakage is there, or whether it is a vapor pressure and other things one has to look at it.

So, corrosiveness and toxicity, suppose there is a leakage, there is a toxic or people are handling, people will be handling the liquid fuel and other things, particularly if it is toxic, then it is a big problem. And last but not least, is the cost because economy drives everything, so therefore cost is very important to reduce the running cost of the these things, and there is a cost stability there are several other properties which will be specific to the solid propellant kind of things and so, also the liquid propellant.

So, now, let us look at the solid propellant now, the solid propellant can be broadly divided 2 categories, one is double base propellant or what we call homogeneous propellant, and other is your composite propellant. But, however, in recent time you know there are another 2 kinds of ((Refer Time: 07:25)) like one is the composite modified double base propellant, and there is another one nitramine propellants. Nitramine propellants it will be basically nitramine waste, the RDX, this our RDX being used either terrorist group kind of things, they are very much familiar with that, do you know what it is.

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Solid Propellants

Types of Solid Propellant

- Double-base/Homogenous Propellants (NC & NG)
- Composite /Heterogeneous propellants
- Composite modified DB propellants
- Nitramine Propellants (RDX, HMX, etc)

Typical DB propellant

Material	%Wt	Purpose
Nitrocellulose (13.25%N)	51.4	Polymer (Fuel)
Nitroglycerine	42.93	Explosive Plasticizer(Oxidizer)
Diethyl phthalate	3.2	Nonexplosive Plasticizer(To improve mechanical properties)
Ethyl Centralite	1.0	Stabilizer: To counteract the autocatalytic decomposer of major constituents
Potassium Sulfate	1.2	Promotes smooth burning at low temperature
Carbon Black	0.2	Added to transparent propellant to prevent transmission of radiant energy which may cause internal ignition around internal voids or impurities.
Candelilla Wax	0.07	Act as a lubricant for extrusion process.

Anybody, because it is coming in newspaper, you must be knowing I guess, what is the full form of RDX is basically research development explosive and what is HMX, high melting explosive. That means, we are doing research to produce the explosive, so that you know other people, and the social elements can use for their winning a war against the people and creating havoc.

That means, we need to be very, very particular about that, not it is important to generate knowledge, but at the same time we should know how to use it properly, so if you look at I mean one can say that double base propellant which is homogeneous propellant also. That means, both the fuel like one example nitro cellulose, other is nitro glycerin, which can be combined together and used, it is like your pre mix flame, pre mix flame means fuel and oxidizer mixed together before combustion takes place, yes or no.

So, I can really make a one fuel, which will be containing the oxidizer, and which will be containing the fuel together and you will get. Therefore, we call it homogeneous propellant, composite is the heterogeneous propellant, which will be having their own identity. Own identity in the sense each suppose there is a fuel and there is a oxidizer, I am talking about solid propellant, they will be having together, it is like your motor, motor you know.

Motor like you use for your concrete making, there will be granules, there will be cement, there will be sand, all together it is having own identity, there is having a surface their own identity, but if I mix together and cast it, it is like a one you cannot identify physically, that is homogeneous propellant. And composite modified double base propellant, and I have already told you RDX and HMX, which are examples of nitramine.

So, typical double base propellant will be like this, one is nitrocellulose which will be containing 13.25 percentage of nitrogen, and 51.4 percent of weight, and is basically a polymer. Polymer is a fuel, we use a lot of polymer in even in the shirt, we will be having some polyurethane everything and other things, plastic. So, and nitro glycerin which is basically a liquid, and it is explosive plasticizer and which is a oxidizer the percentage wise is 42.93.

There are several additives, if we look at 1, 2, 3, 4, 5, 5 additives are being added, but if we look at their percentage are very, very small as compared to the fuel, and as compared to the nitro glycerin which is oxidizer. So, diethyl phthalate is 3.2 percent and which is used as a non explosive plasticizer to mechanic to improve the mechanical properties.

Why we need to mechanical properties, because it will be subjected to a lot of stress high pressure, because in the propellant will be subjected to a very high pressure. And if we look at the ethyl centralite, which is again stabilizer to counteract the autocatalytic effect decomposition of major constituents, there might be some you know because of high temperature it will be some constituently auto catalytic.

So, therefore, you need to avoid it, otherwise it will be explosive you cannot control, so potassium sulphate which is 1.2 percent, it means to promote the smooth burning at the low temperature like atom, low temperature then the propellant may not be burnt, that is a big problem. So, therefore, you need to have a smooth burning, and carbon black which is being used is basically 0.2 percent that is to added to the to make the transparent propellant.

For preventing the transmission of radiation energy, which may cause internal ignition around the internal voids or the impurities; that means, if look at if it will be difficult to really look at it, what it will be. I think you people are may not be getting, I will tell you, so this is basically a double base propellant, it is contains the nitro cellulose and nitro glycerin. If we look at this is having a hole here, this is a surface and this kind of burning is known as what you call side burning grade, this is green basically which will be discussing later on.

So, therefore, and this is contains all the constituent whatever one can think of fuel oxidizer and additive together, this is a propellant and generally this is a double base propellant. And if you look at candelilla wax which is use you know in a very low percentage act as a lubricant for extrusion process, because what I have showed you it actually one has to be extruded.

Various steps you want to have, as you go along you will see it is a cylindrical one, there might be a star step there might be several other steps we will get, so what I was telling that this is basically about the solid propellant kind of things.

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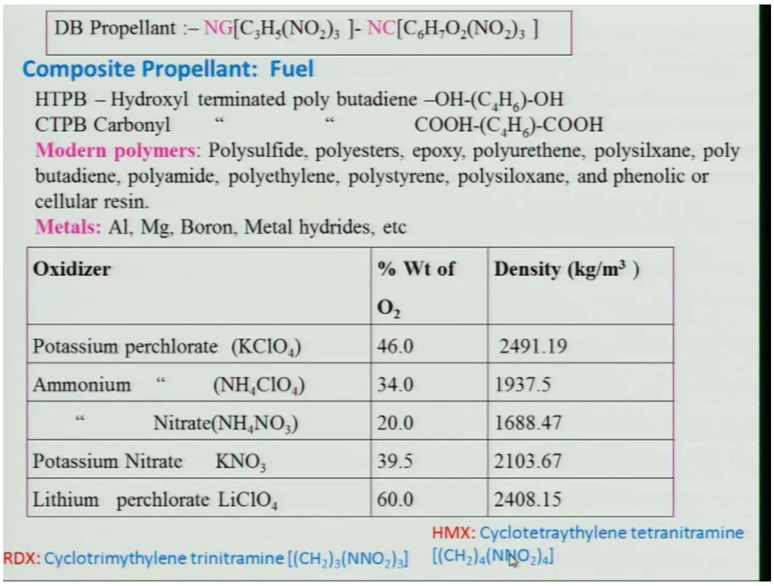

And, the double base propellant if you look at the chemical formula is basically C 3 H 5 N O 2 in the bracket 3 that is nitro glycerin, which is basically a liquid, but when you together it becomes solidified whenever it will come to the nitro cellulose, that is C 6 H 7 O 2 N O 2 bracket. So, there is a composite propellant is basically it can be fuel, it can be oxidizer, it is a heterogeneous in nature, it is a one what is being used is HTPB, which is being used by our in India like hydroxyl terminated poly butadiene.

And CTPB which is similar in nature is basically a polymer kind of thing, carbonyl terminated poly butadiene, and there are modern polymer, there are several other things polysulphide polyesters. Polyesters we use for our cloth and other places, epoxy polyurethane, poly silxane, and poly butadiene, I already told you, basically HTPB, CTPB which is being used.

And polystyrene, poly siloxane, and phenolic cellular resin, several and varieties of them, this is also sometimes known as the binder, it will bind the oxidizer molecule. So, therefore, it is together, and it can be and there are several metals which are being used, but those will be in some very, very less to augment the what you call the burning grade, like aluminum, magnesium, boron, metal hydrides, several other amities can be there.

I will just show you like oxidizers, which are common oxidizer, there might be n number of oxidizer solid propellant, one is potassium per chlorate, and ammonium per chlorate, which is being popularly used. If you look at oxygen percentage generally for potassium per chlorate 46 percent, and it is a quite high density 2491.19 k g per metric cube, ammonium per chlorate and 34 percent, of course it is being used and this density is 1937.

But, beside this like ammonium nitrate, potassium nitrate, lithium per chlorate is being used, but temperature if we look at highest is basically potassium per chlorate, next is lithium per chlorate which is not being very much used, but the ammonium per chlorate is being used very much, it has to be used for explosive purposes. So, as I told you RDX is also is being used is a combined is a cyclotrimythylene tri nitramine, and the HMX is basically is cyclotetramethylene tetra nitramine, and the formula is similar instead of here it is C H 2 bracket 3 H N O 2 bracket the bracket is a 3, but here it is the 4.

So, let us start this lecture 38 with a thought process from Albert Einstein, which states that great spirits have always encountered violent opposition from the mediocre minds. So, very propound statement let we not dwell up on it, and let us recall what we have learnt in the last lecture, we are basically learnt about the how to take care of performance parameter.

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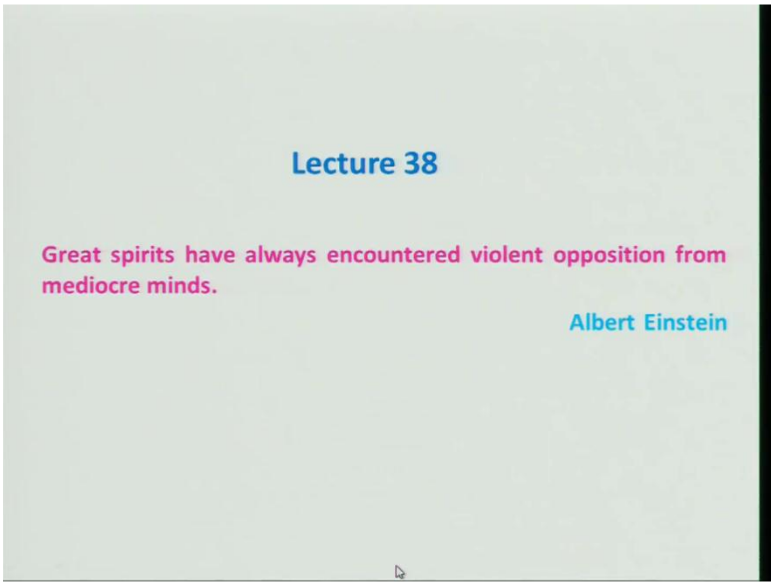

Like your how to call, characteristic velocity and we have derived relationships for that, and then we moved into how to relate this thrust co efficient with the characteristic velocity, and find out the ISP specific impulse. And then of course, we can get thrust from the thrust co efficient and the pressure, chamber pressure and you know knowing the throat area we can get the thrust relationship.

Beside this we also looked at 2 other parameter, one is combustion efficiency, which is basically ratio of characteristic velocity actual divided by characteristic velocity ideally. Ideal you can get from the basically the relation whatever we have derived, but actual you can measure the temperature, and then other parameters, and then you can do that. And beside this effectiveness of the thrust co efficient we have also looked, at it and after that we moved into the propellants. In propellant we looked at propellant general characteristics, then we looked at solid propellant, what we will be doing now is basically looking at the liquid propellants.

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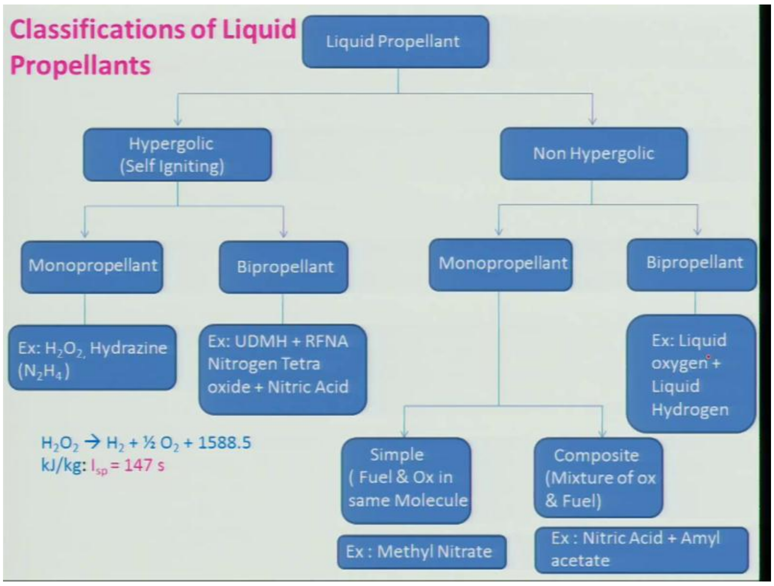

Liquid propellants basically can be classified into 2 categories, one is hypergolic propellant, hypergolic propellant means self igniting; that means, you need not to give any ignition energy for initiating the combustion. Do not you think it will be very you know hazardous to do that, because if I will have to one is fuel and oxidizer or then it will just go, then it will be start react.

There is a very dangerous thing to handle, but that is also being used, and non hypergolic propellant, where you need to provide the ignition energy, requisite amount of ignition energy. So, therefore, it can be broadly divided into hypergolic and non hypergolic, and hypergolic propellant both the hypergolic and the non hypergolic can be divided into 2, basically one can monopropellant, and bipropellant.

Of course, there is tri propellant as well, but I am not discussing about it, so the monopropellant in case of hypergolic. I have taken 2 examples monopropellant means it is the single propellant, where both single propellant, liquid propellant, where both the fuel and oxidizer will be together, it is a very example is hydrogen peroxide. Now, if how it will react, if it is reacting then it is difficult to handle, but what is that it can react at a high temperature, that is one thing.

And other thing is that it will react, when it even in the you know ambient temperature, it can react whenever it will come in contact with the what you call catalyst. So, therefore, the catalyst being used for example, platinum, and then magnesium and some other things, platinum is being preferred although it is very costly. If you react with that in presence of that, S 2 O 2 will be the combust into hydrogen and oxygen, and it will be giving certain amount of heat, but this amount of heat what is being released during this reaction is very, very low.

Generally, it will give around ISP of 147, now question arises where you will use, this use monopropellant, because reliability is more, so therefore it is being used for the small you know thrust label applications are the smaller. Particularly altitude control or you are having a satellite, and it will you will have to put into another you know orbit corrections and other things, then you will be using. And hydrogen is also being used and as a mono propellant, whenever it will be coming in contact with the iridium, catalyst, of course those catalyst are been placed on the surface of the alumina particles are in a conduits and other things, generally particles are being used as a surface area.

So, then it will be decomposed into ammonia, and then hydrogen, and then you know other things, and I will be discussing about that, so those things will release heat, and you will get the also ISP. So, beside this if you look at the bipropellant, under this hypergolic condition UDMH, unsymmetrical dim ethyl hydrazine, RFNA that is basically rate fuming nitric acid. When, they come together and it will be liquid phase, and when they will come together, they will start reacting at a liquid phase, then of course, it will be vaporized, and then heat will be released, and then you will get the unit gas specific reactions.

So, similarly nitrogen tetra oxide and what you call and nitric acid, when they will come in contact they will also start igniting itself, so therefore hypergolic propellants can be there be several other varieties, but I have taken 2 of examples. And these are being used routinely in case of your rocket agents, the monopropellant if you look at it can be have you know again divided into 2 categories.

Whenever, we are discussing about none hypergolic propellant, one is simple where fuel and oxidizer in the same molecule, for example methyl nitrate. Methyl nitrate it is a very, very explosive, what will be the it is detonation velocity, it will be something 8000 meter per second, it is quite high value. If we look at methyl nitrate, it is a very easy to make, of course it is simple, but it is very dangerous, if you take nitric acid and alcohol, methyl alcohol.

And then you put together and then you will get that, but again you will have to do some water will be coming into pictures, and then you will have to condensate it and then get that, but it is a quite dangerous, and which is being use, and one has to be careful about this methyl nitrate. And composite it; that means, mixture of oxidizer and fuel, because if we look at these all fuel and oxidizer in the methyl nitrate in the molecule itself, but here you are making a mixture of nitric acid and amyl acetate.

And then you will have to give energy, like some kind of ignition energy, because it is basically non hypergolic, and beside this the bi propellant there are several varieties. I have taken example as a liquid oxygen, liquid hydrogen, which is being used here, and liquid hydro carbons and then UDMH even you can use, unsymmetrical di metallization MMH mono methyl hydrazine, and other things you can use.

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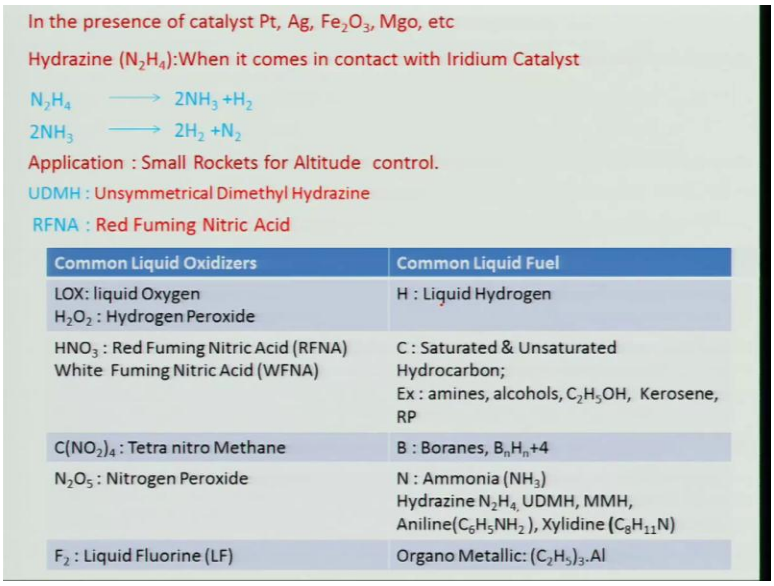

Common Liquid Oxidizers	Common Liquid Fuel
LOX: liquid Oxygen H_2O_2 : Hydrogen Peroxide	H : Liquid Hydrogen
HNO_3 : Red Fuming Nitric Acid (RFNA) White Fuming Nitric Acid (WFNA)	C : Saturated & Unsaturated Hydrocarbon; Ex : amines, alcohols, C_2H_5OH, Kerosene, RP
$C(NO_2)_4$: Tetra nitro Methane	B : Boranes, B_nH_n+4
N_2O_5 : Nitrogen Peroxide	N : Ammonia (NH_3) Hydrazine N_2H_4, UDMH, MMH, Aniline($C_6H_5NH_2$), Xylidine ($C_8H_{11}N$)
F_2 : Liquid Fluorine (LF)	Organo Metallic: $(C_2H_5)_3$.Al

So, as I told you that in the presence of catalyst like a platinum, A g and F e 2 O 3, that is ferric oxide, magnesium oxide several others, one can really decompose this, not you know hydrogen peroxide and also hydrogen. But, hydrogen generally it is being, whenever it will come in contact with iridium catalyst, and then nitrogen, hydrogen, tetra hydride will be converted in to 2 N H 3 plus H 2.

And N H 3 will be again converted into 2 H 2 plus N and keep in mind whenever you are using catalyst, there are several other poisoning of catalyst, and then there will be also a gas will be heat will be releasing the force. Pressure will be release there are several complexities, which I am not getting into it and those thing has to be looked at, and it is as I told you mostly used for small rocket for altitude and attitude control.

And as I told you that UDMH and RFNA is being used for your the liquid fuel kind of things, and the common liquid, I have just taken some example like liquid oxygen, which is being used for a cryogenic engine, along with the liquid hydrogen. And one can use also hydrogen oxide as a another liquid, and of course some other kind of fuel one can use, and H N O 3, that is rate fuming nitric oxide and white fuming nitric oxide WFNO both are being used as oxidizer, along with several fuel like saturated unsaturated hydrocarbon.

Some of the examples, kerosene, that is your research propellant, and then amines, alcohols several other one can think of, and beside this tetra nitro methane which is being used for the oxidizer. And it can be with the borates, several varieties one can think of, like your hydrocarbon C N H 2 N plus 2 are some other things it can be like that, several of them.

Like nitrogen peroxide which can be oxidizer liquid fluorine as a oxidizer, and if you look at these ammonia and hydrogen UDMH unsymmetrical di methyl hydrogen MMH, aniline which is being and xylidine is being also used as a liquid fuel several of them. But, we in India basically people are using UDMH and hydrogen thing, and now it is of course, people are trying to get this liquid hydrogen, liquid oxygen kind of thing, and organo metallic which is a very good one which is coming out.

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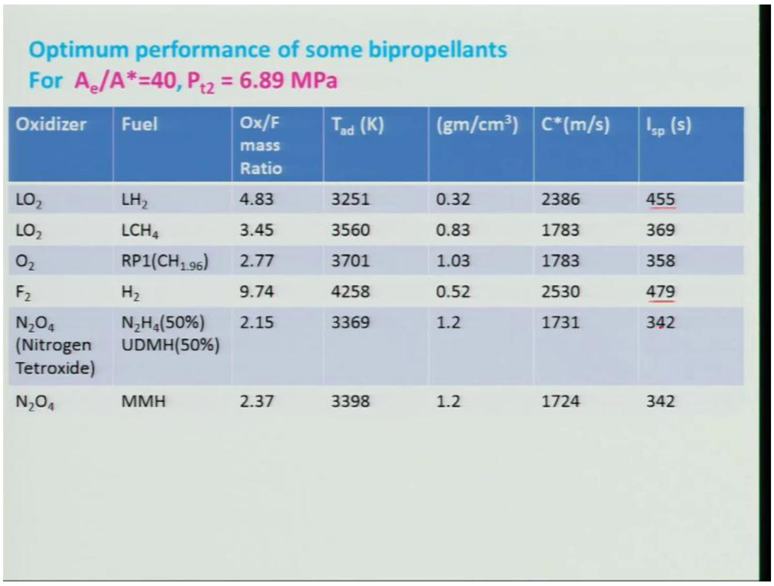

Optimum performance of some bipropellants

For $A_e/A^*=40$, P_{t2} = 6.89 MPa

Oxidizer	Fuel	Ox/F mass Ratio	T_{ad} (K)	(gm/cm^3)	C*(m/s)	I_{sp} (s)
LO_2	LH_2	4.83	3251	0.32	2386	455
LO_2	LCH_4	3.45	3560	0.83	1783	369
O_2	RP1($CH_{1.96}$)	2.77	3701	1.03	1783	358
F_2	H_2	9.74	4258	0.52	2530	479
N_2O_4 (Nitrogen Tetroxide)	N_2H_4(50%) UDMH(50%)	2.15	3369	1.2	1731	342
N_2O_4	MMH	2.37	3398	1.2	1724	342

So, let us look at a optimum performance of some of the bi propellants, just to give a flavor that is liquid oxygen and liquid hydrogen if I take, and oxidizer by mass ratio and adiabatic temperature I will get 3251 Kelvin. Of course, actual temperature will be little lower, and you will get that c star that is a characteristic velocity 2386, and ISP you will get the highest that is 455.

Of course, this is the ideal one, actual one will be little lower than that, see if you look at whatever number I have put it, is all ideal done from the calculations. So, liquid oxygen and liquid methane you can have little much lower characteristic, therefore ISP is lower and if you look at fluorine and hydrogen, this is highest, but it is never been or it is really been used, because of fluorine it is difficult to handle.

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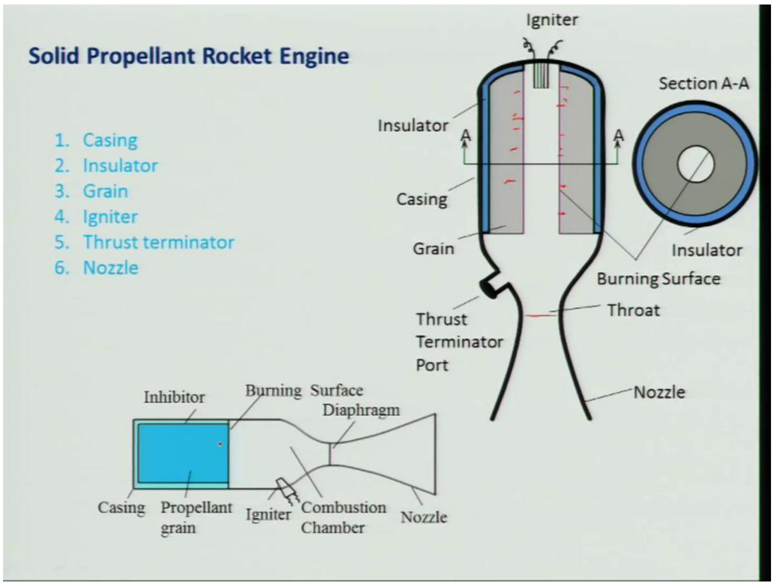

So, other things like nitrogen tetra oxide UDMH and N 2 H 4, the hydrogen 50 percent, this is being used in India for 342 kind of things and then other things, so having talked about this propellant, now we will have to look at the solid propellant rocket engines. If you look at what are the parts one can think of, like we know there will be casing, there will be grain I have told you.

And you need to have insulator, we can have igniter, and of course, you know like once it is fired rocket engine, it has to be terminated if it is there; that means, we should have way of means of terminating, thrust terminator and nozzle. So, these are the constituents, so if I look at diagram, if we look at this is basically your casing, and this is we call grain, grain is basically consist of propellant, I have showed you a grain, where it is having certain structures.

And insulator is given, because heat should not go away, and also it should not get burnt in the in the towards the end, that is also, and this is having a nozzle which is, and this is a thrust terminator and igniters, so that is to initiate the combustion fire. And this is a basically a end burning rate, keep in mind when you start, unless you develop the pressure you cannot really have a thrust, you cannot really burnt it.

For the example like we must have a diaphragm from here, I will be showing the diagram, where will see that there is a diaphragm from here, and when I ignite it as such that it will be burnt some heat will be released, and then it would not allow the gas to go through the nozzle to start with. So, the pressure will build up, and then you will have a higher burning rate that we will see little later on, but I am just telling beforehand that how it is ignited, and this is a end burning grain, and if you look at the side burning.

The burning will be taking place in this zone, over here this is known as side burning grain, and I will be discussing about this is a end burning, it is like a cigarette burning. Like the way you people use cigarette like it will be burning one way, like if it is cigarette the burning is taking place, this is basically end burning grain So, it is having the similar components like casing, insulator, grain, igniter, thrust terminator and nozzle, now when we talk about that, what really is happening what are the processes involved in the solid propellant.

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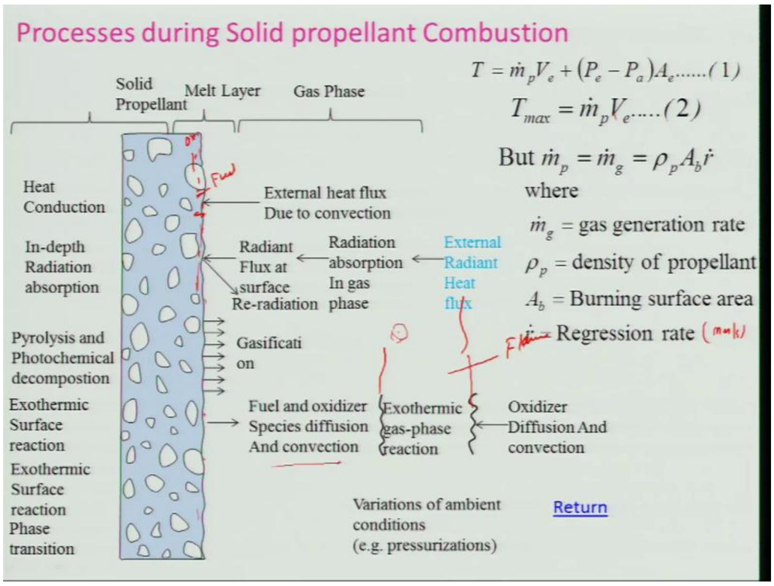

As, I have told you that it is basically when you are igniting, you are giving certain amount of ignition energy, what it will be doing, it will be transfer to the solid surface, because it is very difficult for a solid surface. How we ignite in a wood, how do we do, of course most you might not be knowing, how to ignite a wood, wood is a solid fuel, because all of you are using LPG gas, just you go and you know click button and you will get a flame.

But, to burn a wood is very difficult you will have to need a another flame, with a some kind of a paper or a some other kind of a flame, candle or a wake flame and then help, because initial times it take time. Similarly, in this case will be using a igniter, which will give you some crust and some particulate will be there also, so if you look at what really is happening, suppose I am igniting some here. That means, some gases will be here, it will be going, and then it will be igniting here, locally some particulate will go hot particulate will go and impasses into that person, that is one local ignition will be taking place.

And let us say that what will happen after that flame is established, let us say there is a flame, if you look at this is basically a flame, if flame is established then what is happening, the heat is going. Like if it is a heat can go by the radiation, and this radiation there might be some surface, flame need not to be near to the what you call this propellant, and when the heat will come then there will be some melting may happen, some liquid may be formed.

You might have seen when you are putting the wood into the fire, you will see the water is bubbling out, because water is there, in similarly in this propellant water would not be there, but there will be some constituent will be first converted into the liquid. And then it is not that all the propellant will be there some this characteristic, but some of them. So, then heat can be converted due to convection, it can come to the solid surface by conduction, and it can come by the radiation, when it comes then what will happen it will be trying to melt and sometimes it will be pyrolysis is occurring, what is this pyrolysis.

Pyrolysis will be a process where the thermal degradation of the fuel will be taking place without really coming in contact with the oxidizer, or in the absence of oxidizer or in the very, very lower quantity of oxidizer. So, that is thermal degradation will be taking place, and this will give to the gasification also, gasification is a next phase where it will be converted solid into the gas.

That may be liquid which will be converted into again gas, and then when will go the fuel and oxidizer will be diffusing towards the flame, and the flame will be coming over here. So, if you look at this a very, very complex process; that means, if you look at let us say this is your oxidizer, this is your fuel; that means, the fuel portion and the granular portion is oxidizer, because generally in a if we look at composite propellant the binder is basically a fuel.

Binder means this is which will be mixing together, like your cement in a motor it is a binder, so similarly exothermic reaction, if you look at it is a quite complex process. We need to know now how these surface is residing; that means, this surface will be residing it will be going towards that as the time progresses, it is getting consumed this solid fuel will be converted into the liquid, and sometimes and directly to the vapor.

And the vapor will be there, and it will participate in the combustion, and the flame will occur, and once this flame is formed this flame will support the all combustion process make itself sustained. But, we need to understand like how much propellant is being burnt, because we need to look at the thrust, because thrust expression m dot p V e and of course, this portion is there.

If I say that this is fully expanded nozzle, I will get a thrust is M dot P into V e, and I need to know what is this m dot P; that means, mass of the propellant which is passing or going through, which is being generated due to the burning of the solid propellant. So, if you look at that is of course, for the time being we are saying that this propellant solid propellant is converted into gas; that means, whatever the solid is been converted into gas that is the mass fluorite of gas.

And which is nothing but, rho p, rho p is the density of the propellant A b is the surface area, if I take surface area is perpendicular to this plane, then I will get a whole surface area. And r dot is the regression rate; that means, the amount of the propellant is regressive reduced, and keep in mind that this will be mm per second or you can say centimeter per second, generally it is a very, very low rate at which it is being receded the surface. So, therefore, we call it as a, we use it mm per second, keep in mind it will be always perpendicular to the surface of the propellant.

So, having done that question arises how will determine, because if you look at the processes what is happening we have seen it is quite complex, and one can say look I will model it. Yes, people have attempted to model, but it is not that easy, till today also people are struggling to get a model it, model prediction to be as good as experiment, but till it is not that in a position to give good result.

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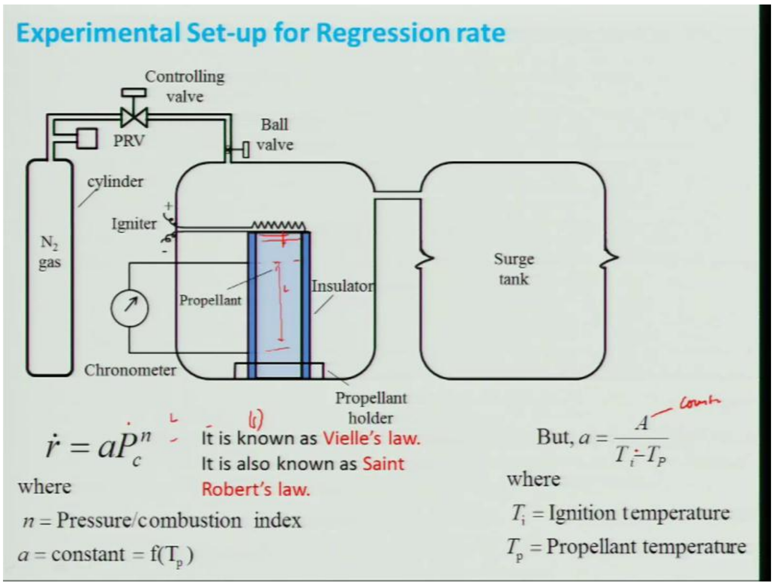

But however, experiment is being conducted, keep in mind that in experiment being conducted under a steady state, there is no flow conditions in actual situations flow will be there and several complex. Here, it is a steady state, you use a burner which is a propellant here and having insulation, it is having a propellant holder and it is in a chamber, and I can use this pressurize this chamber, with the help of nitrogen, of course controlling valve and ball valve.

First fill this chamber after installing this propellant in the prevalent holder, I can pressurize it, and then I can ignite it, when it is ignited this mass burning rate, rate will be going out with the propellant will be receding in this direction. It is one dimensional almost one can assume, then there will be increase in pressure, now I need to keep the pressure constant, so there will be a search tank which will keep the pressure constant.

Whatever being consumed, whatever being produce the gas, because the solid and it will be converted into gas; that means, chamber temperature will increase, so that will be taken care, so that you can keep constant pressure. And you will be finding out what is the time it take from here to travel the distance this front of the propellant surface, and how much time it will take.

It will take the length if I know, this length, and if I know the time, I can get what is this burning rate that will be mm per second. So, by this way we can estimate, we can determine the regression rate of the burner, if you look at this is basically r dot it goes by a p c n, you can say that this is basically empirical relation. There might be some several other of them, but generally it is a well known and it is being used, but; however, literature is having also other relationship, we will be using this relationship in this course, and it is known as Vielle's law, and also it is known as Saint Robert's law.

Keep in mind that A is a constant is not a constant, but you can get that as a combustion constant kind of thing, and which is a function of propellant temperature, because temperature propellant will be having certain temperatures. And ace is basically the combustion index, because it is dependent on the pressure, like if we look at what we are learning from here, the degradation rate will be dependent on the chamber pressure.

That is and it is power to the end, end can be any value that we need to obtain from the experiments, chronometer will tell you how much distance it travelled, and what is the time you can measure. Of course, there is a several other things have come up, you can take a photograph you can have a ware, and you can find out how much time it is taken for travelling certain distance, that will be basically it is a chrono, chrono means time wise kind of thing will come.

So, if you look at a constant is basically A, this is a constant, t i is the self ignition temperature of the propellant, and t p is the propellant temperature, and t p will be changing depending upon the environment, depending upon the other things, whatever it is. But, whereas, self ignition temperature will be dependent on the type of propellant being used it is remain same, so basically if you look at a is not really a constant, because t p will be varying will see that how it is varying, how it is effecting the degradation rate.

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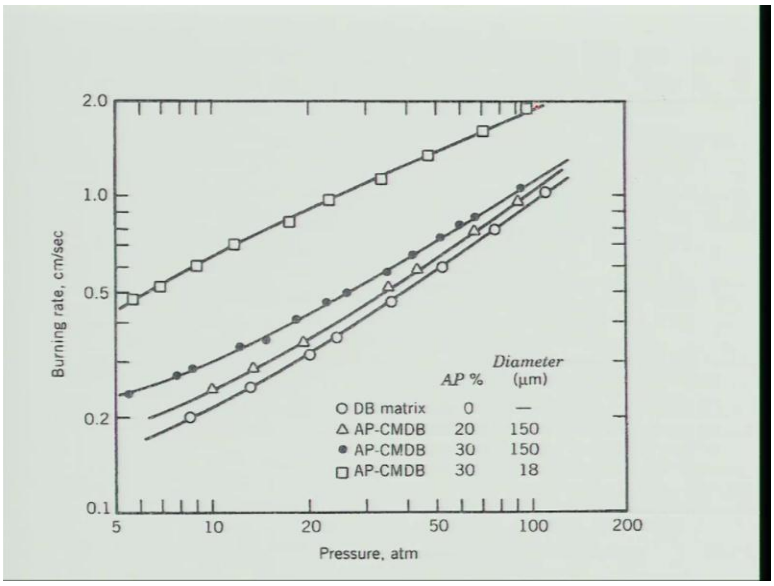

So, let us look a typical data burning rate in centimeter per second versus the pressure keep in mind that pressure is plotted in the logarithm scale, and burning rate also being plotted in the logarithm scale, that you should keep in mind. If you look these double base propellant, this is what you call nitro cellular then nitro glycerin being generally used, and it is goes on increasing with pressure, but; however, it is a very low value as compared to APCMD. That is combined modified double base propellant, composite modified double base propellant, if you look at that is twenty percent and hundred fifty microns, and the other one is your same thing, but it is having 30 percent AP and 150 microns. So, you get a higher you can think why not increase it further, but if we increase then the structural acidity, because ammonium per chlorate is a crystals, size will be dependent on that. Therefore, is a limitation, but you can increase further to some extent, not to a larger extent, and very interesting thing you will see this is 150 microns the average size diameter of the AP particles. But, if I reduce to 18 you get a very higher burning rate which is having similar BIBM so far pressure is concerned; that means, if I go on reducing; that means, it also depends on the particle size, people are now talking about nano particles, because nano technology, nano science is coming up. So, people are doing research and they will get a higher burning rate, and always it is important to enhance the regression rate, at the same time keeping this pressure index as the smaller one why it is we will see in a moment, may be this thing.

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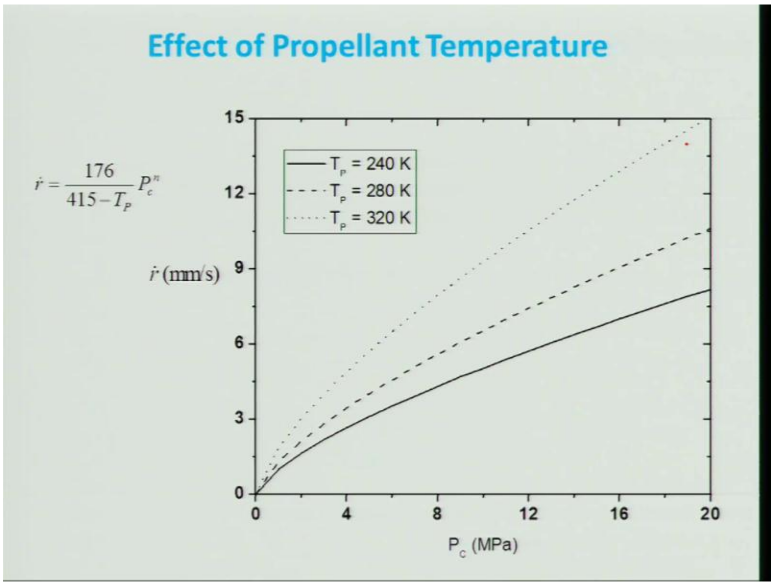

So, if I will vary this t p and keeping this A as a constant, and t i self ignition temperature particular propellant, if I plot this r dot n p c you can see that, when t p is 240, you will see that this is burning rate it is increasing, but it is having a low value as compared to the t p of 280 and 320 is having higher value. That means, it is indicating that propellant temperature also plays an important role in enhancing the regression rate for a particular chamber pressure, so if you look it is a function of various parameter. And keep in mind that this relationship is semi empherical means one has to be very careful about the units used in the particular expression, it is not a generalized one you must keep in that mind. So, therefore, one has to be very careful while using it is unit, and you should use the same unit whatever it is given, that you will have to be very careful, and it will be good to have a predicting this regression rate. Of course, lot of work is going on, but still it is in a or a what you call not in a mature state, I cannot say immature not in a mature state.

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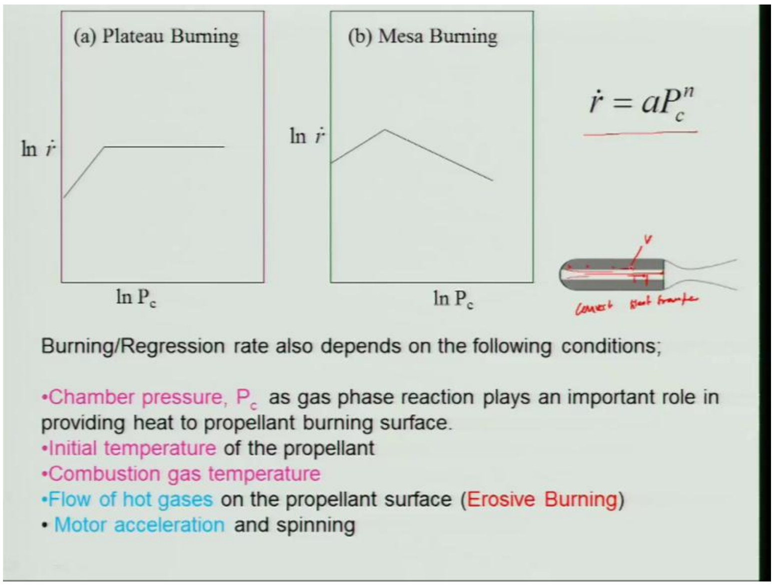

So, now, if we look at we talked about this r dot a p c n, and now question is regression rate is a function of chamber pressure, now there might be several ways we have seen that ways one can think of. One is I am plotting here ln r with the ln p c will see there is a regression rate basically increases with the pressure, but after that it is remaining constant, that kind of thing is really very, very important to know. And keep in mind that this relationship will be valid for the which it is being obtained, that means experiment is conducted for certain pressure ratio it will be valid for that. So, you find a very strange kind of propellant like plateau burning, and similarly mesa burning; that means, the regression rate increases and it decreases. And people deliberately do that, because there is a something you are having a requirement the thrust should increase, then you need to have a decrease you can go for this or you have a thrust as a increase thrust unit, and then you will go on keeping the same thrust label, so you can use a platoon. I will just summarize what we have learnt that burning rate or the regression rate, see I will be using this term interchangeably depends on the following conditions. That is one is chamber pressure, because the gas phase reaction plays an important role in providing heat to the propellant burning surface, and initial temperature of the propellant that is t p. And it will be dependent on combustion gas temperature, and very important thing which I did not discuss, that is the flow of hot gases, which will be, for example in a this thing suppose the propellant is burning. And then the gases will come and it will be moving at certain velocities, and this velocity because it is moving some heat transfer will be taking place so; that means, some convective, heat transfer will be taking place and that will affect the regression rate. So, that is known as erosive burning and we will be discussing little bit, because you now I am not getting into erosive burning other thing, but we will be discussing sometimes. That also will affect the regression rate, which we cannot get in these expression, this expression you cannot get, because this is under the tradition no flow is taking place, so therefore that has to be conducted in a actual rocket engines like this, what I have shown. And beside this motor acceleration has been, for example motor is accelerating, it will also be affecting the regression rate, and spinning suppose it is moving and then taking a turn, so that is also will be also affecting the rocket irrigation rate kind of things.

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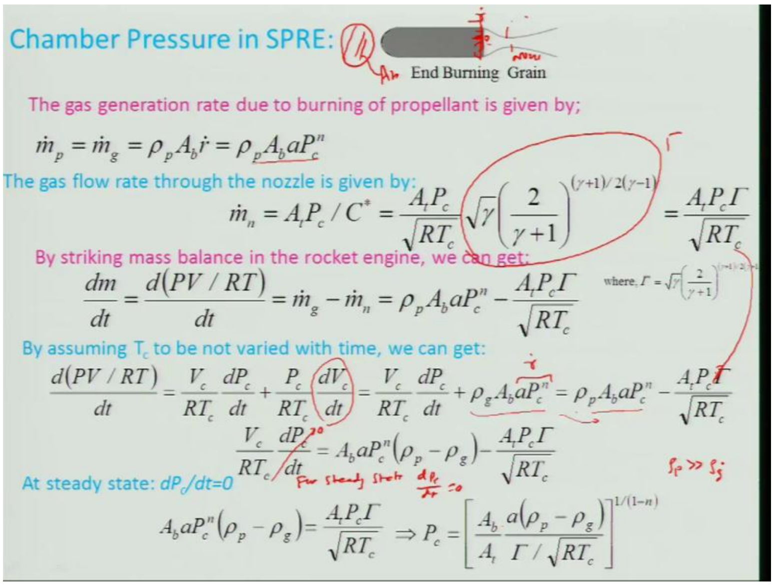

So, we will look at this chamber pressure in a solid propellant rocket engines, because we are interested to look at what is really happening in the rocket engines kind of thing. For a as I told you there will be 2 kinds of burning grain one can think of end burning grain, and then this is the let us consider that and gas being generated due to the burnings, because what will happen this will be burning out. So, when it is going then some will be generated here, and it will be passing through the nozzle, so if we look at the mass of the propellant, which is getting burnt, which will be equal to rho P A b. This is your A b, if I take this cross section over here, I will get a surface this is basically A b, and then r dot, r dot is moving perpendicular to this, this is basically r dot which will be moving, with a certain rate. That we call the regression rate, which will be perpendicular to this surface that is r dot, and we have already using this relationship instead of r dot it will be a P c n. Now, and certain amount of mass flow rate which is passing through the nozzle, because some being generated, because of burning of propellant surface or the propellant, and the gas is also going through the nozzle, and we will assume for the time being or may be most of the cases it is in choked one.

So, we will say that what is the amount of mass flow rate will be passing through under choked condition, that is we have already derived that is A t P c root over R T c root over gamma 2 by gamma plus 1 powered to the gamma plus 1 divided by 2 gamma minus 1. You can say that this portion is nothing but, your capital gamma, so by striking a mass balance in the rocket engine, we can say that the amount of mass accumulated. In these will be basically the amount of gas, which is being generated due to the propellant burning that is m dot g minus the amount of mass which is going out through the nozzle. That means, some of the mass will be accumulated in the combustion chamber with the time, as the time goes it will be accumulated, so and if I take this as an ideal gas mass, then I can write down P v m mass is equal to P v by r t. And if I will assume the t c the chamber temperature to remain constant for a particular propellant during the operation, then I can integrate that one that is v c by R T c d P c by d t plus P c R T c d v c by d t. Keep in mind that this one is what change in the chamber volume per with respect to time, and these one is change is due to burning a propellant, so that will be basically, if you look at it is what you call rho g into A b A P c n; that means, rho g A b and r dot this is nothing, but your r dot. So, this the amount of change in volume with respect to time, and of course the for m g mass we have already derived here, and then this is for your this case for the nozzle. So, you will get this expression; that means, if I look at these this is basically, if I take this portion over this side I will get v c divided by R T, see d P c by d t is equal to A b, because A b is common A P c n is common. So, rho P minus rho g minus A t P c gamma divided by root over R T c, and if I will assume this to be steady state; that means, this is 0 for steady state d P c by d t is 0. So, if that is the case then what I will get, that I will get A b A P c by n rho P minus rho g is equal to A t P c gamma divided root over R T c is just simple under steady state condition.

So, if I take this out, I will get P c is equal to A b by A t, A in the bracket rho P minus rho g divided by root over R T c power to the 1 1 minus 1 divided by 1 minus n. So, if you look at here very simplification one can think of, rho P is very, very greater than rho g. For example, if I take a solid propellant, while will be density, it will be something

150 k g per meter cube, if I look at gas density what it would be high temperature, it will be very, very low, it will be may be 0.2, 0.3 k g per meter. Because, if we take ambient air, it will be order of 1 k g per meter cube, because the pressure is high, but at the same time temperature is high, so if you look at it is very, very small, so one can neglect this term to simplify. So, with this I will stop over, we will see how we can use this relationships and arrive at the thrust law; that means, the variation of thrust with respect to time for different grain configuration.