Jet and Rocket Propulsion
Prof. Dr. A. Kushari
Department of Aerospace Engineering
Indian Institute of Technology, Kanpur

Lecture - 37

Good morning everyone. So, we are back again with the course on rocket propulsion. Till now what we have done is, we have talked about the vehicle dynamics, we have talked about orbital mechanics, we have talked about the multi-stage rockets and how they function, the performance of rockets, then we have gone into the nozzle, the nozzle design and then the combusted design. So, that pretty much gives the basic fundamentals of rocket propulsion and every component. Now, what we do is for the remaining lectures, we will go to specific type of rockets and discuss how they work and what are the specific features or special features of those rockets. So, today we will start with solid propellant rockets. After that we will go onto liquid propellant rockets and that will finish our discussion on chemical rockets. Then the couple of lectures we will dedicate to electric propulsion.

(Refer Slide Time: 01:14)

Solid Propellant Rocket Motor

- Solid fuel rockets rely on controlled burning of a mixture of substances which are in their solid phase
- Nearly a homogeneous material that is burned
- Similar to gunpowder ~ (75% potassium nitrate, 10% carbon, and 15% sulfur)
- Advantages
  - High thrust
  - Simple
  - Storability
- Disadvantages
  - Low Isp (compared to liquids)
  - Complex throttling
  - Difficult to stop and restart
  - Safety

So, now coming to the solid propellant rockets. Solid propellant rocket motor essentially as the name suggests the fuel is solid. So, solid fuel rockets rely on controlled burning of a mixture of substance which is in their solid phase. So, the name solid propellant comes from this word that they are in their solid phase and typically, of course not always the entire solid propellant mixture is fairly homogenous. So, nearly homogenous material is burned. The composition of this propellant is quite similar to gun powder that is about 0.75 percent potassium, nitrate, 10 percent carbon and 15 percent sulfur. This is the composition of gun powder by the way, but the solid propellant rockets, the propellant will have slightly different composition or sometime, even drastically different composition, but essentially all of them will be in solid stage.

Now, what are the advantages of solid propellant rocket? First of all, the thrust produced by these rockets are fairly high. The advantage is since the propellant is solid, therefore, mass per unit volume is high and there is the mass, the density of the propellant is high. So, therefore, the same mass can be packed into a much smaller volume. So, a small size rocket can produce fairly high thrust. So, therefore, thrust to weight ratio is very high for the solid propellant rockets. Second advantage is very simple or relatively simple to make. They have much less components compared to a liquid propellant rocket. So, these are the two major issues apart from that the third issue is the storability. These rockets can be stored, can be prefabricated and made ready and can be stored for a large period of time and because of that, they are very good devices as weapon or missiles because they can be kept ready and can be fired at ease. So, these are the basic advantages of the solid propellant rocket.

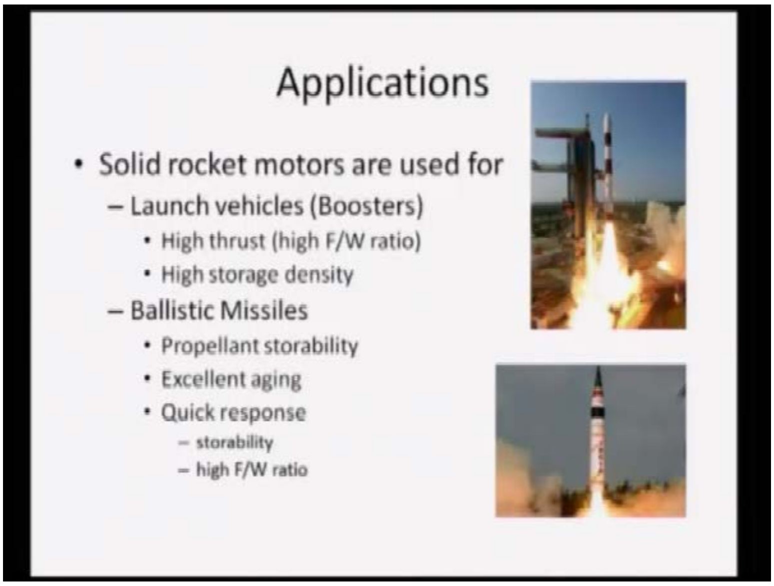
However as with any other device, there will be some disadvantages as well. The main disadvantage is that the specific impulse compared to liquids of course is fairly low. If you recall towards the beginning of the course, I discussed that what the specific impulse for different type of rockets, solid propellant rockets are. The specific impulse is in the range of 200 to 300 second whereas a liquid propellant rocket let us say cryogenic rocket can be as high as 450 seconds. So, it is almost double as specific impulse can be obtained by a liquid propellant rocket compared to solid propellant rocket.

Second disadvantage is throttling or changing the thrust at need is fairly complex. Actually, it has to be pre-programmed, so that you can get the thrust variation as you go along, but online throttling is very difficult because the solid grade is burning to change the burning rate as it flies is very difficult, almost impossible to attain. However, there are advanced rockets where specific materials are embedded which can be triggered at will to give some kind of throttling, but again it is very complex to do.

So, the throttling is fairly complex process. Third difficulty is it is very difficult to stop and restart since it is a solid propellant, and it would not have anything else in between. Once it starts to burn, it is almost impossible to stop the burning. So, therefore, stopping the rocket from firing completely is very difficult and even if by some means let us say we have pre-programmed it to cut the combustion or the burning in between. If we do that, then the restart becomes a difficult issue because we will discuss today that one of the component of solid propellant is the igniter and igniters actually are one shot devices. So, once it is used up, you cannot relight it again.

So, therefore, unless you have multiple igniters, you cannot relight it on the go. So, that makes it difficult for re-ignition of these rockets if it is stopped, and safety because many times as we will go along, we will see many times explosives are used as propellants. So, therefore, have controlled reactions of these explosives which are known to burn at a very rapid rate is a major challenge. So, therefore, unless they are handled properly, safety issues are always present in solid propellant rockets.

(Refer Slide Time: 06:00)



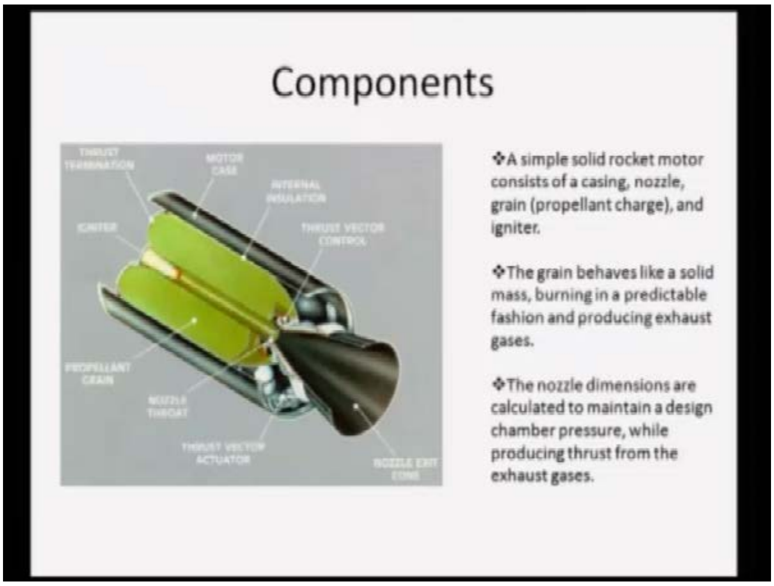
Applications

- Solid rocket motors are used for
  - Launch vehicles (Boosters)
    - High thrust (high F/W ratio)
    - High storage density
  - Ballistic Missiles
    - Propellant storability
    - Excellent aging
    - Quick response
      - storability
      - high F/W ratio

So, with this little bit of introduction, let us look at some applications of solid propellant rockets. As far as launch vehicles are concerned, solid propellant rockets are more widely used in boosters and as you can see here, a picture where the booster is lighted and it is taking it up. If you look at the picture of this rocket, the solid propellant boosters are fairly small. As you can see compares to the large rocket, but within the small boosters, large amount of energy is packed because of the high thrust to weight ratios of these vehicles or these devices as well as high storage density of these devices.

So, primarily solid propellant rockets are used as booster rockets for rocketry application. However, they are very extensively used for missile applications, particularly ballistic missiles because of the propellant storability which I have just discussed few minutes back. I am sorry then the excellent ageing process and quick response. So, they can be kept ready and they can be lighted very easily. So, unlike liquid propellant rocket, where you are required to have lot of preparation time just before the launch, we will discuss those issues. Solid propellant rocket does not require any preparation time. They are ready to fire. Once they are built, they are ready to fire. So, that is why because of this quick response, they are the best option for missile applications and of course, the high weight to the thrust to weight ratio will give you more payload carrying capability. So, these are couple of applications of solid propellant rocket.

(Refer Slide Time: 07:44)



Components

- ❖A simple solid rocket motor consists of a casing, nozzle, grain (propellant charge), and igniter.
- ❖The grain behaves like a solid mass, burning in a predictable fashion and producing exhaust gases.
- ❖The nozzle dimensions are calculated to maintain a design chamber pressure, while producing thrust from the exhaust gases.

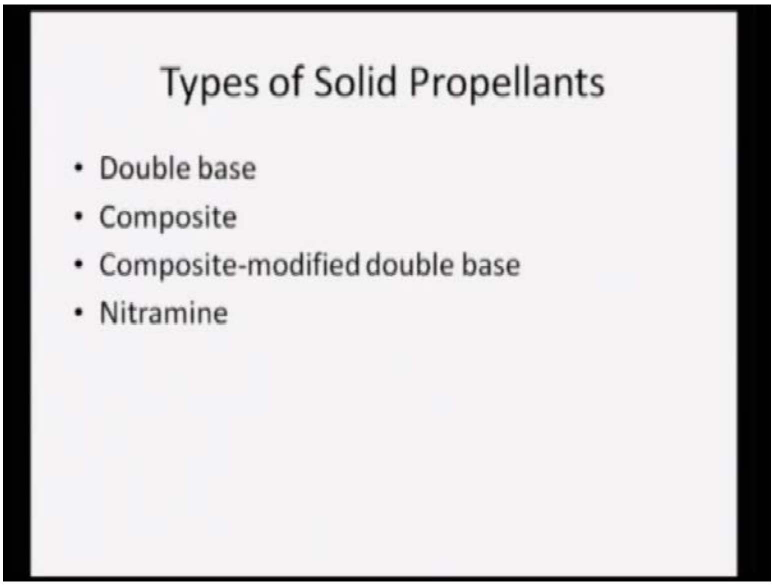
Now, let us come to various components of a solid propellant rocket. Here is a schematic of a solid propellant rocket. The green part here is the propellant grain. This is the thing which will be burning. You can see there is something like a cube going through. This green part, this is the igniter and you can see that there is some kind of charge here which will ignite this grain like I was mentioning that this is a one shot kind of application. It can be a small rocket itself or some charge will be used. I will discuss the igniters in detail. So, this is the igniter which will initiate the combustion process because this is a solid propellant. So, there are fairly closely packed and lot of initial ignition energy is required to start the ignition process. Once that starts, then it will flow on its own, but the initial ignition requirement is quite high. Therefore, the igniter is a must to provide that initial ignition energy. Apart from that, of course this thrust has to be terminated somehow.

So, you see in this end, there are some plates which work as the thrust terminator. Then this is the casing. Now, when the rocket will burn, lot of energy will be produced. We do not want this energy to be lost laterally through the casing, so that all the energy should flow out of the nozzle. So, in order to do that, there is thruster insulation between the motor case and the grain. You can see here the internal insulation is present. So, this will stop the heat transfer to the casing and then if you recall when we talked about the wide vehicle mechanics, we said that in order to get lateral stability, so that the lift is 0. You need to have the rocket nozzles slightly tilted which is thrust vector. So, rocket has been using thrust vectoring for more than 100 years now. From the very early beginning of modern rocketry, that thrust vectoring was used.

So, therefore, that thrust vector as you can see here, this is the thrust vector control at the nozzle throat and this is the thrust vector activator which will turn the nozzle above this point. So, essentially to give the lateral stability to the vehicle and then this is our nozzle, this is the converging diverging nozzle, this is nozzle exit cone through which the burned product will expand to the ambient, ok. So, if I go back to what is written here, it is a simple solid rocket motor schematic is given here which consists of a casing, a nozzle, the propellant charge or grain and the igniter. So, these are the four main components of a solid propellant rocket. The grain behaves like a solid mass which burns in a predictable fashion. So, therefore, the grain is designed in such a way that they will burn at a predictable fashion and thus, producing the exhaust gases, the nozzle dimensions.

On the other hand, we have talked about nozzle design in detail. The nozzle dimensions are calculated to maintain a design chamber pressure p c naught. We will discuss this also while producing the thrust from the exhaust gases because the thrust will depend on how much chamber pressure is generated inside this rocket plus chamber pressure, and temperature. So, the nozzle will ensure that that pressure and temperature is maintained.

(Refer Slide Time: 11:06)

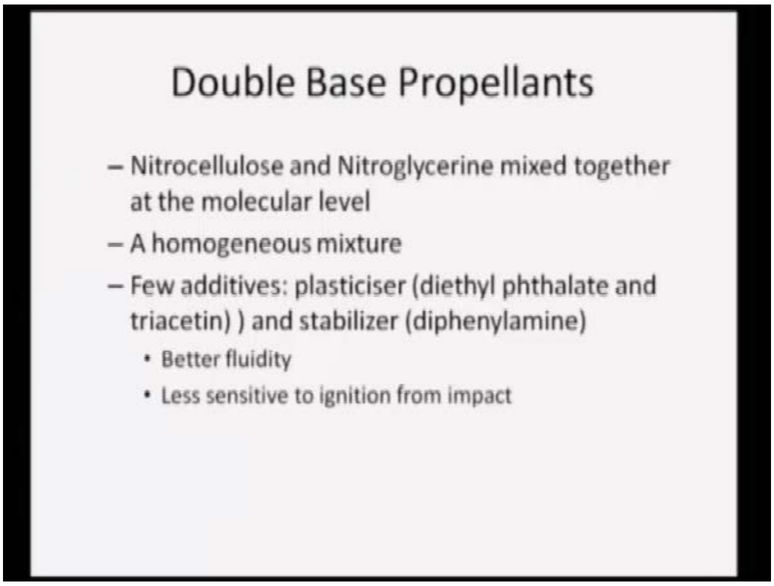


Types of Solid Propellants

- Double base
- Composite
- Composite-modified double base
- Nitramine

Now, let us come to the types of solid propellant. Use the propellant what I mean is the fuel and oxidant together. Now, since I have been saying that it is like a homogenous mixture completely. So, both the propellant that is the fuel and oxidizers are mixed together in this propellant. So, it will be a single solid piece. So, primarily there are four types of solid propellants which are used. One is a double based, then a composite propellant, then composite modified double base and nitramine propellant. So, these are the four types of propellants primarily used for different rockets, solid propellant rockets. Now, let us discuss each of them one at a time.

(Refer Slide Time: 11:51)



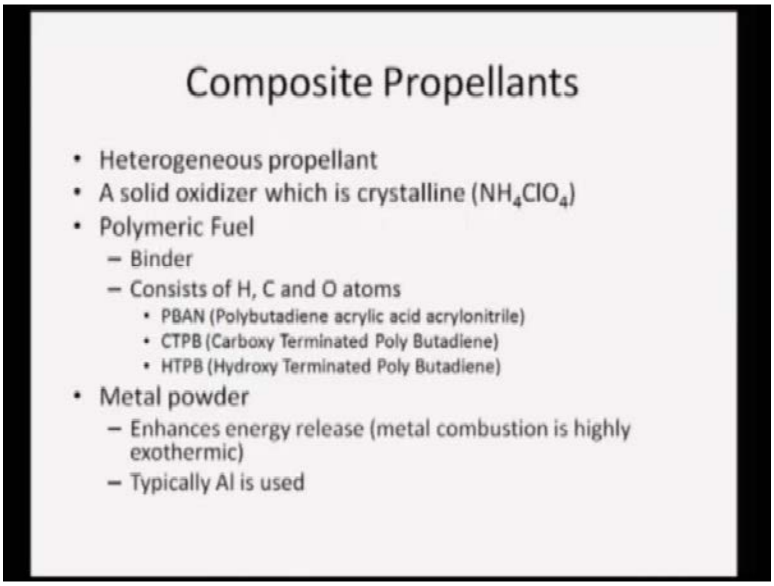
Double Base Propellants

- Nitrocellulose and Nitroglycerine mixed together at the molecular level
- A homogeneous mixture
- Few additives: plasticiser (diethyl phthalate and triacetin)) and stabilizer (diphenylamine)
  - Better fluidity
  - Less sensitive to ignition from impact

So, first let us start with double base propellants. What are double base propellants? Typically, these are nitro cellulose or nitroglycerine mixed together at the molecular level. So, this is a mixture of these two propellant nitrocellulose and nitroglycerine. One of them is the fuel, the other is oxidizer. So, they are mixed in the molecular level. So, therefore, homogenous mixtures of these two are created. Now, when I have to be mixed in the molecular level, you have to add some additives. One of the additives is a plasticizer which is typically diethyl phthalate and triacetin. This essentially allows these two nitrocellulose and nitroglycerine to be compacted together. So, it gives like the binding agent. It works like binding agent to keep them together. At the same time, you need some kind of stabilizer to control the burning rate. The stabilizer controls the burning rate. So, it works like a damper, so that you can get a required burning rate. So, diphenylamine is used as the stabilizer with this propellant. So, the additive gives it better fluidity.

So, it burns at a constant rate and also, it is less sensitive from to ignition from impact. Now, ignition as I mentioned that if it is ignited, it is almost impossible to stop it. So, therefore, ignition should not be starting on its own. So, these two will actually provide a threshold of ignition energy, so that from the ignition system we have to provide at least more than that energy, so that the ignition can start. So, therefore, essentially ignition cannot be started by accident, thus the idea of putting these things. So, these all four of these will be mixed together and processed, and a propellant rod will be created and then this rod will be put inside the case and when ignited, this rod will burn depending on the exact design and the mixture ratios at a particular rate which will give us the required pressure and temperature.

(Refer Slide Time: 14:04)



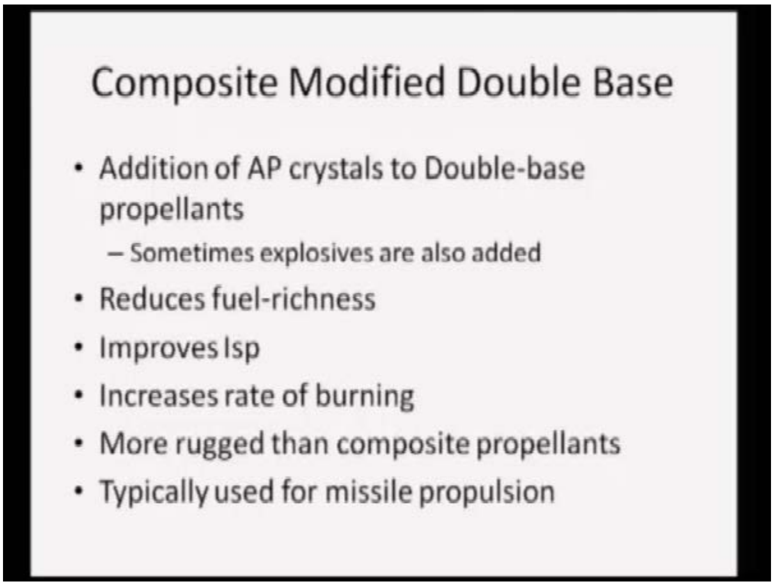
Composite Propellants

- Heterogeneous propellant
- A solid oxidizer which is crystalline (NH_4ClO_4)
- Polymeric Fuel
  - Binder
  - Consists of H, C and O atoms
    - PBAN (Polybutadiene acrylic acid acrylonitrile)
    - CTPB (Carboxy Terminated Poly Butadiene)
    - HTPB (Hydroxy Terminated Poly Butadiene)
- Metal powder
  - Enhances energy release (metal combustion is highly exothermic)
  - Typically Al is used

The second type of propellant is a composite propellant. These propellants are typically heterogeneous propellants that they do not have a smooth mixture everywhere, mixture fraction everywhere, but there will be local non-homogeneity embedded in a homogenous mixture. So, therefore, this is a heterogeneous propellant typically oxidizer which is crystalline in nature like, say ammonium perchlorate which is a solid oxidizer will be embedded. So, this is an oxidizer, but it also works as a fuel which I will talk about that it breaks into two components. One is ammonia and one is hydrogen chloride. So, ammonia is fuel hydrogen and chloride is oxidizer, but it predominantly works as oxidizers. So, therefore, in the presence of this, sorry in the presence of the ammonium chloride, the combustion process will be fuel lean because we are adding more oxidizer. So, in the vicinity of those propellants, we have a fuel lean combustion going on. Then typically polymeric fuels are used for this type of application that is composite propellants which requires a binder. It consists of some hydrogen, carbon and oxygen atoms.

Typically, the different type of propellant used are PBAN which is poly butadiene acrylic acid acrylonitrile or CTPB, carboxy terminated poly butadiene or HTPB which is hydroxy terminated poly butadiene. These are typically the propellant which are polymeric fuel that are used as composite propellants apart from this. So, the polymeric fuel, the oxidizer sometime we also embed some metal powders into this propellant. So, this metal powder typically aluminum is used as the metal powder. Aluminum nano particles will be used as the metal powder which will be mixed along with these composites, so that you get actually more non-homogeneity, more heterogeneity rather. So, it will be like a grainy structure. Now, the advantage of this metal powder is that when the metal burn, they burn in a highly exothermic manner. So, therefore, the energy density increases, the energy release is enhanced. So, these metal powders will be burning giving additional energy. So, therefore, these composites will have a higher energy density compared to the double base propellants because of this structure.

(Refer Slide Time: 16:39)



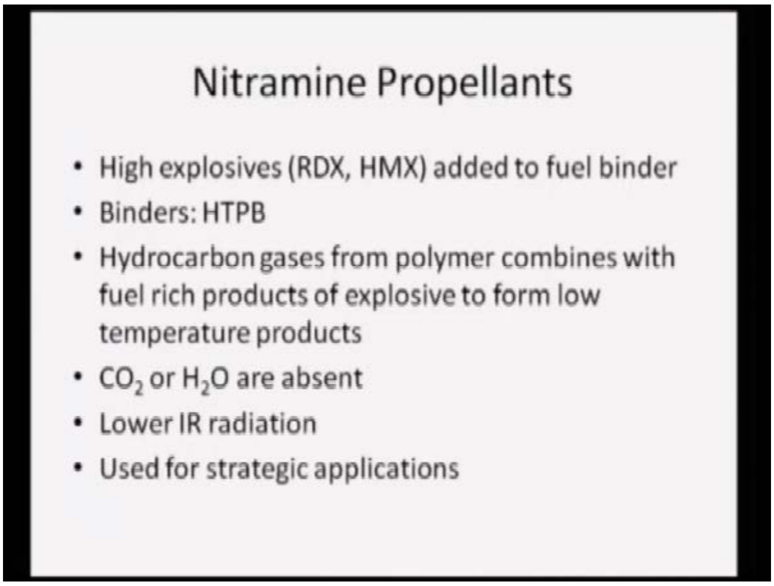
Composite Modified Double Base

- Addition of AP crystals to Double-base propellants
  - Sometimes explosives are also added
- Reduces fuel-richness
- Improves Isp
- Increases rate of burning
- More rugged than composite propellants
- Typically used for missile propulsion

The third type of propellant is composite modified dual base. Here in double base, sorry here in addition to the ammonium perchlorate crystal, sometime even some explosives are added. So, we add some ammonium perchlorate to double base propellants which we have already discussed, so that changes this double base to something like a composite on top that sometime even some explosives are added. So, therefore, the reaction rate is even more enhanced and first of all, the double base propellant typically burns like in a diffusion flame because although they are mixed in the molecular level, this is not premise because it is solid propellant. So, it has to vaporize and then the vapors will mix and then burn the presence of ammonium perchlorate gives the local fuel leanness, right.

So, as I said this is an oxidizer. So, locally it will be fuel lean. So, therefore, the overall mixture will be less fuel reach. So, having the ammonium perchlorate mixed with a double base propellant reduces the fuel richness. So, it moves towards more complete combustion because of that the specific impulse improves. So, we get a better specific impulse. With this type of propellants, it increases the rate of burning because of explosives are used and also the crystal will burn at a particular rate higher than the double base propellant burning rate. So, because of that, there is an increased burning rate also, and these are more rugged compared to composite propellants typically used in missile propulsion. So, this type of propellant which is a composite modified double base propellants are typically used in missile propulsion.

(Refer Slide Time: 18:27)



Nitramine Propellants

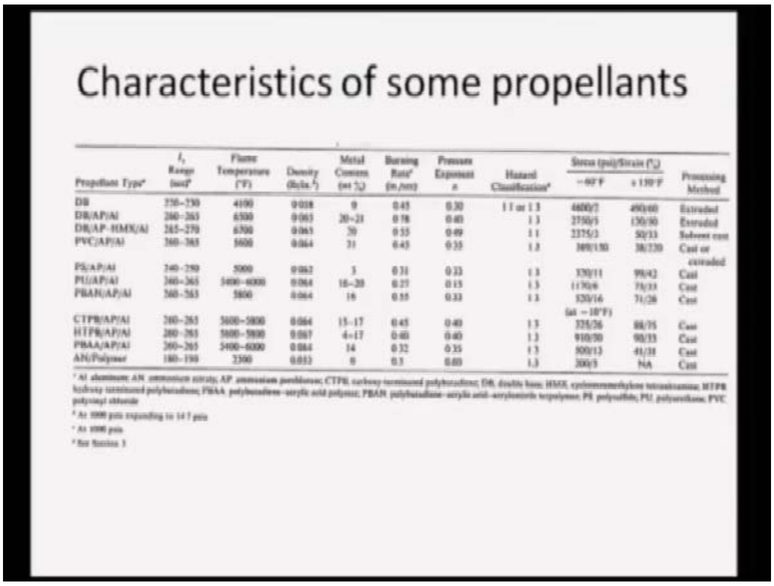
- High explosives (RDX, HMX) added to fuel binder
- Binders: HTPB
- Hydrocarbon gases from polymer combines with fuel rich products of explosive to form low temperature products
- CO_2 or H_2O are absent
- Lower IR radiation
- Used for strategic applications

So, this is the third type of propellants we talked about. Now, let us come to the fourth type of propellant which is the nitramine propellant. This actually contains high explosives like RDX or HMX. High explosives are added to the fuel binder, typical binder is HTPB. So, HTPB we have discussed in the case of composites. Hydroxyl terminated poly butadiene, this is the binder. So, in this binder, you have RDX or HMX added. So, these are explosives. So, therefore, now that makes it more dangerous to handle, but if they are burned in a controlled manner, they will provide much higher energy density. So, the hydro carbon gasses from the polymer combines with the fuel reach products of explosives to form low temperature products. So, the explosives will not have the freedom to burn on its own because of the presence of this binder. So, that kind of dumps out the explosiveness of the explosive and gives a controlled burning which essentially helps in producing the required condition for our thrust generation.

So, the carbon dioxide and water vapor are absent in this mixture. Typically as you know that most of the hydro carbons, they burn because they have oxygen, hydrogen and carbon. Many times they produce carbon dioxide in water vapor, but in this type of propellant, carbon dioxide and water vapor are absent. Now, what does carbon dioxide and water, particularly water vapor does? It is a very good signature of I R infrared. So, typically the identification of missiles path is by the I R signature, right infrared signature.

So, if you do not have water vapor, the I R signature will be drastically reduced. So, therefore, you have much lower I R radiation. So, therefore, it is very difficult to detect these missiles because they are coming at a high speed and if you do not have these detectors to detect the I R signature, it is very difficult to detect them. So, therefore, these used for strategic applications, they have a fairly good stealth capability because of the low I R signature or low I R radiation. So, this is a propellant which is typically used for strategic applications in missiles.

(Refer Slide Time: 20:48)



Characteristics of some propellants

Propellant Type[a]	I_s Range (sec)[b]	Flame Temperature (°F)	Density (lb/in.^{3})	Metal Content (wt %)	Burning Rate[c] (in./sec)	Pressure Exponent n	Hazard Classification[d]	Stress (psi)/Strain (%) −40°F	Stress (psi)/Strain (%) +150°F	Processing Method
DB	220–230	4100	0.058	0	0.45	0.30	1.1 or 1.3	4600/2	490/60	Extruded
DB/AP/Al	260–265	6500	0.065	20–21	0.78	0.40	1.3	2750/5	120/50	Extruded
DB/AP-HMX/Al	265–270	6700	0.065	20	0.55	0.49	1.1	2375/3	50/33	Solvent cast
PVC/AP/Al	260–265	5600	0.064	21	0.45	0.35	1.3	369/150	38/220	Cast or extruded
PS/AP/Al	240–250	5000	0.062	3	0.31	0.33	1.3	370/11	99/42	Cast
PU/AP/Al	260–265	5400–6000	0.064	16–20	0.27	0.15	1.3	1170/6	75/33	Cast
PBAN/AP/Al	260–263	5800	0.064	16	0.55	0.33	1.3	520/16 (at −10°F)	71/28	Cast
CTPB/AP/Al	260–265	5600–5800	0.064	15–17	0.45	0.40	1.3	325/26	88/75	Cast
HTPB/AP/Al	260–265	5600–5800	0.067	4–17	0.40	0.40	1.3	910/50	90/33	Cast
PBAA/AP/Al	260–265	5400–6000	0.064	14	0.32	0.35	1.3	500/13	41/31	Cast
AN/Polymer	180–190	2300	0.053	0	0.3	0.60	1.3	200/5	NA	Cast

[a] Al aluminum; AN ammonium nitrate; AP ammonium perchlorate; CTPB carboxy-terminated polybutadiene; DB double base; HMX cyclotetramethylene tetranitramine; HTPB hydroxy-terminated polybutadiene; PBAA polybutadiene–acrylic acid polymer; PBAN polybutadiene–acrylic acid–acrylonitrile terpolymer; PS polysulfide; PU polyurethane; PVC polyvinyl chloride

[b] At 1000 psia expanding to 14.7 psia

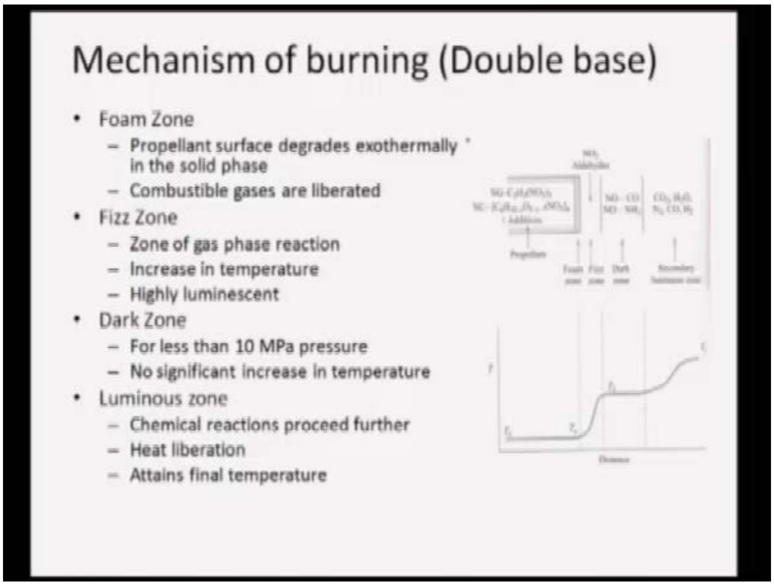
[c] At 1000 psia

[d] See Section 3

Now, here is a table giving the characteristic of some of the propellants. So, DB stands for double base. Then DB/AP/AI is double base with aluminum perchlorate with ammonium perchlorate with alumina solid particles. So, I just show few features. First column gives the ISP. You see typically ISP for all of them range between about say 180 to about say 270. So, it is about 250-260 range and typically range of about 10 among all of them. So, this is fairly close flame temperature. However, if you look at the double base is about 4100 Fahrenheit, but for double the composite one, it goes to as high as 6500 and then with the embedded HMX, it goes to 6750 Fahrenheit, that is a fairly high temperature and because of that high temperature, particularly if you look at the burning rate because of the presence of this ammonium perchlorate and alumina.

If you compare the burning rate of a double base and a double base with aluminum perchlorate, the composite you see that there is a vast difference in the burning rate. Burning rate is much higher here. So, these are the different propellants which are traditionally used and different conditions for all of them. Now, this special exponent NI will discuss this because it is part of the burning rate equation which will come when I talk about the burning rate. So, these are various propellants which are used extensively and the properties of those propellants are listed here. Now, next let us talk about the mechanism of burning. How these solid propellants rockets burn or the solid propellants burn?

(Refer Slide Time: 22:36)



Mechanism of burning (Double base)

- Foam Zone
  - Propellant surface degrades exothermally in the solid phase
  - Combustible gases are liberated
- Fizz Zone
  - Zone of gas phase reaction
  - Increase in temperature
  - Highly luminescent
- Dark Zone
  - For less than 10 MPa pressure
  - No significant increase in temperature
- Luminous zone
  - Chemical reactions proceed further
  - Heat liberation
  - Attains final temperature

First, let us start with double base. So, here you can see a schematic of a double base propellant, so nitroglycerine and the other propellant nitrocellulose and nitroglycerine. So, NG stands for nitroglycerine, NC stands for nitrocellulose plus the additives. So, this is our double base propellant which is fairly homogenous. Now, in the combustion of these propellants like we have discussed earlier in various courses, in combustion courses that solid propellant goes through a particular process of burning. The first process is pyrolysis, where because of the supply of certain energy, the propellants starts to evaporate from the surface, but in pyrolysis like say pyrolysis of coal or wood, it is a full hydrocarbon and the oxidizer is in the atmosphere.

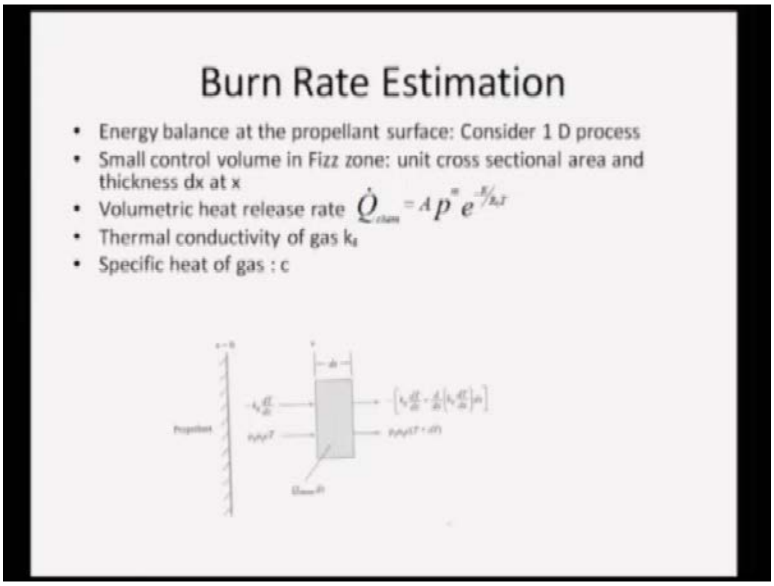
So, when it evaporates, it mixes with atmospheric oxygen and then the combustion takes place, but in this double base, both the oxidizers and fuel are together. It is not reacting with the atmosphere. So, therefore, the combustion mixture will be formed right next to it without any outside help. So, first you see this is the propellant. The first zone here is the foam zone. Here in the foam zone, the propellant surface degrades exothermally. That is because when we start the ignition process, the propellant surface absorbs this energy and then it starts to change its phase. It changes from solid phase to the combustible gas phase. So, the combustible gasses are released in the foam zone, but combustion does not take place. There combustion takes place slightly ahead of it which is called a fizz zone.

In the fizz zone which is the zone of gas phase reactions, you can see here this is the zone of gas phase reaction or fizz zone. So, reaction takes place here because we have both the fuel and oxidizer present in the vapor. They mix and burn. So, in the fizz zone, the actual reaction takes place. So, if you look at this bottom plot, the temperature is here same. Then close to the surface, there is slight increase. Then in the fizz zone, there is a substantial increase in the temperature and it goes to a temperature T1. So, I will discuss this T1 also later.

So, there is a zone of gas phase reaction which increases the temperature as I just discussed, and this zone is highly luminescent. So, most the flame color comes from this zone. Now, luminescent means that most the radicals are present in that zone, right action when they occur; most of the radicals are present in that zone. After this luminescent zone, there is one zone called dark zone. In the dark zone which will be typically present if the pressure is less than 10 mega pascal. There is not much significant increase in the temperature that takes place only there is some kind of convection of these propellants take place and more mixing will follow. So, after that, after this dark zone where nothing much happens, we have the secondary luminous zone or secondary combustion zone, where these molecules as you can see here NOCO or NONH2, these are heavier molecules. They further breakdown into more fundamental molecules like carbon dioxide, water vapor etcetera. So, this is the secondary luminous zone here. The chemical reactions further proceed and get completed.

So, by the time we come to the end of this zone, the chemical reactions are completed and all the heat is liberated. Because of that as you can see here, it attains the final temperature at the end of this zone. So, this is the mechanism of burning for double base propellant. Now, let us talk about the estimation of burn rate at what rate it is burning because later we will see that the pressure and temperature will depend on this burning rate.

(Refer Slide Time: 26:17)



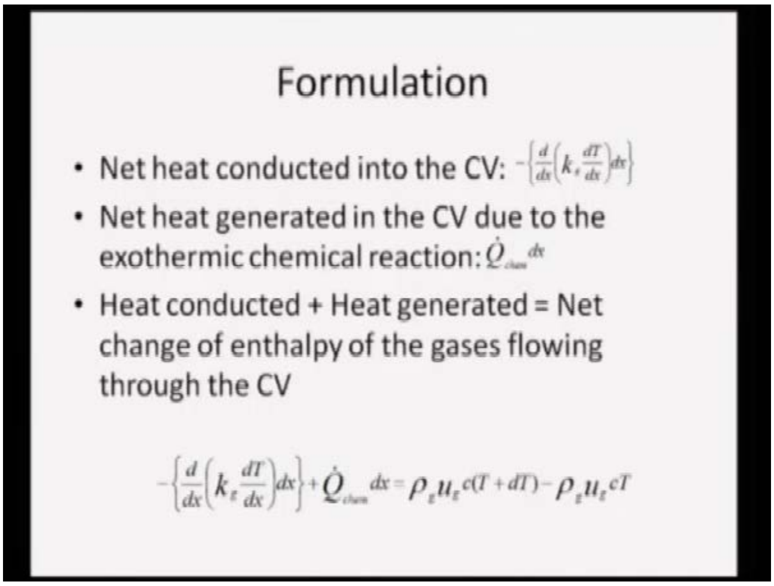
Burn Rate Estimation

- Energy balance at the propellant surface: Consider 1 D process
- Small control volume in Fizz zone: unit cross sectional area and thickness dx at x
- Volumetric heat release rate $\dot{Q}_{chem} = A p^{m} e^{-E/R_0 T}$
- Thermal conductivity of gas k_g
- Specific heat of gas : c

So, the burn rate is typically estimated by energy balance at the propellant surface that is at in the fizz zone mostly at the foam, and fizz zone will consider a one-dimensional process. So, this is here you can see a propellant is given here x equal to 0. This is my fizz zone. Let us consider a small control volume in this fizz zone at a distance x from the propellant surface having a width of d x and with a unit cross sectional area for this propellant. Now, this propellant is burning. As the burning takes place, there is some amount of heat that will be released. So, this heat release is given here by q dot k m. This is the heat released by the combustion process. So, it is given by Ap to the power m, e to the power minus e by r naught a t. So, this comes from Arrhenius law which represents the rate and then this represents the magnitude of the heat release.

So, this is the total heat release rate that will come out from this expression. P is the pressure. This is one index which has to be estimated. A is a constant again that needs to be estimated, this e is the activation energy, r naught is the universal gas constant and T is the temperature. So, this is the volumetric heat release rate for this propellant which is burning. Apart from that, what are the other energy transfers taking place? First of all, there is conduction of heat into this control volume and there is convection of enthalpy. There is a change in enthalpy across this control volume, right.

(Refer Slide Time: 28:10)



Formulation

- Net heat conducted into the CV: $-\left\{\frac{d}{dx}\left(k_g\frac{dT}{dx}\right)dx\right\}$
- Net heat generated in the CV due to the exothermic chemical reaction: $\dot{Q}_{chem}dx$
- Heat conducted + Heat generated = Net change of enthalpy of the gases flowing through the CV

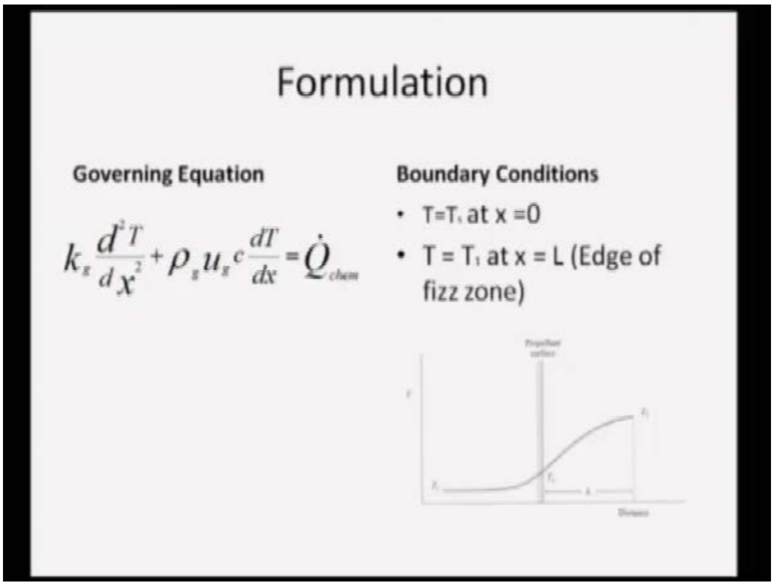
$$-\left\{\frac{d}{dx}\left(k_g\frac{dT}{dx}\right)dx\right\}+\dot{Q}_{chem}dx=\rho_g u_g c(T+dT)-\rho_g u_g cT$$

So, now if I do a full energy balance of this process that is occurring, then what we have is, first of all let us identify three sources of energy. One is rather three changes in energy, not sources. One is the net heat conducted into the control volume. So, the rate of heat conduction will be given Fourier's law which is k g dT dx, where k g is given here thermal conductivity. So, therefore, the rate of conduction of heat will be given by the double derivative of that. Now, you can derive it also. If I go back here in the left surface, the energy, the conduction is given by minus k g dT dx and what is leaving is this amount that is this plus slight increase, right.

So, difference of these two that is this amount is the net range rate of heat conduction into the control volume. So, that is given by this term. Then next what we have is the net heat generated in the control volume due to the exothermic chemical reaction that is taking place. So, that will be equal to q dot d x time 1 because the area is one in the depth, right is a unit area. So, therefore, the surface, the total volume will be given by 1 times d x. So, q dot will be the net heat generated in the control volume. So, now, this heat conducted plus the heat generated is the net change of enthalpy from energy balance. So, there is the net change of enthalpy of the gasses flowing through the control volume.

So, how do we get the net change of enthalpy? This term is the enthalpy of the gases flowing out, where rho g is the density of the gasses, u g is the velocity of the gasses, c is specific heat and T plus d T is the temperature at the right surface. Similarly, rho g is the density of the incoming gasses, u g is the density of the incoming gasses, velocity of the incoming gasses, c is the specific heat and T is the temperature of the incoming gasses. So, therefore, this term in the right hand side is the net change in enthalpy. So, now, this is our expression for enthalpy balance. As we can see this is a differential equation. So, we have to solve this differential equation with certain boundary condition to get the details of the process.

(Refer Slide Time: 30:23)



Formulation

Governing Equation

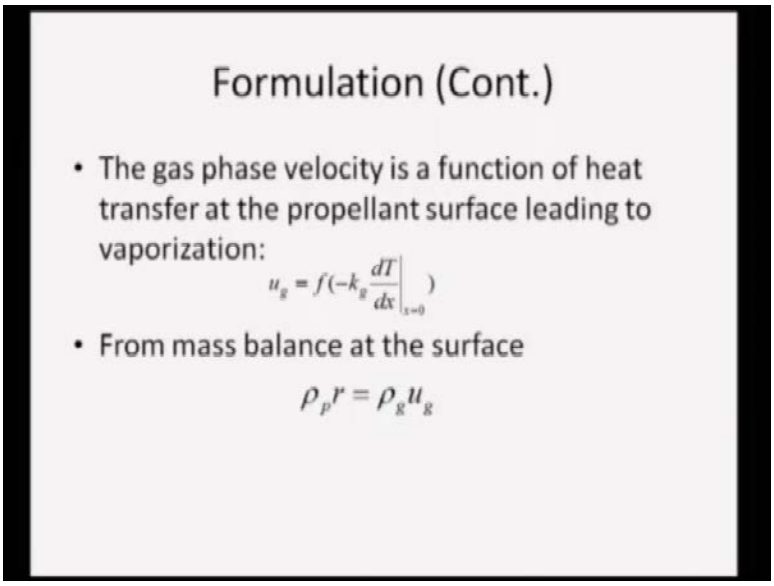
$$k_g \frac{d^2T}{dx^2} + \rho_g u_g c \frac{dT}{dx} = \dot{Q}_{chem}$$

Boundary Conditions

- T=T_s at x =0
- T = T_1 at x = L (Edge of fizz zone)

So, this is the formulation. Then this is our governing equation given here which is k g d square T d x square plus rho g u g c d T d x equal to Q dot c. Now, this Q dot will come from the chemistry which we have already discussed, right. So, now, we can solve for the temperature field from this what are our boundary conditions. First of all, the temperature at the surface is T s at x equal to 0 at the surface temperature is T s at a distance of l which is the edge of the fizz zone. The temperature is equal to T1, right. So, therefore, these are the two boundary conditions. With these two boundary conditions, we need to solve this governing equation. So, I am not going into the details of solution. Let us just look at few specific features of this formulation.

(Refer Slide Time: 31:15)



Formulation (Cont.)

- The gas phase velocity is a function of heat transfer at the propellant surface leading to vaporization:

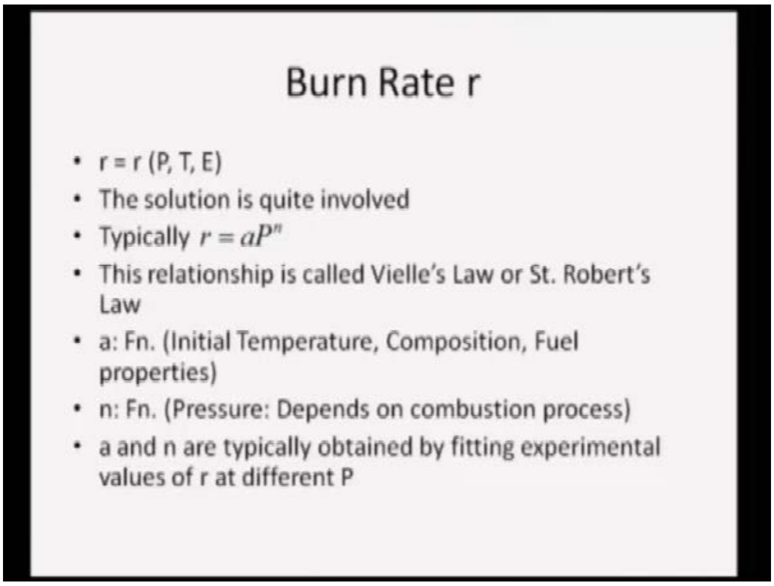
$$u_g = f\left(-k_g \left.\frac{dT}{dx}\right|_{x=0}\right)$$

- From mass balance at the surface

$$\rho_p r = \rho_g u_g$$

First of all, the gas phase velocity that is u g is a function of heat transfer to the propellant surface leading to vaporization, right. So, the rate at which is vaporizing in the gasses are moving is my u g. So, therefore, it is a function of the heat conduction to the surface, right and from mass balance at the surface if I do a mass balance at the surface, the propellant density times the burning rate gives the mass flow rate of the propellant from the surface. Now, this mass flow must be conserved. Therefore, the mass flow rate of the gasses moving out should have the same value. What is the value for the gasses moving out? This rho g u g because rho g is my density of the gasses, u g is the velocity. Therefore, this equation must be satisfied at the surface, where r is my burning rate and this is what I want to find out.

(Refer Slide Time: 32:19)



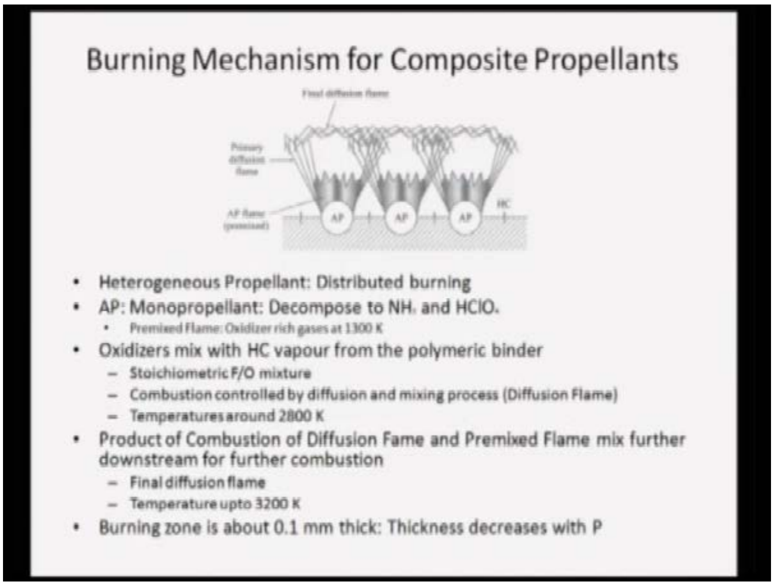
Burn Rate r

- r = r (P, T, E)
- The solution is quite involved
- Typically $r = aP^n$
- This relationship is called Vielle's Law or St. Robert's Law
- a: Fn. (Initial Temperature, Composition, Fuel properties)
- n: Fn. (Pressure: Depends on combustion process)
- a and n are typically obtained by fitting experimental values of r at different P

So, let us look at burn rate r. First of all, this r is a function of pressure, temperature and activation energy E. So, therefore, as you can see from here that Q dot will depend on this or this depends on Q dot vice versa, right. So, now, the solution of this entire process is quite involved. I will not go to the details of that, but typically it has been seen that r that is the burning rate is given as this a P to the power n, where a is constant depending on the particular propellant. We are using P is the pressure and n is the index that gives the burning rate. So, the table that I had, let me go back to the table as I was discussing this pressure exponent n.

See here this pressure exponent n is that I am talking about now. So, that is typically obtained experimentally. So, this is the expression for the burn rate. Now, r equal to a P to the power n, this relationship is called Vielle's law or Saint Robert's law. This dictates the burning rate of solid propellant, typically the double base propellants. Now, here a is a function of initial temperature composition and fuel properties, and n is a function of pressure typically. Therefore, it depends on the combustion process. This a and n are typically obtained by fitting experimental values of r at different pressure. So, how do we get it? We conduct experiments at different pressure measure. The burn rate or estimate the burn rate and do a curve fit to get this relationship, and from there we estimate a, and n. That is how typically the exponents are estimated. So, this is the burn rate of double base propellants.

(Refer Slide Time: 34:13)



Burning Mechanism for Composite Propellants

- Heterogeneous Propellant: Distributed burning
- AP: Monopropellant: Decompose to NH_3 and $HClO_4$
  - Premixed Flame: Oxidizer rich gases at 1300 K
- Oxidizers mix with HC vapour from the polymeric binder
  - Stoichiometric F/O mixture
  - Combustion controlled by diffusion and mixing process (Diffusion Flame)
  - Temperatures around 2800 K
- Product of Combustion of Diffusion Fame and Premixed Flame mix further downstream for further combustion
  - Final diffusion flame
  - Temperature upto 3200 K
- Burning zone is about 0.1 mm thick: Thickness decreases with P

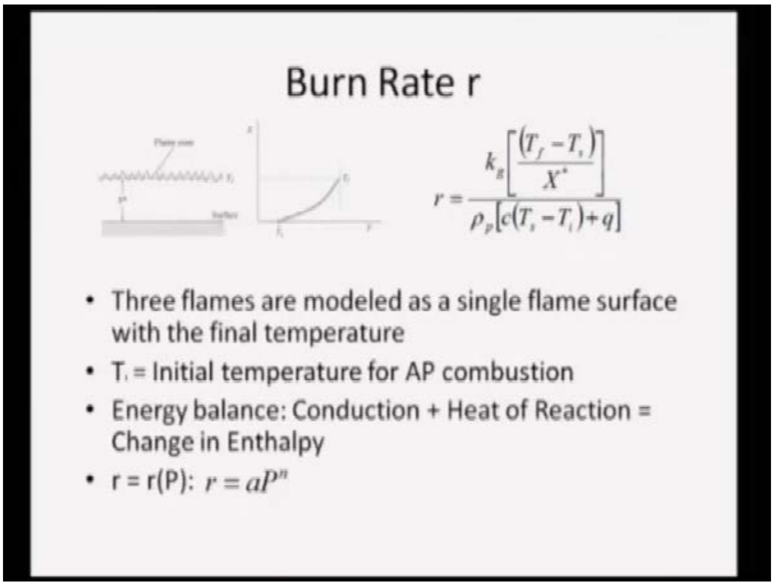
Next let us look at the composite propellants. So, burning mechanism, first for the composite propellants is little more complex. Here you can see a schematic representation of the burning of a composite propellant, a c is the hydrocarbon. So, this is the main fuel. It can be a double base fuel and all a P is the ammonium perchlorate which is embedded in it. Now, a P itself first of all because of this as you can see that the burn rate is not constant everywhere. There is locally some higher burning and then other places there is a lower burning and finally, away from the surface, we get fairly constant flame, but in between there is a lot of in homogeneity in the entire process because of the heterogeneous nature of the propellant.

So, since the propellant is heterogeneous, we have distributed burning. Now, first of all let us look at the ammonium perchlorate. This ammonium perchlorate like I was mentioning sometime back is actually a mono propellant. It can burn on its own. So, when it is burning, it will decompose into ammonia and HCLO4. So, this after burning of a P, we produce this and now because of this being a mono propellant, it can burn on its own. So, it is like a premixed flame, right. So, when it is heated, it will burn with releasing this vapor in a premixed flame and in this flame, this is a fuel lean flame. So, therefore, it is an oxidizer reached gasses will be released after it is burned and typically, this temperature will be about 1300 Kelvin.

Now, let us look at the ammonium perchlorate. As I have mentioned earlier that this is a mono propellant. Therefore, when it can burn on its own and decompose into ammonia and HCLO4. So, since it is mono propellant burns on its own, it is like a premixed flame because it is mixed in the molecular level and burn on its own. So, this is a premixed flame is produced when burning this propellant, and this typically gives an oxidizer reach gas or a fuel lean reach gas, fuel lean gas sorry at 1300 Kelvin.

Now, this oxidizer mixes with the hydrocarbon vapor which is produced by evaporation of this hydrocarbon from the polymeric binder and stoichiometric fuel. Air mixture is created slightly away from the surface and therefore, now at this surface burns in a diffusion mode. So, a primary diffusion flame is created and the combustion is controlled by diffusion and mixing process as it is seen here. Temperature will be increased as much as 2800 Kelvin. Now, the product of this diffusion combustion and this premixed combustion finally mixed to give us this final flame which is the final diffusion flame sitting slightly away from it downstream from this is the final diffusion flame is created, where everything else whatever is remaining unburned will burn, and the temperature will go as much as 3200 Kelvin. So, this entire burning zone is about 0.1 mm thick and the thickness decreases with increasing pressure. So, this is how composite propellant will burn.

(Refer Slide Time: 37:31)



Burn Rate r

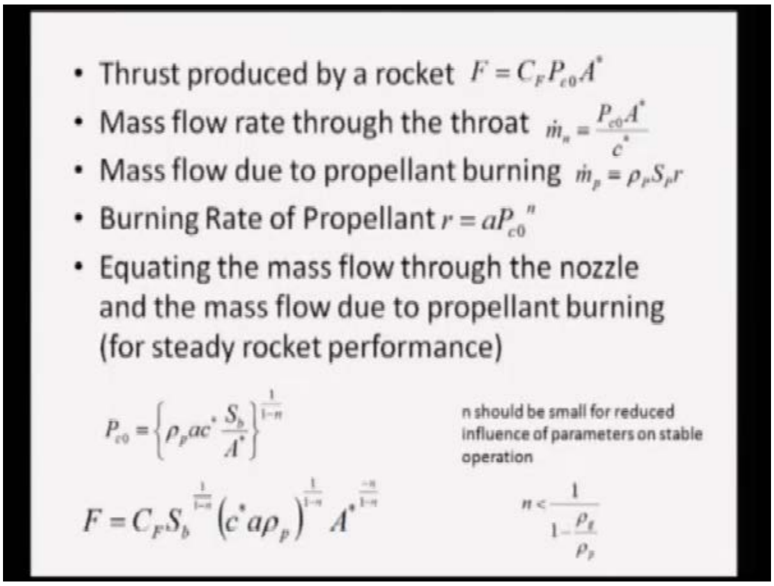
$$r = \frac{k_g\left[\frac{(T_f - T_s)}{X^*}\right]}{\rho_p\left[c(T_s - T_i) + q\right]}$$

- Three flames are modeled as a single flame surface with the final temperature
- T_i = Initial temperature for AP combustion
- Energy balance: Conduction + Heat of Reaction = Change in Enthalpy
- r = r(P): $r = aP^n$

Now, the burning rate of a composite propellant is simplified here represented in simplified manner here, but this is the surface of the propellant and this is where the flame is located. The T x is T s is the surface temperature, T f is the final temperature, this x is the distance of the flame from the surface and this is the variation of temperature. The burning rate is given by this expression. Again the burning rate is estimated by energy balance similar to the process we have discussed earlier.

So, this is the burning rate is given by this expression. So, all the three frames are modeled as the single flame surface with the final temperature. T f T I is initial temperature of the ammonium perchlorate combustion which is appearing here, and the energy balance once again as I was mentioning the conduction plus heat of reaction is equal to the change in enthalpy. So, for this also it can be shown that r is equal to a P to the power n. So, similar functional representation is present only these values of a and n will be different, right for the different propellant or composite propellant, but the basic mechanism is like this and therefore, it satisfies this basic functional relationship as well. Now, let us see that how do we use this information for actual rocket design.

(Refer Slide Time: 38:51)



- Thrust produced by a rocket $F = C_F P_{c0} A^*$
- Mass flow rate through the throat $\dot{m}_n = \frac{P_{c0} A^*}{c^*}$
- Mass flow due to propellant burning $\dot{m}_p = \rho_p S_p r$
- Burning Rate of Propellant $r = a P_{c0}^{\,n}$
- Equating the mass flow through the nozzle and the mass flow due to propellant burning (for steady rocket performance)

$$P_{c0} = \left\{ \rho_p a c^* \frac{S_b}{A^*} \right\}^{\frac{1}{1-n}}$$

n should be small for reduced influence of parameters on stable operation

$$F = C_F S_b^{\frac{1}{1-n}} \left(c^* a \rho_p \right)^{\frac{1}{1-n}} A^{*\frac{-n}{1-n}}$$

$$n < \frac{1}{1 - \frac{\rho_g}{\rho_p}}$$

So, thrust produced by a rocket f is given by C F P c naught A star. CF is the thrust coefficient, P c naught is the stagnation pressure, and A star is the throat area. Mass flow rate through the throat is m dot n is given by P c naught A star c star, where c star is the characteristic velocity. We have discussed this in detail. I am not going into it again now.

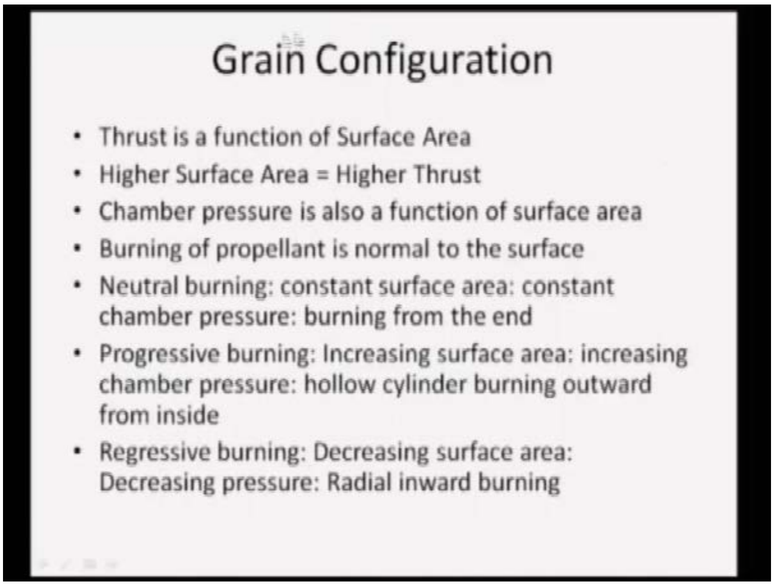
However, the mass flow rate due to the propellant burning is the propellant density times, the surface area of the propellant times the burning rate of the propellant. So, surface area of the propellant is given by SP, the burning rate of the propellant r.

On the other hand, as we have just discussed is equal to A P c naught to the power m because P c naught is my combustion chamber pressure. So, I can replace it here equating the mass flow through the nozzle, and the mass flow due to propellant burning for steady rocket performance. We can get this expression. By the way here this S b is the surface area of the propellant is same as this S P. So, these two are same S b and S P. Here I have written as S P because I just wanted to show that it is the propellant. Now, this is the burning area, S b is the burning area. So, these two areas are same. So, this is the expression just by equating this and this, I get this equation.

So, this is the chamber pressure as I like I was mentioning at beginning, the chamber pressure is dictated by the burning rate etcetera which now you can see here, where n is the exponent of this. So, this should be small for reduced influence of parameter on stable operation. Typically n should be less than this value that is 1 upon 1 minus rho g by rho p. It should be less than that. So, now, once we have this P c naught, we can put it back here in this expression and get the expression for the thrust. So, now, in this expression, we have the burning rate properties or the characteristics also embed included. So, this gives me the equation for thrust produced by a solid propellant rocket burning at a certain rate.

Now, the rate at which the propellant will burn depends on the surface area, right. So, as we can let us go back to previous slide. This S P or S b, they will dictate at which rate it will burn, right. So, therefore, identifying the effect of this surface is very important and that depends on the configuration of the grain.

(Refer Slide Time: 41:29)



Grain Configuration

- Thrust is a function of Surface Area
- Higher Surface Area = Higher Thrust
- Chamber pressure is also a function of surface area
- Burning of propellant is normal to the surface
- Neutral burning: constant surface area: constant chamber pressure: burning from the end
- Progressive burning: Increasing surface area: increasing chamber pressure: hollow cylinder burning outward from inside
- Regressive burning: Decreasing surface area: Decreasing pressure: Radial inward burning

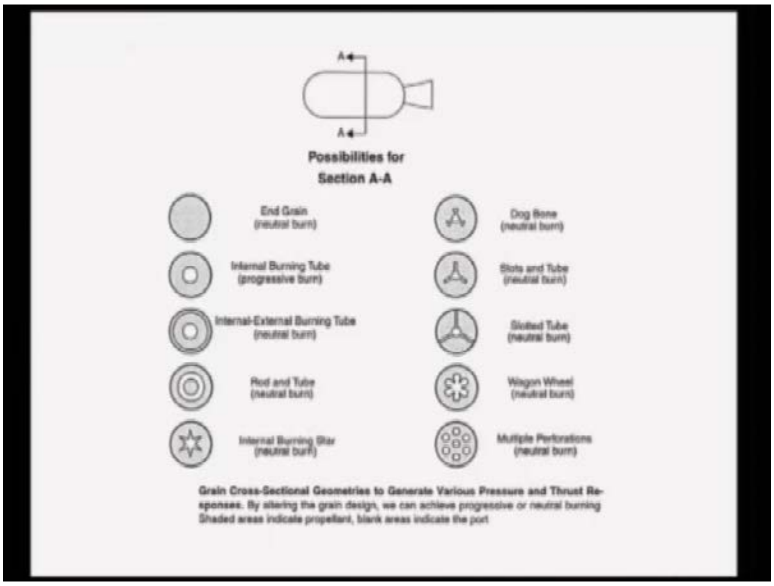
That is why grain configuration plays an important role. So, thrust is a function of surface area we have just discussed. So, higher surface area means higher thrust and chamber pressure is also a function of surface area. Burning of the propellant takes place is now we can have three types of burning. We can have a neutral burning, where the surface area is constant and because of that constant surface area, we get constant chamber pressure and typically burning from the end will give that because if surface area is constant, then the chamber pressure is not going to change. So, this is a neutral burning.

On the other hand, we can have burning called progressive burning in which the surface area, the burning surface area increases with time and as the surface area increases, this increases the chamber pressure. So, chamber pressure becomes a function of time. Typically this type of burning is seen in hollow cylinder burning outward from inside. So, if the combustion starts from the inside of hollow cylinder and burns outward, the surface area will increase and that will lead to an increase in chamber pressure.

Of course, it is very rarely seen regressive burning where we have a decreasing surface area and because of that a decreasing pressure. We know that we want to operate always at higher pressure. So, it is something very rarely used a decreasing pressure. This is if we have a radial inward burning, it starts to burn from the outer radius and burn inside.

That will give us a regressive burning. Now, with this background of grain configuration, let us look at some of the grain configurations which are typically used.

(Refer Slide Time: 43:07)

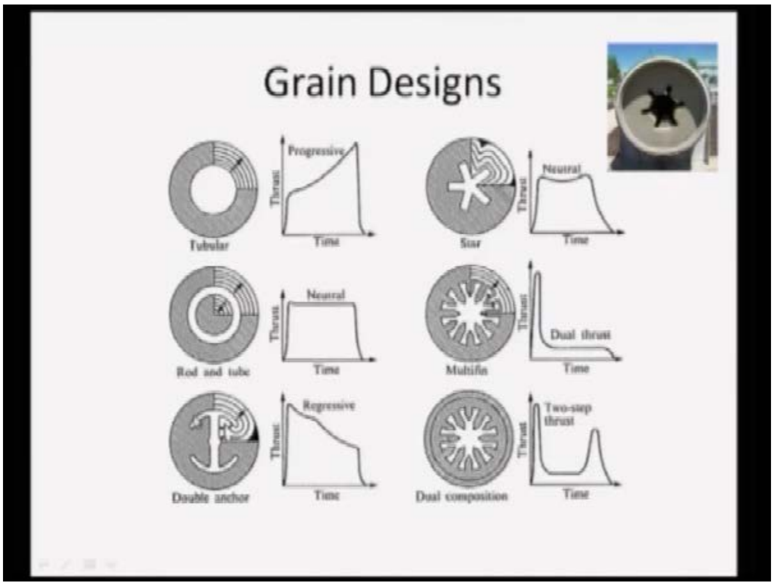


Grain Cross-Sectional Geometries to Generate Various Pressure and Thrust Responses. By altering the grain design, we can achieve progressive or neutral burning Shaded areas indicate propellant, blank areas indicate the port

So, here I have some schematic of certain grain configurations. This is for a neutral burn end grain completely filling up. Then we have a dog bone, where we have a shape like this. This will also give us neutral burn. This internal burning cube where we have a hollow cylinder going in is a progressive burning. So, it will start to burn from here. The area will increase. So, this is progressive burning and then we have slots and tubes also give neutral burning, internal external burning tube, neutral burning slotted tube, also neutral burning rod and tube, also neutral burning wagon wheel, neutral burning internal burning star, also neutral burning or multiple perforations.

So, as you can see here, more often than not we actually go for neutral burning. Why? It is because then my chamber pressure remains constant and if chamber pressure remains constant, my nozzle behaves properly. If the chamber pressure starts to change, your nozzle will not be behaving or producing the required thrust because the nozzle conditions inlet conditions keep on changing. Therefore, it is always advisable to go for a neutral burning, so that the chamber pressure remains constant. So, that is why you see that most of these configurations give us neutral burning.

(Refer Slide Time: 44:15)

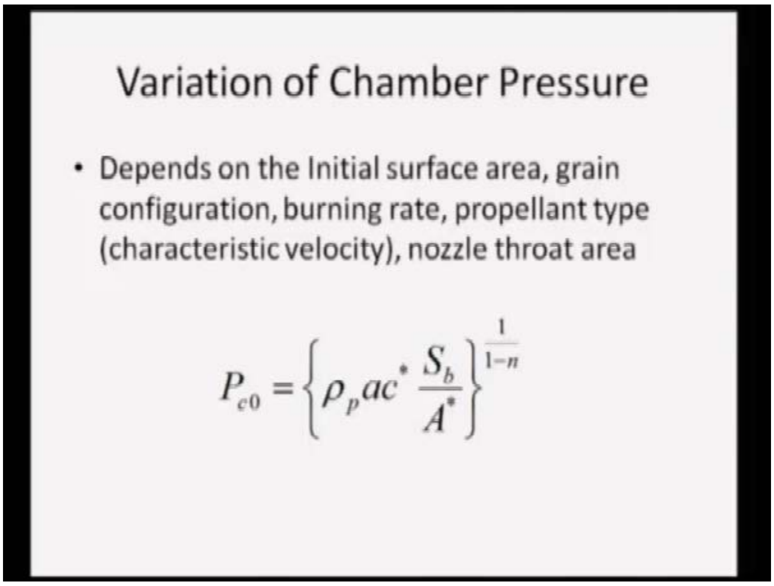


Grain Designs

Some of the grain designs are shown here. If you have tubular, the variation of thrust as you can see with time will change. If you have a progressive burning, the thrust will increase with time. On the other hand, if you have this configuration is a neutral burning for quite a bit of period like you can see here in this schematic, then you can have a rod and tube. Again a neutral burning for quite a bit of period of course in the initial and final stages will not be neutral. It is progressive and regressive, but otherwise it is neutral. Then sometime we need double thrust or dual thrust. As I was saying the thrust can be programmed in the grain design. You can see here this multi fin gives us a dual thrust. It is initially high thrust, then a lower thrust just because of this grain configuration.

How does this vary? It is because the chamber pressure varies and then we have a double anchor configuration. This gives us regressive burning and we can have a dual composition which gives us two steps thrust. So, by properly designing the grain, we can actually program the thrust history required to attain a particular mission. We can get different type of thrust at different time instance, so that is you can see here a different grain configuration will give us that.

(Refer Slide Time: 45:35)



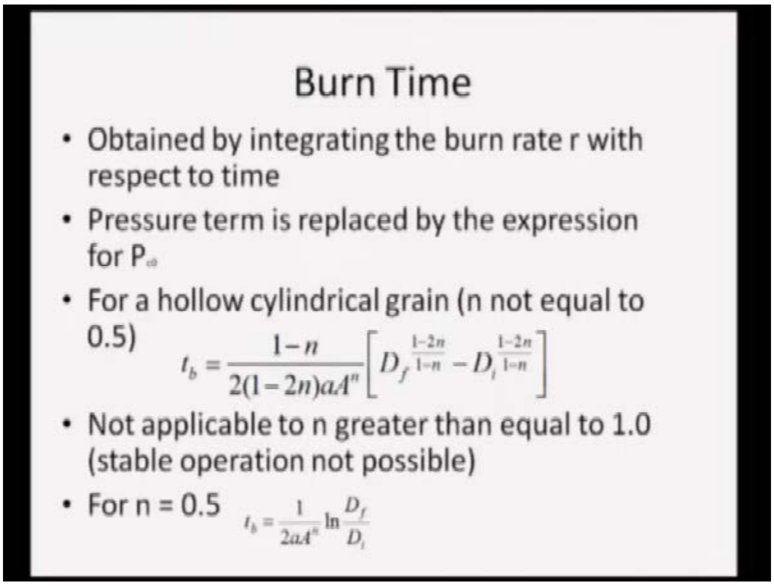
Variation of Chamber Pressure

- Depends on the Initial surface area, grain configuration, burning rate, propellant type (characteristic velocity), nozzle throat area

$$P_{c0} = \left\{ \rho_p a c^* \frac{S_b}{A^*} \right\}^{\frac{1}{1-n}}$$

Next, let us look at the variation of chamber pressure. The chamber pressure depends on initial surface area S b. We have just discussed about the grain configuration burning rate and propellant type. So, essentially the characteristic, the velocity will be dictating what will be the chamber pressure as well as the nozzle throat area. So, this expression we have already talked about gives us the chamber pressure variation with different parameters. Now, let us look at the burn time. How much time it will take to complete the burning a particular grain?

(Refer Slide Time: 46:05)



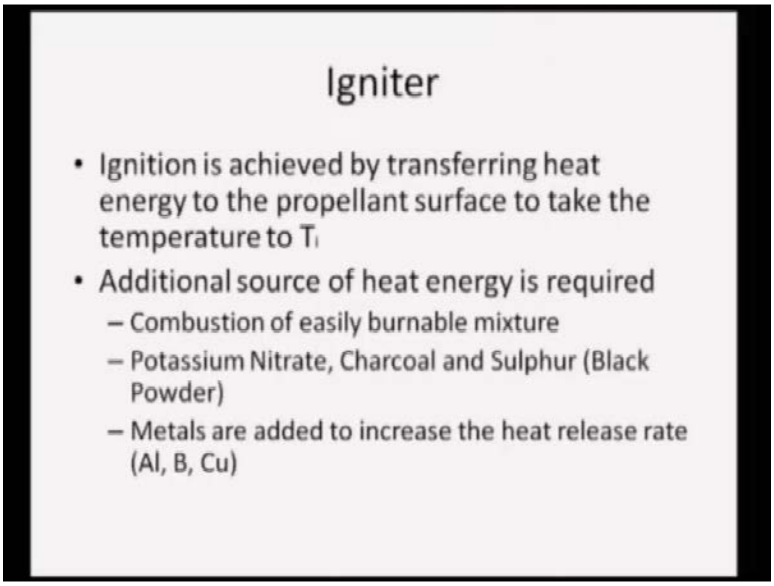
Burn Time

- Obtained by integrating the burn rate r with respect to time
- Pressure term is replaced by the expression for P_{c0}
- For a hollow cylindrical grain (n not equal to 0.5) $t_b = \frac{1-n}{2(1-2n)aA^n}\left[D_f^{\frac{1-2n}{1-n}} - D_i^{\frac{1-2n}{1-n}} \right]$
- Not applicable to n greater than equal to 1.0 (stable operation not possible)
- For n = 0.5 $t_b = \frac{1}{2aA^n} \ln \frac{D_f}{D_i}$

This is obtained by integrating the burn rate r with respect to time. So, pressure term can be replaced in the burn rate equation. The pressure term can be replaced by the expression for P c naught. So, for a hollow cylindrical grain where n naught equal to 0.5, we get this expression for the burning time. So, this is the time. It will take for it to burn out starting from the initial diameter D i to the final diameter D f. This will the time that will be taken by this entire grain to burn out completely.

So, this is the duration where the reaction is or the burning is taking place. This is not applicable to n greater than or equal to 1 and because of that stable operation is not possible. If n is greater than 1 because this gives us a stable operation for n equal to 0.5. This is the expression for the burning rate. Why it is different from this? It is because if you look at this expression n equal to 0.5 will make this term 0. So, T b will be infinite. So, therefore, it is singularity. There singularity is removed and we get this expression for the burn time if n equal to 0.5. So, this is the burn time that will be essentially a function of P c naught also now. So, this completes our discussion on the complete burning process.

(Refer Slide Time: 47:31)



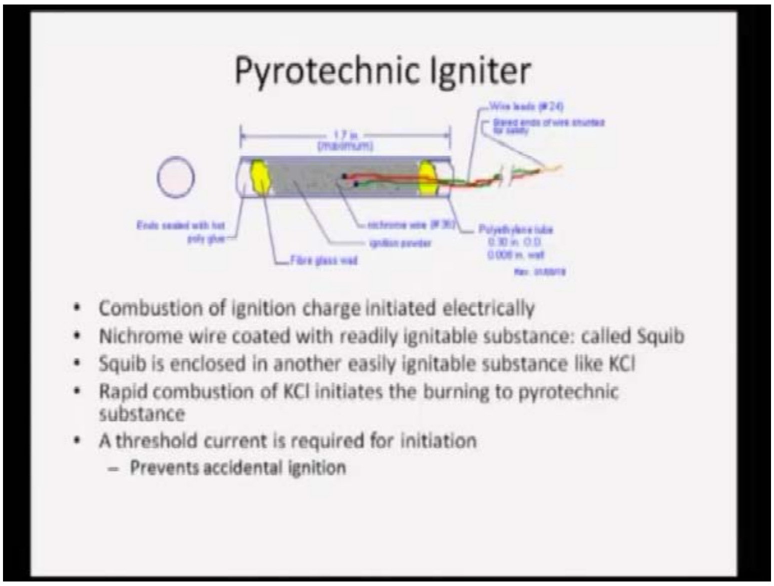
Igniter

- Ignition is achieved by transferring heat energy to the propellant surface to take the temperature to T_i
- Additional source of heat energy is required
  - Combustion of easily burnable mixture
  - Potassium Nitrate, Charcoal and Sulphur (Black Powder)
  - Metals are added to increase the heat release rate (Al, B, Cu)

I mentioned that one of the component is the igniter. So, let us now discuss the igniter. Igniter essentially helps in achieving the ignition process which is achieved by transferring heat energy to the propellant surface to take the temperature of the surface to T i which is my ignition temperature. So, that requires additional source of heat energy.

Now, this heat energy can be obtained by combustion of easily burning mixture, or it can have potassium nitrate, charcoal and sulphur like the black powder. We can also add some of the metals like aluminum, boron, and copper into it to give further enhance the heat release. So, igniter is something that is a device which will initiate the ignition process or the combustion process or burning process.

(Refer Slide Time: 48:14)



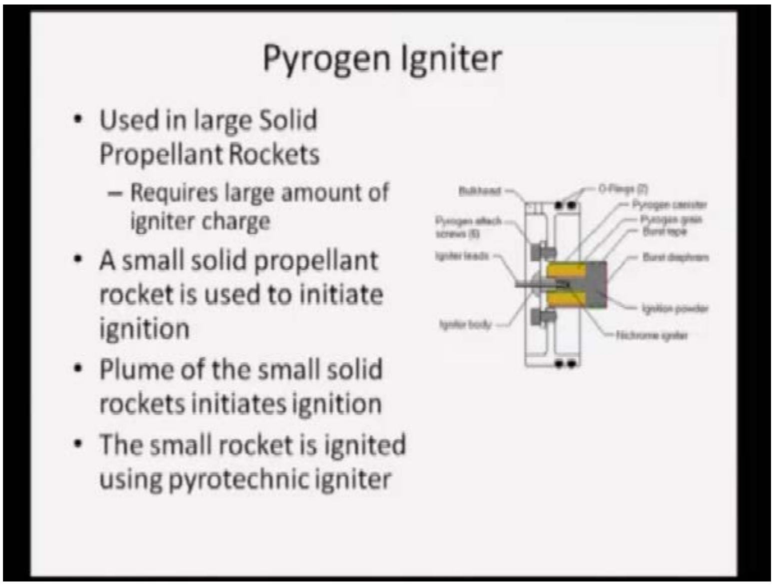
Pyrotechnic Igniter

- Combustion of ignition charge initiated electrically
- Nichrome wire coated with readily ignitable substance: called Squib
- Squib is enclosed in another easily ignitable substance like KCl
- Rapid combustion of KCl initiates the burning to pyrotechnic substance
- A threshold current is required for initiation
  - Prevents accidental ignition

So, these are typically type of igniters which are used. One is pyrotechnic igniter which is a long tube on one end and we have sea sealed with hot poly glue inside this. We have this ignition mixture or ignition powder. It can be gun powder and then we can see this nichrome wire is placed here, and it is connected to the power supply. When you supply electricity, it gets heated up and it starts to burn and then it burns at a rapid rate providing the energy to the propellant to burn. So, this is my igniter.

So, combustion of ignition is initiated electrically which is essentially a nichrome wire. This is also called squib. So, it is a squib ignition. Squib is enclosed in another easily ignitable substance like KCI rapid combustion. This KCI initiates the burning of this pyrotechnic substance which is given here. Now, why we need this is, there is a particular threshold current is required. Only then it is the ignition will start. So, it is also a safety device. It not only provides the ignition requirement, it is safety device. Unless we have that current, it will not ignite.

(Refer Slide Time: 49:39)



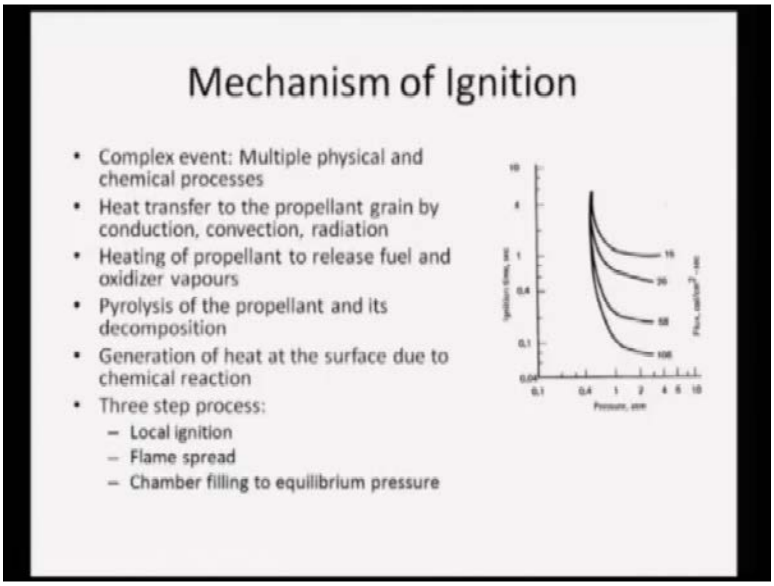
Pyrogen Igniter

- Used in large Solid Propellant Rockets
  - Requires large amount of igniter charge
- A small solid propellant rocket is used to initiate ignition
- Plume of the small solid rockets initiates ignition
- The small rocket is ignited using pyrotechnic igniter

So, this is the pyrotechnic igniter. It prevents accidental ignition also. It is most commonly used igniter. We can also have pyrogen igniter which is nothing but a small solid propellant rocket in itself. Pyrotechnic is separate. It is not a rocket pyrogen ignition. On the other hand, it is a small rocket in itself where we have everything. All the components of a rocket is a small propellant charge exigency. The ignition powder is this is the burst (( )). It will burst when the ignition pressure reaches a particular value and then it will start to ignite the entire process. So, this is used in large solid propellant rockets because it requires large amount of ignition charge.

So, a small propellant rocket is used to ignite, to get the initial ignition, and plume of the solid rockets initiates the ignition as you have seen here and the small rocket is ignited by pyrotechnic igniter. This is the pyrotechnic igniter sitting here and this is the small rocket and the different things is here present. So, this will be ignited by this and then this on the other hand will ignite the main rocket. So, that is the pyrogen igniter.

(Refer Slide Time: 50:32)



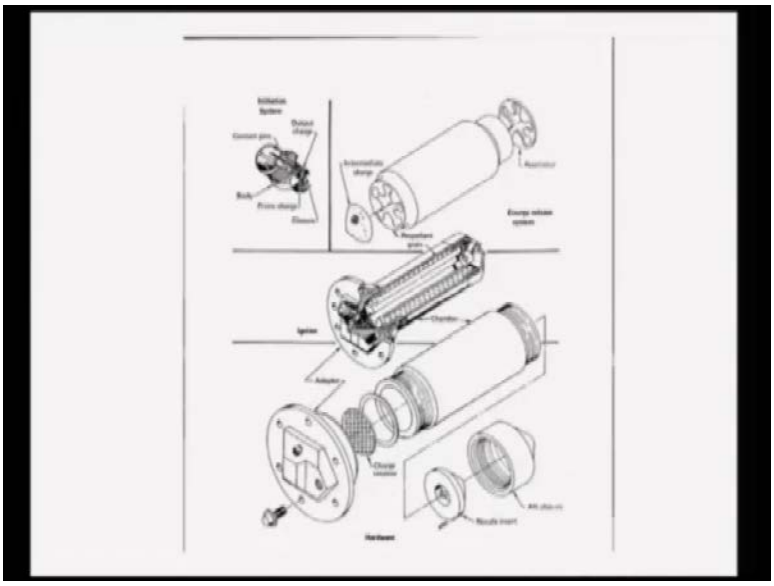
Mechanism of Ignition

- Complex event: Multiple physical and chemical processes
- Heat transfer to the propellant grain by conduction, convection, radiation
- Heating of propellant to release fuel and oxidizer vapours
- Pyrolysis of the propellant and its decomposition
- Generation of heat at the surface due to chemical reaction
- Three step process:
  - Local ignition
  - Flame spread
  - Chamber filling to equilibrium pressure

Now, how does ignition takes place? This is a very complex process is the multiple physical and chemical processes takes place. We have heat transfer to the propellant gain grain by the conduction conviction and radiation, then heating of propellant to release fuel and the oxidizer vapor and then pyrolysis of propellant and its decomposition, then generation of heat at the surface due to chemical reaction. So, all these must be present to give the proper ignition.

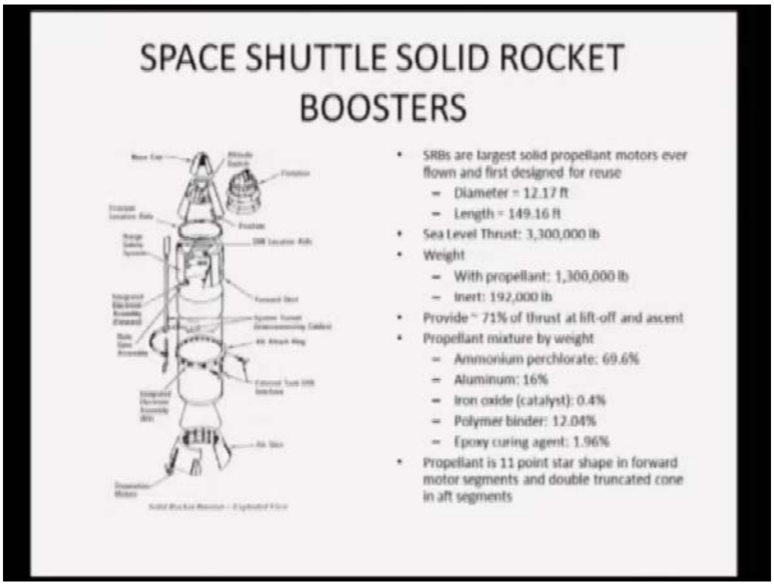
Essentially it is a three step process. First, we have a local ignition, and then the flame produced by this local ignition spreads. So, it is a flame spread and then finally, the entire chamber is filled to equilibrium pressure. When the ignition process is complete, we get equilibrium pressure in the entire chamber. Ignition time as you can see from here, it depends on the flux, heat flux. So, as the higher heat flux will give less ignition time, also the chamber pressure at higher chamber pressure we get less ignition time. So, if a higher pressure means the reactions will be faster, so we require less time for ignition.

(Refer Slide Time: 51:34)



So, now what I have here is a complete schematic of an actual rocket. You can see here this is the propellant grain, this is the igniter fixed in here, this is the propellant grain and then everything is put together. This is nozzle insert and aft enclose makes it the complete solid propellant rocket, this is a complete solid propellant rocket in parts. Now, one of the most widely known solid propellant rocket is space shuttle solid rocket booster.

(Refer Slide Time: 52:00)

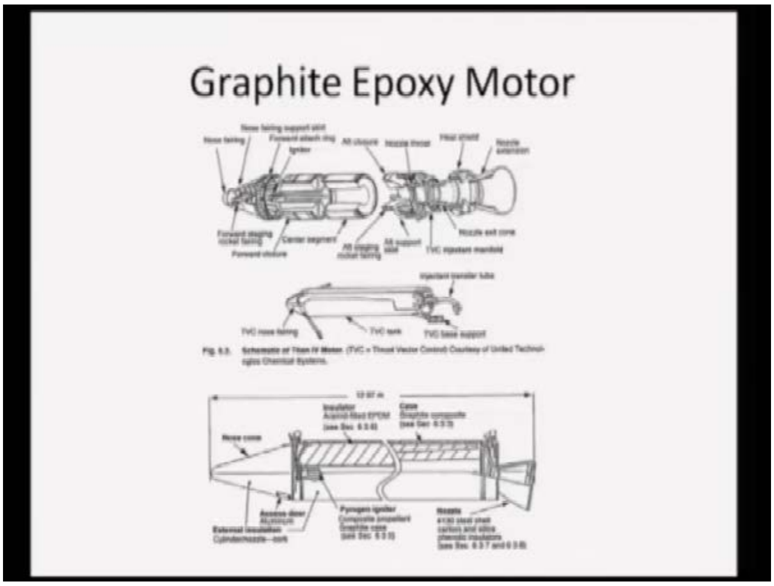


SPACE SHUTTLE SOLID ROCKET BOOSTERS

- SRBs are largest solid propellant motors ever flown and first designed for reuse
  - Diameter = 12.17 ft
  - Length = 149.16 ft
- Sea Level Thrust: 3,300,000 lb
- Weight
  - With propellant: 1,300,000 lb
  - Inert: 192,000 lb
- Provide ~ 71% of thrust at lift-off and ascent
- Propellant mixture by weight
  - Ammonium perchlorate: 69.6%
  - Aluminum: 16%
  - Iron oxide (catalyst): 0.4%
  - Polymer binder: 12.04%
  - Epoxy curing agent: 1.96%
- Propellant is 11 point star shape in forward motor segments and double truncated cone in aft segments

So, this is a space shuttle solid rocket booster with all its component. It is perhaps one of the biggest rocket ever made. SRBS is a largest solid propellant motor ever flown and its diameter is 14.17 feet, length is about 150 feet. It is a huge rocket sea level thrust. It produces 3.3 million pound and its weight with the propellant is about 1.3 million pound. This is a huge rocket which provides 71 percent thrust at lift off of the space shuttle. So, you can imagine how big this rocket is. The propellant mixture by weight, it has ammonium perchlorate, aluminum iron oxide polymer binder and epoxy cutting agent is the composite propellant, and the propellant is 11 point star shape in forward motor segment and double truncated cone in aft segment. It was two types of propellant grain that is used at two different locations. So, this is the full schematic of a space shuttle solid rocket booster.

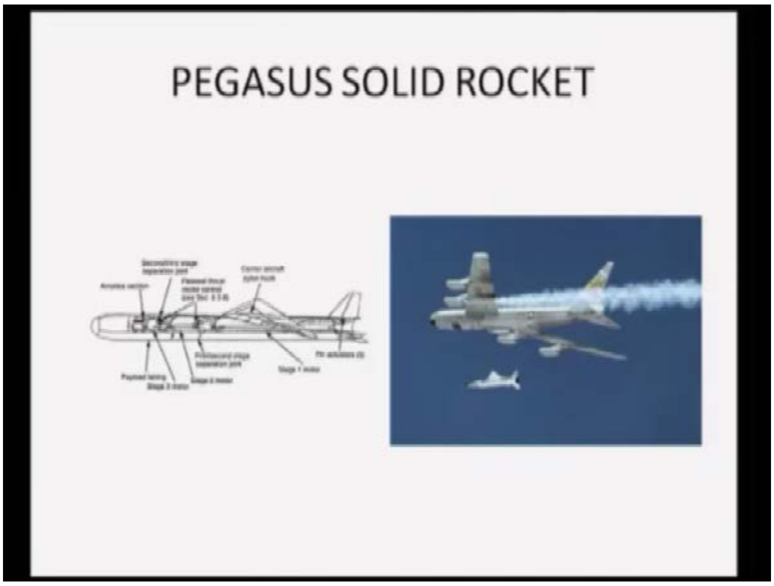
(Refer Slide Time: 53:05)



Graphite Epoxy Motor

We have another which is a graphite epoxy motor whose schematic is given here. Again we have a graphite propellant and then the igniter. This is a thrust vector nozzle and every component I will not go into the detail of that. You can see that is a different variant of the solid propellant rocket. Then another which was used is Pegasus solid rocket.

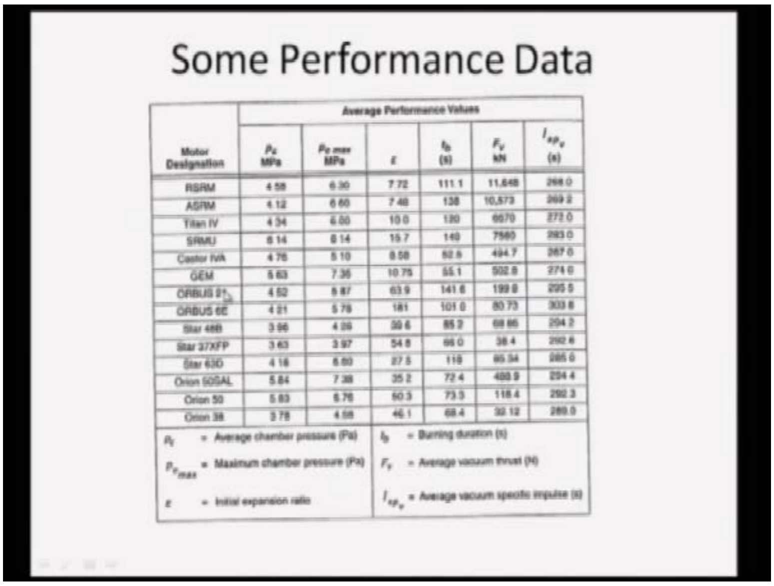
(Refer Slide Time: 53:26)



PEGASUS SOLID ROCKET

So, you can see the full Pegasus solid rocket picture here, and it is Pegasus being launched from here. So, this is the solid propellant rocket Pegasus.

(Refer Slide Time: 53:36)



Some Performance Data

Motor Designation	Average Performance Values					
	P_c MPa	$P_{c\,max}$ MPa	ϵ	t_b (s)	F_v kN	I_{sp_v} (s)
RSRM	4.59	6.30	7.72	111.1	11,648	268.0
ASRM	4.12	6.60	7.48	138	10,573	269.2
Titan IV	4.34	6.00	10.0	130	6670	272.0
SRMU	6.14	8.14	15.7	140	7580	283.0
Castor IVA	4.76	5.10	8.58	62.6	494.7	267.0
GEM	5.63	7.36	10.75	55.1	502.8	274.0
ORBUS 21	4.52	5.87	63.9	141.6	199.8	295.5
ORBUS 6E	4.21	5.79	181	101.0	80.73	303.8
Star 48B	3.96	4.29	39.6	85.2	68.66	294.2
Star 37XFP	3.63	3.97	54.8	66.0	38.4	292.6
Star 63D	4.18	6.60	27.5	118	65.34	285.0
Orion 50SAL	5.84	7.38	35.2	72.4	488.9	294.4
Orion 50	5.83	6.76	60.3	73.3	118.4	292.3
Orion 38	3.78	4.58	46.1	68.4	32.12	289.0

P_c = Average chamber pressure (Pa)

$P_{c_{max}}$ = Maximum chamber pressure (Pa)

ϵ = Initial expansion ratio

t_b = Burning duration (s)

F_v = Average vacuum thrust (N)

I_{sp_v} = Average vacuum specific impulse (s)

Some performance data is tabulated here for variant various motor designation, various chamber pressure and the burning time, the thrust and I s p. You can see that for the solid propellant, the maximum I s p is in this one ORBUS21 is 295.5. No sorry. ORBUS63 is 103.8. On the other hand, the maximum thrust is in this RSRM, right 116848 kilo Newton. That is a huge thrust being produced. So, in general, these are lower thrust and the chamber pressure is given here. So, this is the full data for most of the solid propellant rockets which are used widely, and as this is given just to give you an idea of what are the numbers of thrust and specific impulse, etcetera.

(Refer Slide Time: 54:42)

THANK YOU

- Rocket Propulsion, K. Ramamurthi, Macmillan Publishers India, 2010.
- ntrs.nasa.gov/archive
- www. wikipedia.org
- www.google.com
- http://www.nakka-rocketry.net

So, this brings us to the end of this lecture. I think I have over shooted the time. So, I want to acknowledge first of all the book by Doctor Ramamurthi and the some of the web pages from which I got the material. So, with this I stop here and in the next lecture, we will talk about the liquid propellant rocket which is another class of a chemical rocket and with that, we complete our discussion on chemical rocket.

Thank you.