Rocket Propulsion
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Module No. # 01
Lecture No. # 18
Factors Influencing Choice of Chemical Propellants

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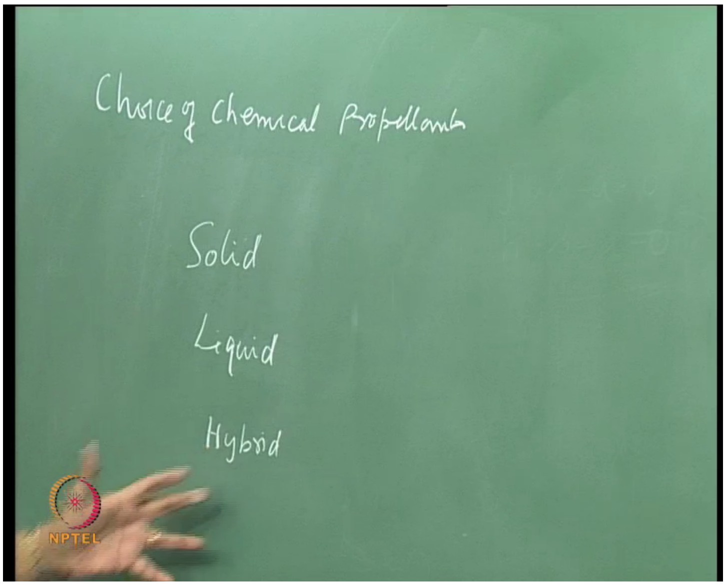

Good morning. In today's class, we will discuss the choice of chemical propellants. By choice I mean, the criterion what we need to follow. How we say this propellant is chosen as suitable because there are so many chemicals available. What are the chemicals, which we can use? We will see with respect to solid propellants, liquid propellants and any other form of propellants like hybrid. We will make a judicious choice and then go into details of the propellant used in a solid propellant rocket. We will then look at liquid propellant rockets and the other types of rockets.

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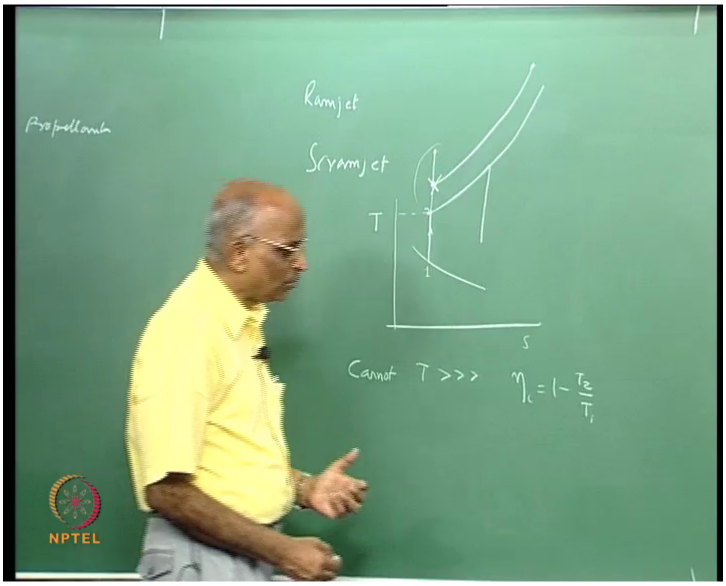

Before I get into the topic, I would like to clarify something from the last class. When we consider ramjets and scramjets, does dissociation play a role like for instance in rockets? Let us make a diagram of the performance of a scramjet or a ramjet on a T S diagram. What do you do? In the intake we, assuming an ideal condition, isentropically compress the air from a temperature one to two. Then, what is it we do? We add heat at let us say constant pressure and then expand the gasses again. We expand the gasses again in an ideal isentropic process.

Now, if we were to enhance compressing the gasses more and more, we would have the temperature after the compression, which is higher. If we increase the compression still further we end up in still higher temperature after the compression process. In other words, as we go to higher and higher temperature, the air will get dissociated as the temperature will be high. If the temperature is so high that we cannot add any more heat in the combustion process, we cannot have any useful engine. But the question is if we still increase the amount of heat addition, even though the temperature here is high, can we still have an engine, which develops thrust?

If we increase the heat addition to a very high value, we get intense dissociation. The chemical energy is not fully available, as completely burnt gases are not formed. Therefore, you do get some bounds of possible temperatures. Dissociation plays a role in the choice of the upper bound of temperatures in which some of these engines can operate. Let us keep it in mind. Dissociation is not very peculiar to rockets alone, but to all other engines. As per the ideal Carnot engine, we would like to have the high temperature to be as large as possible. That is when we get maximum efficiency.

If the highest temperature is increased, we get a higher efficiency because the efficiency of a Carnot engine is equal to 1 minus low temperature divided by the high temperature. If we can make the high temperature to be near infinity, we get a very higher value of efficiency. But to be able to achieve these temperatures would be difficult as the hot gas begins to dissociate. That means I will be using my chemicals or reactants very poorly. Let us keep in mind with respect to the restriction of high value of temperature.

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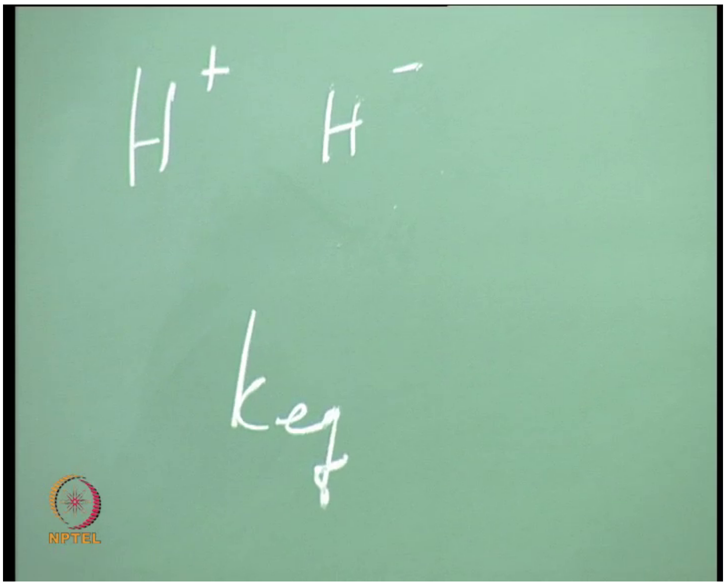

Another point which I also thought we must note is it is not only the species which are getting dissociated when we go to high temperatures; but we could form ions. We can get H^+ ions. We can get the plasma and we can write the equation for these plasmas using the equilibrium constant. We can also find out how much of the atoms get into different forms of excitation.

Having said the above, let us keep the focus of this class very clear. We want to examine the different choice of chemicals which can be used for solid propellants, liquid propellants and hybrid propellants. What are the points we have done so far which will help us?

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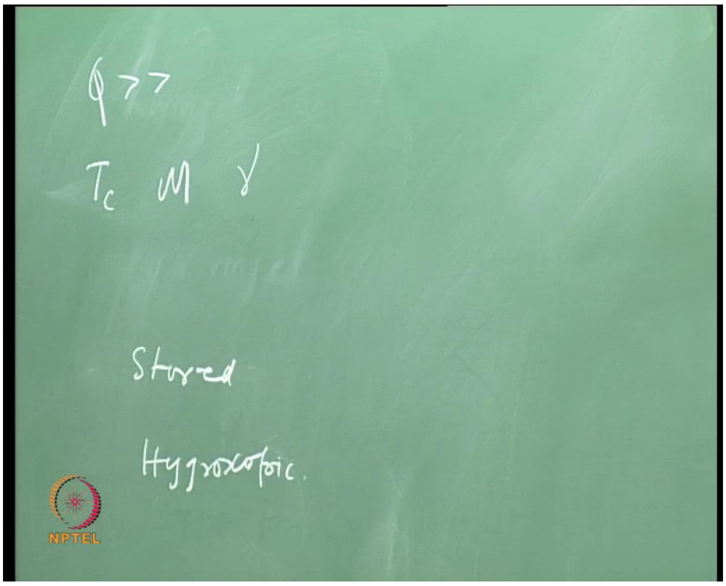

We would like to get a high value of heat release. We would like to get a high value of temperature. We would like to get a low value of molecular mass. Well, γ really did not matter very much.

Well, we addressed the above points earlier; but a chemical must be capable of being handled. That means chemical must be capable of being stored. It must not readily absorb moisture from the air; sort of being hygroscopic. It must be stable. It must not happen before I start using the chemical, it begins to spontaneously react. Therefore, there are other factors in addition to the performance which also plays a role and which we will be addressing as we study the different propellants.

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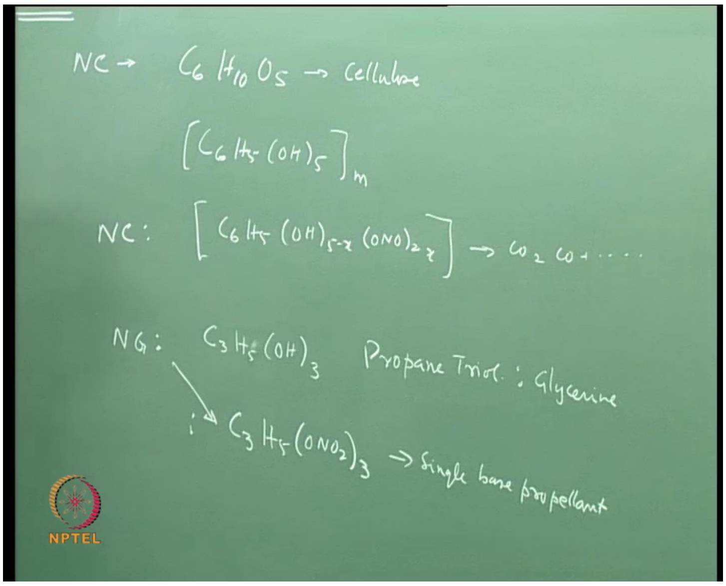

Let us get started with some details of solid propellants. We have already seen the different chemicals in solid phase. We said that we could use nitrocellulose, which we said was an explosive. What was the formula for nitrocellulose? We had cellulose as $C_6H_{10}O_5$. Cellulose is like paper. This could be written as $C_6H_5(OH)_5$ and this comes as a chain with m of them. For nitro cellulose, we substitute part of OH by the nitrate radical. That means out of 5 OH replace x by nitrate i.e., $(ONO2)_X$ and balance 5-x of (OH) to give $[C_6H_5\,(ONO_2)_x(OH)_{5-x}]_m$.

We had talked of this earlier in the class. We had said that this contains both oxygen and carbon, is terribly fuel rich, but can still dissociate to release heat. May be CO, may be other species could come out as products and this could be used as a propellant. In other words, we could call it as a single base propellant because it is a single substance which dissociates and does the job.

We could have nitroglycerine and we had said that nitroglycerin is little better than nitrocellulose because nitrocellulose had a very large and negative value of heat of formation. Nitroglycerin was better that way.

What was nitroglycerine? It was derived from propane C_3H_8. We take propane, and instead of 3 of hydrogen substitute it by OH to form an alcohol propane triol $C_3H_5(OH)_3$. This is also known as glycerine. We now substitute OH by nitro radial. That means we have $C_3H_5(ONO_2)_3$ and this is what is nitroglycerine.

Again in the earlier class, we found this is slightly oxidizer rich, but it contains O, C and H. It can be used by itself. Well, this could also a single base propellant. We call it as a single explosive propellant or a single base propellant just like nitro cellulose, which was fuel rich and could be used. In this case, it is slightly oxidizer rich. However, both nitrocellulose and nitroglycerine are seldom by themselves.

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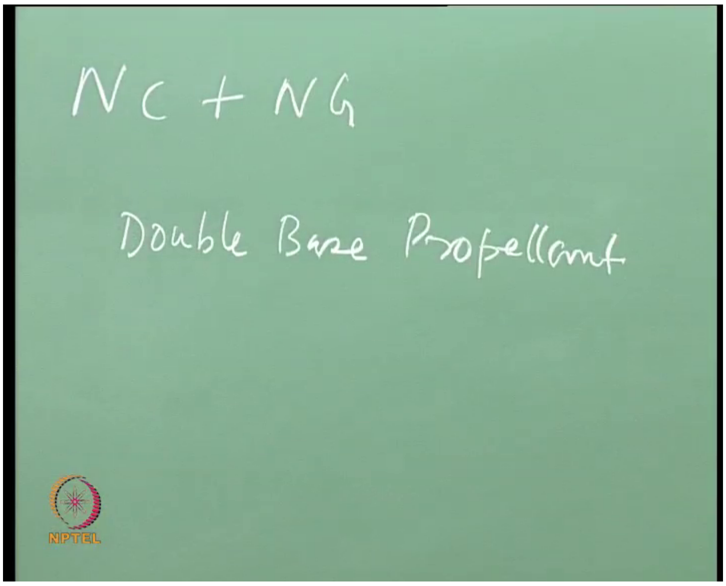

What is done is we mix nitrocellulose that is fuel rich and nitroglycerine that is oxidizer rich. That means you have two constituents or bases and this double base is what is known as a double base propellant. Therefore, the first solid propellant what we study, viz., a double base propellant.

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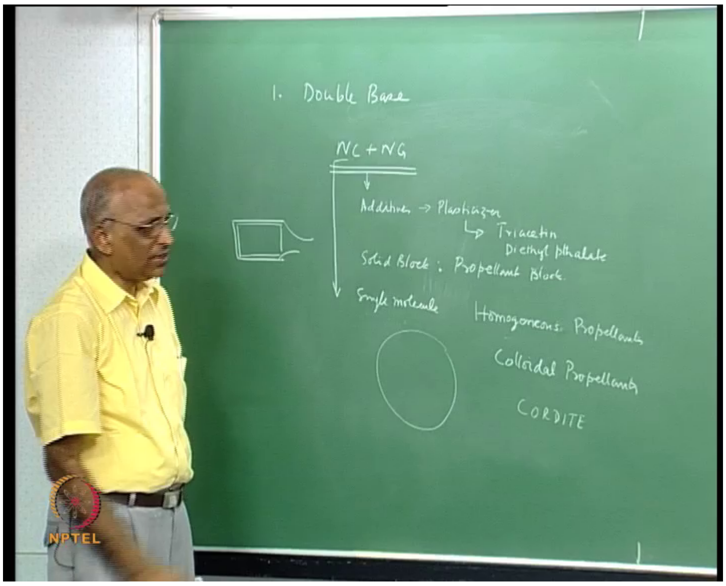

It consists of nitrocellulose and nitroglycerine. Nitrocellulose is fuel rich and nitroglycerin is slightly oxidizer rich and you get much better performance than if these were individually used as single base propellants.

How do we make it? Well, we take nitrocellulose. We put nitroglycerine in it, make it as a colloidal solution and add some more additives to it. What are additives? You know whenever we make a propellant; it is not just mixing and forming some hard solid material because we want it as a solid. What do we add? We add some plasticizer, so that it becomes more plastic. We add additives, which will make it flow so that we would like the two to mix together. We make it into a colloid, we cure it, make it as a solid block and this solid block what we call as a propellant grain or propellant block.

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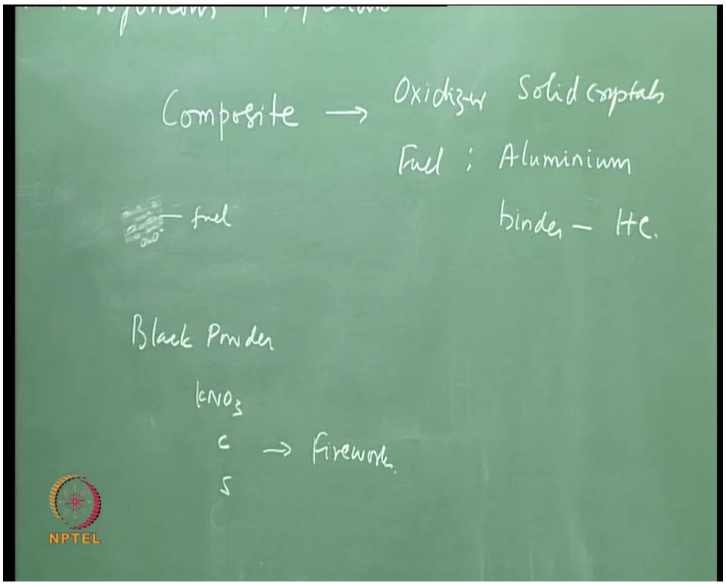

Let us list a couple of names of the plasticizers, which are added. Plasticizers used are triacetin, diethyl phthalate, etc.

What do you mean by a plasticizer? You know something which makes it a little more plastic. That means it makes it little less sensitive to impact. A rigid solid, when hit, forms a spark. The plastic sort of absorbs the impact, but at the same time, it gives some more consistency to it and therefore, the first propellant we say consists of nitrocellulose and nitroglycerin with a small amount of plasticizer, such that we can make a solid block. In this the nitrocellulose and nitroglycerin are mixed so perfectly that it is homogenous or molecularly mixed and the double base propellants are also called homogenous propellants.

The mixture is essentially something like a colloid. Colloid means suspension in liquid and therefore, this is also known as colloidal propellants. The trade name for a double base propellant is Cordite. We have a factory at Aravankadu in Nilgiris in South India, which specifically manufactures Cordite propellant for use in defense. Therefore, we say that the first solid propellant that we consider is the double base propellant of nitroglycerin and nitrocellulose.

Individually, these are single base propellants and together they form the double base propellant because you have two bases and we also add some amount of trace quantities of plasticizer and some more additives to make sure that the final product which is workable with suitable mechanical properties. I would like to machine the solid block to have fixed dimensions. I would like to have a rocket with this solid block or grain.

Let us go to the next type of solid propellant. There are only four types out of which the second one about which we will discuss is very widely used. Unlike a homogenous propellant like the double base propellant, that means everywhere it is exactly same and we cannot find out the differences in composition or otherwise, the second propellant is what we call as heterogeneous propellant. This is also known as composite as distinct from the double base propellants, which are uniform, which are something like a single molecule or uniform throughout. The composite propellants are heterogeneous. We add oxidizer in a solid form, we add aluminum again as a fuel and we glue it together using some particular fuel.

What do we understand by this? You know all of us have talked in terms of this black powder in the course on explosions. What was black powder? We had KNO_3, which was ground, we had carbon, which was ground and we had sulfur, which was also ground. We mixed the three, put gum and make it as a paste and use it when dry as an explosive for fireworks.

So also a composite propellant consists of a solid oxidizer, may be a fuel and may be the material that bonds these together. Material that bonds is called as binder and could is a fuel. Therefore, a composite propellant will consist of an oxidizer, which is something like a solid crystal say solid ground crystals, a fuel which could be aluminum, and a fuel which binds the solid crystals and aluminum together. The binder fuel could be something like a hydrocarbon.

Therefore, as distinct from homogenous propellants, a composite propellant consists of an oxidizer or fuel and this fuel glues the particles of the oxidizer together. Let us take some examples and the composite propellant and this will become further clear to all of us. Let us first see the types of oxidizers we could use in a composite propellant.

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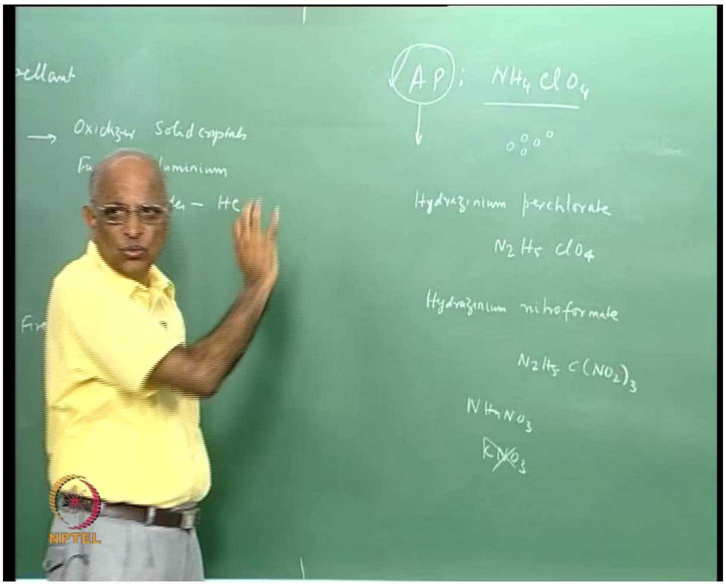

One of the oxidizer, which is very widely used is Ammonium Perchlorate. We call it as AP, and the chemical formula is NH_4ClO_4. Mind you, it consists of hydrogen, but amount of oxygen that it contains is higher so that it is still in oxidizer. It also contains chlorine as an oxidizer. May be this is why it is very widely used. It dissociates easily and it is not hygroscopic. It can be easily ground and can be made as small particles without any problem and that is why ammonium perchlorate is the most preferred choice of oxidizer for solid heterogeneous propellants.

We have still more energetic oxidizers like hydrazinium perchlorate. Let me get the chemical formula of it correctly. It should contain some hydrazine. That means it should be $N_2H_5ClO_4$. Another one is hydrazinium nitroformate and the formula for this will again be hydrazinium N_2H_5 into CNO_2 three times. You know these two solid oxidizers are being investigated upon, but the only oxidizer, which is widely used today is still AP. We have coated AP instead of having the raw AP, such that it is more easily processable. We will come back to this point a little later.

Therefore, we say, we could have choice of different types of oxidizers, but the oxidizer, which is generally used is AP. We could use Ammonium nitrate NH_4NO_3. It also contains oxygen, but it is hygroscopic. Not much energy as with AP. We could in fact use Potassium nitrate KNO_3, but again the potassium K has a larger value of atomic mass and therefore, it is not a preferred oxidizer. Therefore, whatever be the oxidizer for a composite propellant, ultimately what is being used today is only ammonium perchlorate. These are about oxidizers for composite propellant.

Let us take a look at the fuels, those that could be possible contenders and then, we will put things together and see what is involved in a composite propellant.

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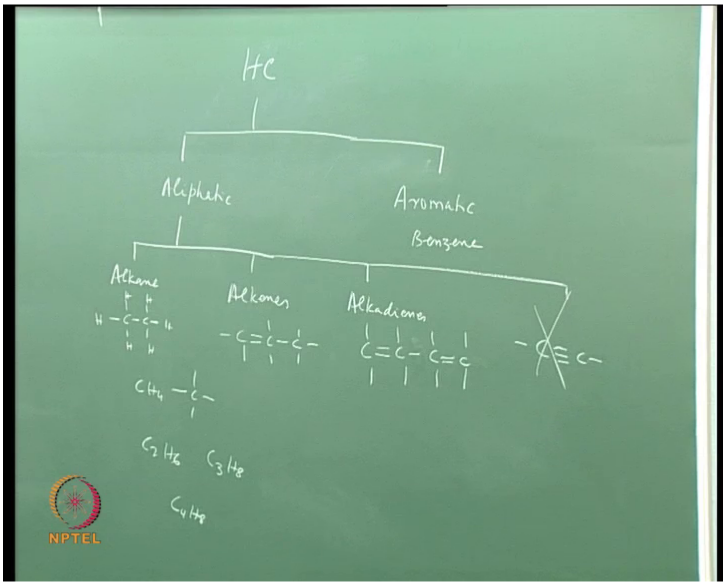

When we say fuel, it could be a hydrocarbon fuel. Let us see what are the different types of hydrocarbons and how we could use hydrocarbon as fuel.

Let us start with the classification of the hydrocarbons. We know hydrocarbons consist of aliphatic compounds and a little bit of review of organic chemistry is always useful. Aromatic hydrocarbons are those having a strong smell. Why does the smell come? Because you have the benzene molecule in it whereas aliphatic compounds are either straight chain or cyclic chain compounds. This could be either saturated or unsaturated. The saturated chain hydrocarbons are known as alkanes.

What do you mean by saturated or straight chain compounds? Carbon chains are all single bonds. The second we said is alkenes having one double bond and the remaining as single bonds. The third one is alkadiene, which have two double bonds. May be something like as shown in the slide. The two double bonds and a single bond here for the C atoms.

In summary, for single chain hydrocarbon structure, we could have single bonds, which are alkanes, one double bond along with the remaining single bonds that are alkenes and we could have two double bonds, which are alkadienes.

We could also have one triple bond like acetylene C_2H_2. These are known as alkynes. You know the triple bond is highly unstable and acetylene is an explosive. Therefore, we cannot use the alkynes. We are trying to find out how we choose the fuel in a propellant and that is why I am going through this. If you have alkanes, well the example is methane CH_4, C_2H_6 ethane, C_3H_8 propane. Mind you, all these are gases. I cannot use the gases anywhere, but there is a tendency today to liquefy the gases like liquid methane, liquid propane and use it for liquid propellants. We will come back to this at the end of this class.

Therefore, we say the alkanes are gases are not so useful for solid propellants. How about butane? Butane is also a gas C_4H_8. Let us take the butane form of alkanes, alkenes and alkadiene viz., butane, butane and butadiene.

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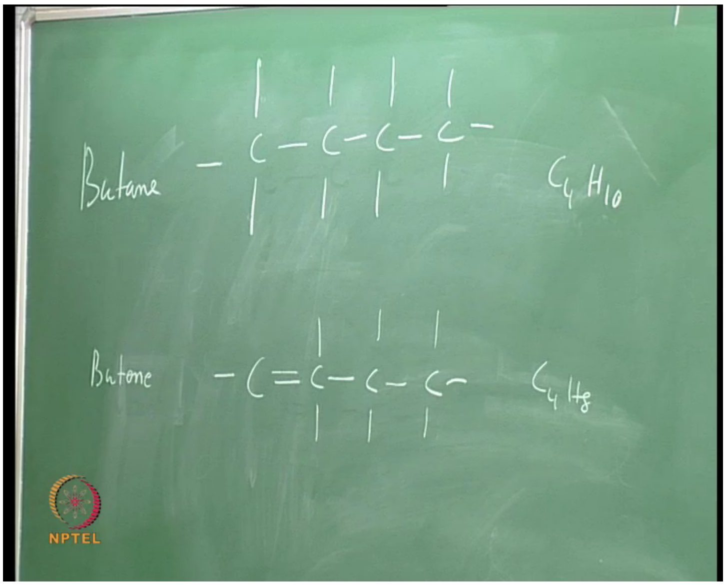

Butane has the formula is C_4H_{10}. This is the structure of butane. Butane is also a gas.

Let us go to the next form viz., alkenes. Well, I have double bond in butene C_4H_8.

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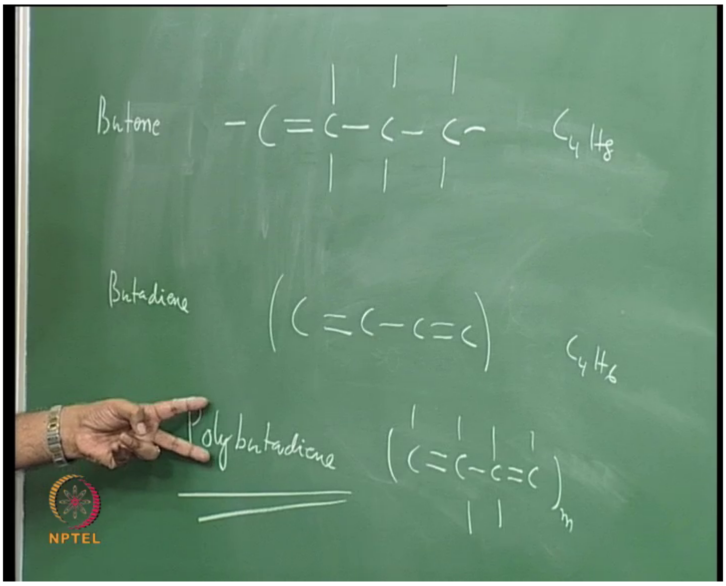

If I now have butadiene with two double bonds, well I have two double bonds and the formula will be C_4H_6 because I proportionally have decreased the hydrogen.

Now amongst these choices in aliphatic compounds; we are talking of the differences between alkanes, alkenes and alkadienes? You know this structure of butadiene is something, which you do not lose so much of heat of formation. See another thing which I forgot to tell you was we found that the heat of formation of methane was small negative value. The heat of formation keeps getting increasingly negative and therefore, very complex substances having large number of carbon atoms are not desirable.

But butane and butene are gases. With butadiene we are still with a simple hydrocarbon. With a poly butadiene molecule we make a closed chain and this is very widely used as a fuel. But poly butadiene is just carbon with hydrogen and to be able to form a good fuel out of poly butadiene, we alter the end chains. We now come to the actual fuel that we use as the binding agent. I want to make it into a good polymer, which has a long chain which can embed the oxidizer particles in it.

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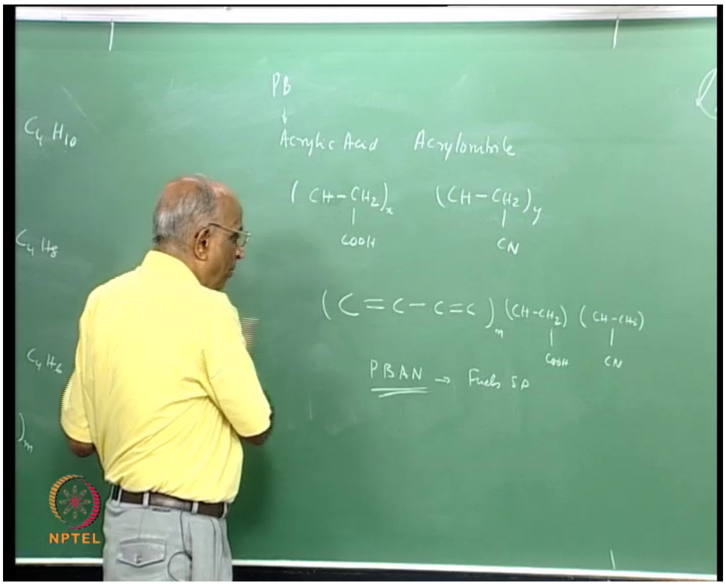

We take these poly butadiene whose structure we have just seen. Butadiene is a linear chain. It can stretch freely. I need to make it a little strong, so as that it can hold things together. Therefore, I add something like acrylic acid and acrylonitrile at the ends of the chain.

What is acrylic acid? It is $CHCH_2COOH$ giving carbo oxalic acid. The component Ch CH_2 is may be x times as shown. This is what acrylic acid is. Similarly, acrylonitrile is $CHCH_2CN$. May be y molecules of acrylonitrile. We do have this chain of poly butane: C C C C is a polybutane as shown with m molecules of it of it; at the end of the chain we add acrylic acid $CHCH_2COOH$ may be a few of them, then we add $CHCH_2CN$ viz., acrylonitrile. What does this do? Though something like a chain, the COOH and CN cross link it and give it rigidity in the lateral direction. We thus have poly butadiene acrylic acid acrylonitrile.

That means, we add the acrylonitrile and acrylic acid at the ends of the poly butadiene chain. I call this as PBAN - poly butadiene acrylic acid acrylonitrile and this is one of the fuels which are used for solid propellants. You would have read about it. PBAN is used in the space shuttle and in the huge solid rockets. Why it is used? It is possible to make it as a binder and it is possible to have it with more hardness and strength. This is one way that we use the poly butadiene.

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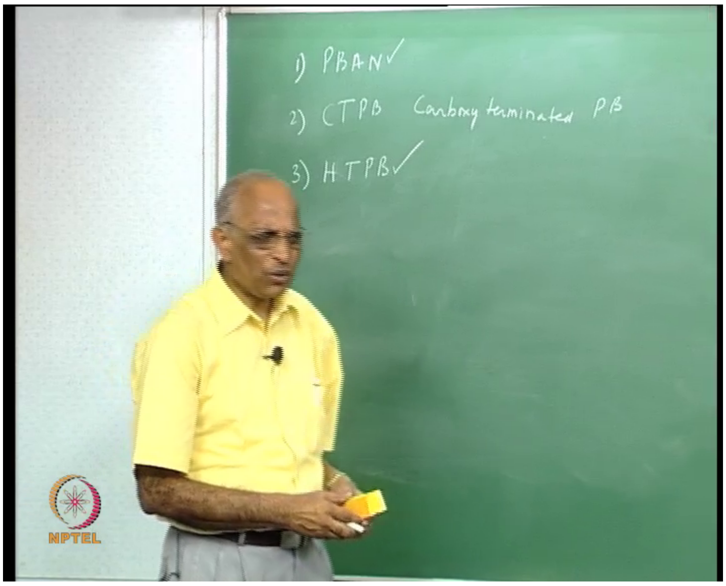

Therefore, the first fuel for solid propellant is poly butadiene acrylic acid acrylonitrile which we call as PBAN. PBAN is hard due to the cross-linking. We also see that it has lot of inert nitrogen atoms in it. If is it possible to somehow get rid of nitrogen, we could have a better fuel. Just substitute the end groups by the carboxylic acid namely, the acid part of it. That means, I terminate the poly butadiene with a carboxylic acid. This type of chain termination of poly butadiene is known as carboxy terminated poly butadiene (CTPB). That is the second hydrocarbon fuel.

There are not many variants: just some two or three of them. You know all what we have done is we removed the acrylonitrile part of it, keep the carboxyl acid here and stop the chain here. May be it gives little better properties and has more energy than PBAN propellant; but the choice for major booster today is still PBAN. Let us see whether some improvements in CTPB are possible.

The question is why not have a poly butadiene in which we do not terminate the chain with COOH, but we just put OH at the ends. We put OH as shown in the slide. In other words, we have hydroxyl radicals which are used at the ends of the chain. We have poly butadiene C C C C again. May be n molecules of it in the chain. At the end of the chain, we put hydroxyl radical and we call it as hydroxy terminated poly butadiene (HTPB).

The advantage of using OH is that more hydrogen is available. It is much lighter, stronger and is more energetic. Therefore, the most popular propellant today or rather the most popular fuel for propellant is HTPB. The reason being is more energetic, but for boosters, especially for very large boosters, we still find PBAN continuing to be used.

The most popular fuels are PBAN and HTPB and we must be aware of the reasons. Yes. HTPB is more energetic because it contains H compared to C and N. But basically we have the poly butadiene chain, which is terminating in these type of radicals. These are the type of fuels what we use.

In fact, HTBPB is very widely used in the tyre industry. There are one or two exotic fuels, which are being talked presently. Fuels, that we should be aware of.

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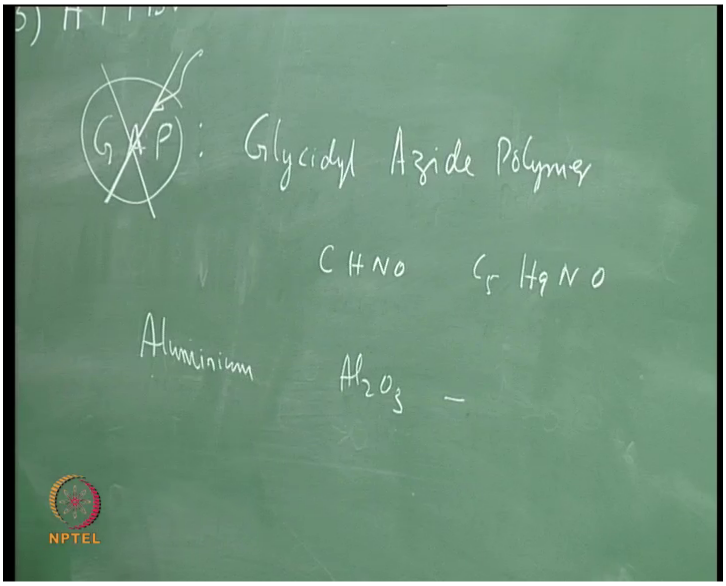

One is GAP, known as Glycidyl Azide Polymer and this has a formula something like CHNO. In different proportions, it has been tried something like C_5H_9NO. But we must keep in mind that GAP contains little more hydrogen than even HTPB. The current line of research is to increase the energy content of the fuels. How do you increase the energy content? Have more hydrogen on the lines of hydroxyl terminated poly butadiene.

The oxidizers for composite propellant could be AP. The fuels could be something like PBAN, CTPB, HTPB or GAP. We could also use aluminum powder as fuel. What is the advantage of aluminum powder? It could form Al_2O_3 in the products. We said Al_2O_3 has a very large negative value of heat of formation and we could increase the energy release in the combustion of solid propellants.

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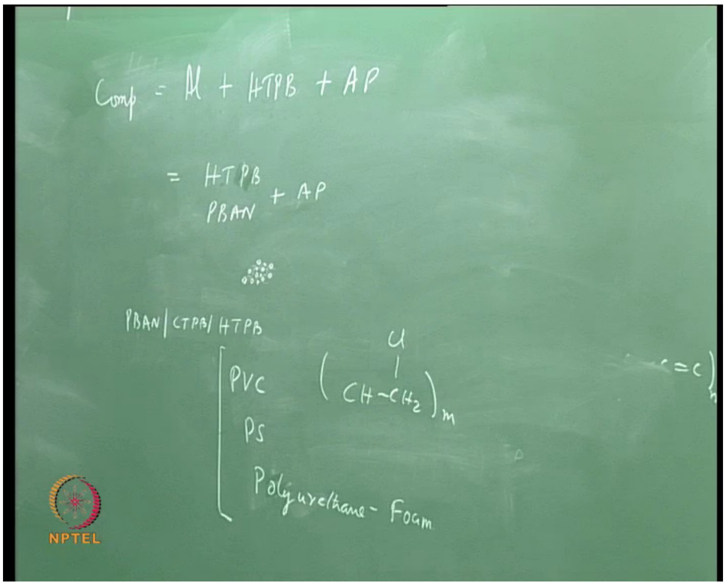

Therefore, a composite propellant basically consists of these three constituents. Aluminum powder, which we said is a fuel, a binder, such as HTPB as a fuel and AP for the oxidizer. The fuel binder is also used for binding aluminum and AP crystals. This is what constitutes a composite propellant.

In the absence of aluminum, the solid propellant could still consist of HTPB or CTPB or PBAN plus ammonium perchlorate. These are what are called as composite propellant because ammonium perchlorate comes as crystals, small spheres, or particles and this you bind together using the binder fuel. This is a non-aluminized composite propellant. If we add aluminum powder to it, we get this particular aluminized composite propellant. These are the composite propellants.

So, whenever we talk of composite propellants, we have in mind something like a polymer, ammonium per chlorate and may be some metal powder. It may not always have a metal. If you want more energy, we add a metal. With metal in the propellant, we have high temperature exhaust and the plume becomes very noticeable. Radar can observe it and therefore, for strategic purposes either a double base or some other form of propellants, which does not have such thermal signatures are used. We will take a look at some of the requirements.

In the past, instead of PBAN or CTPB or HTPB, polyvinyl chloride PVC has been used as a fuel. What is PVC? It consists of $CHCH_2$ with Cl as a large chain, but these are not energetic. Nowadays, it is not used. People tried poly sulphide, people tried foam, which is polyurethane. These have been tried, but these are all very low energy fuels and therefore, it is not used significantly. What is used is essentially HTPB, PBAN and to a certain extent CTBP.

Therefore, we summarize the second form of propellant as a composite propellant and it consists of a composite of oxidizer particles bound by fuel. May be metal particles like aluminum and a binder or a polymer, which keeps the composite together.

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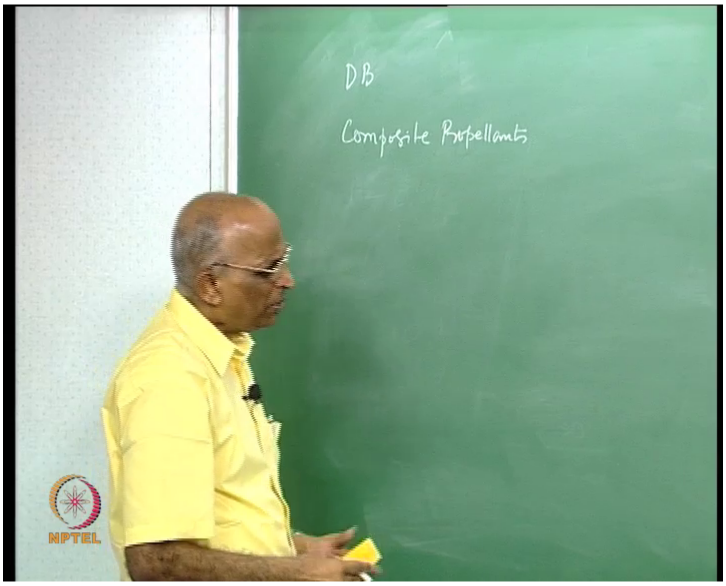

Therefore, we talk in terms of double base propellants and composite propellants. With composite propellants, there is something about particle sizes that we should know.

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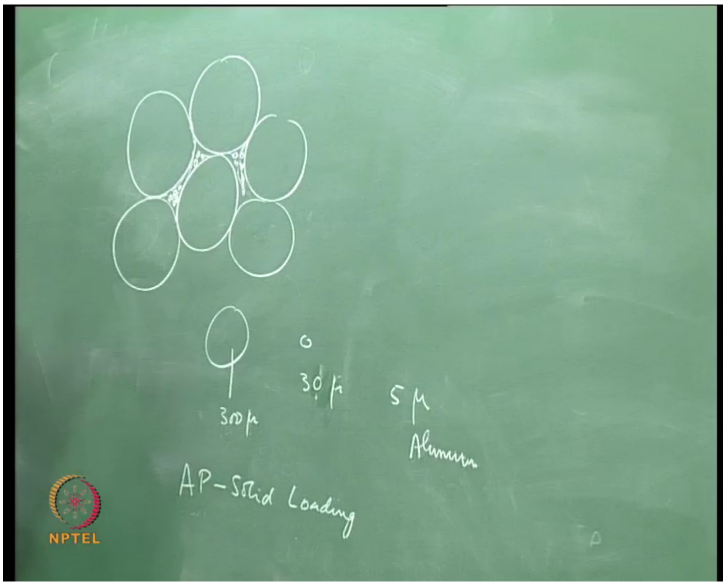

We have oxidizer particles in the propellant. Let us presume that we have spherical oxidizer particles. We have AP as shown in the figure. If we have a single size of AP, the amount of AP that can put together in a given volume will be small whereas, if I can have two sizes of particles one large and the other small, the smaller one can occupy the gap between the large one and the loading of AP can be increased. Let us say we have AP size of let say 300 microns. Then, if we try to fill with AP and we have binder, which binds all these particles together, it is going to bind it like this. Here I have polymer as shown. The amount of AP, which we can put in the propellant is restricted. We call the amount of AP in a solid composite propellant as solid loading in a propellant.

Now, instead of having say 300 micron size of AP, we make AP of two sizes mainly, we make 300 micron size and another one as 30 micron size; then, the small particles can be put over here in the gaps. That means, we can increase loading of AP in the propellant. Therefore, in almost all the composite propellants that we use today, we just do not use a single size of AP, but we use bi-model size typically between 300 and 30 microns. Why it is used? I want to increase the amount of AP as much as possible and when we use aluminum; aluminium is even smaller size, typically around 5 micron size of aluminum.

Why aluminum? Aluminium is again a solid. I can improve the loading of solid and therefore, I can have a dense propellant as it were and this is all about composite propellants.

The other two types of solid propellants in are derived from these two. We say composite modified double base propellant. We have already seen double base propellant is nitrocellulose and nitroglycerin.

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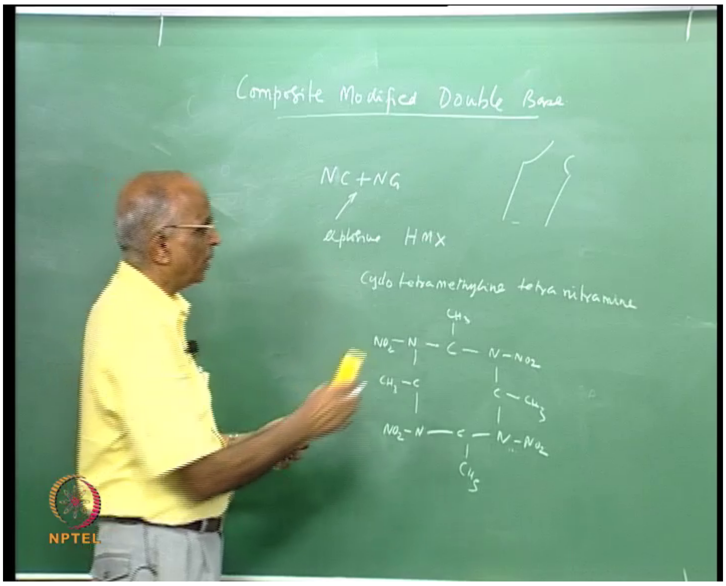

Supposing, we want to increase its energy. We add oxidizer ammonium perchlorate used in composite to double base propellants and make it more oxidizer rich. We could also add explosive to enhance the energy and the explosive we add is something like an explosive known as HMX. What is an explosive? It consists of fuel and oxidizer together. This HMX consists of something like cyclo tetra methylene tetra nitramine.

HMX stands for Her Majesty's Explosive because it came from UK. It consists of a box like structure with chain C CH_3 . You have N here and NO_2 . The methylene radical CH_3 with C and you have NNO_2. This is just an explosive and I do not think we should spend much time on it. All what you do is you add a HMX to a double base propellant. It becomes composite of a double base and this particular HMX explosive and this is also known as composite modified double base propellant (CMDB).

It is used for strategic purposes in the defense because they would like to have their missiles, which are more energetic than double base propellant. They would like to have properties of the propellant, which can be modified as per their requirement.

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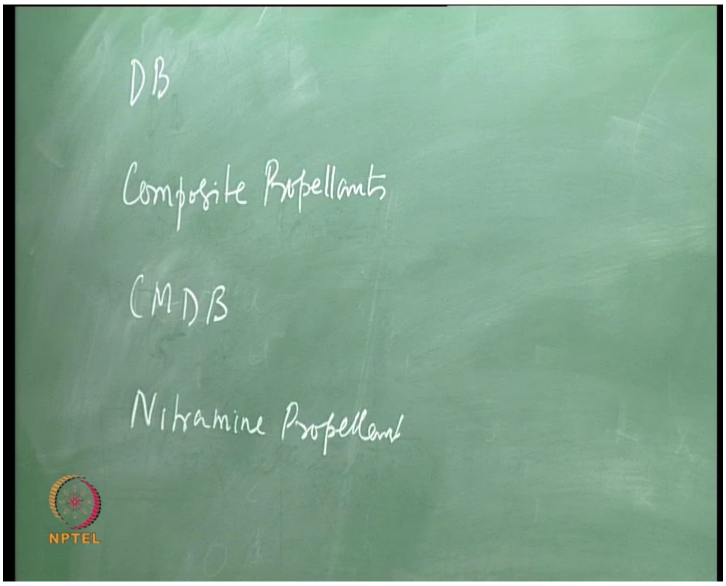

Therefore, the third propellant we say is a mixture of a double base and AP or an explosive.

The last type of solid propellant is what we call as nitramine propellant. You know all these propellants have distinct characteristics. You know why? They have a burn rate that changes with pressure and this varies with the type of propellant. We will consider this when we study the burn rate of solid propellants. We are just trying to take a look at what are the constituents of the different solid propellants and what are these different solid propellants.

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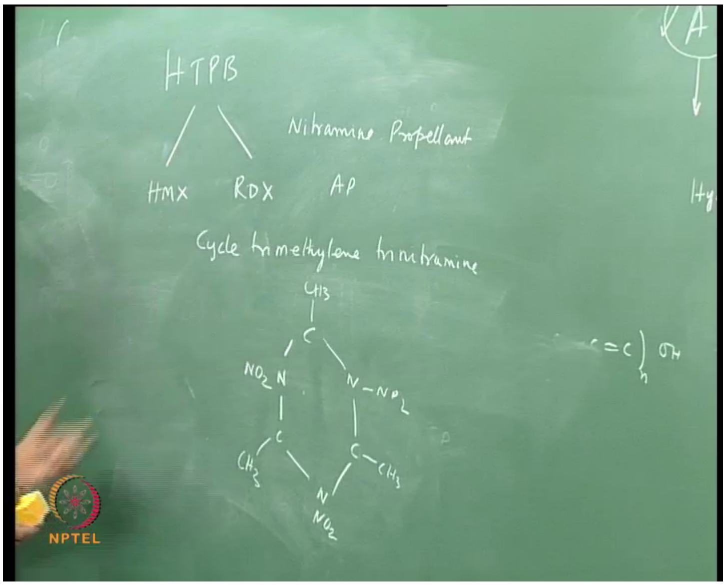

Nitramine propellant has a binder like HTPB which is a polymer. To this is added HMX which is an explosive or a slightly less energetic explosive like RDX which is cyclo tri methylene tri nitramine. What is the difference in structure? It is tri therefore, you have three of CCH_3, three of NNO_2.

Therefore, you add an explosive into the HTPB binder and what you get is a nitramine propellant. What is the advantage? See HMX is fuel rich, HTPB is fuel rich, therefore what happens is you do not get high temperature, but it is able to generate gas at low temperature and still propel the rocket. Therefore, an enemy cannot see that a rocket is going up because he uses radar to see the temperature of the plume. Therefore, each of the propellant has its own advantages plus the burning rate will change. We will look at it when we deal with burn rate of solid propellants.

In addition to adding HMX, RDX known as Research and Development explosive which is cyclo tri methylene tri nitramine is also used. You add almost 80 to 85 percent of these explosives to the fuel binder. We find that AP is also being added to give AP plus HMX or RDX and HTPB to give nitramine propellants.

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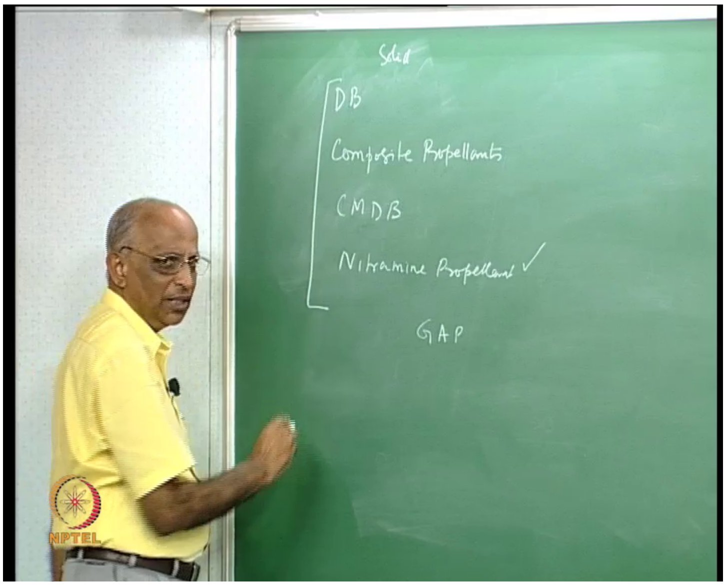

The research in propellants is on fuel GAP viz., glycidyl azide polymer since it has more hydrogen and is a more energetic fuel. You add HMX or RDX and it could not therefore be only HTPB, but glycidyl azide polymer (GAP), which could also be used instead.

We will not get into too much of the details because our main concentration would be the composites, may be the double base propellants. How they burn and how they are applied in rockets. Therefore, we say solid propellants essentially consists of double base, composite, composite modified double base and nitramine propellants. We will look at their characteristics when we study the solid propellant rockets.

Let us now move to liquid propellants. They are extremely simple, much simpler than what we talked in terms of solid fuels and oxidizers and they are classified in a slightly different way. We do not classify them into four such categories such as we did with solid propellants.

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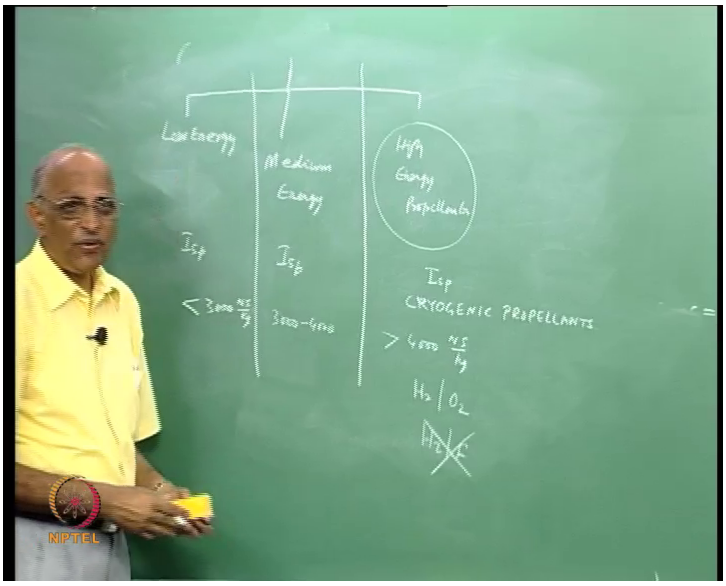

Liquid propellants are categorized into three categories. These are low energy propellants, medium energy propellants and high energy propellants.

May be by now you can tell me which will be high energy and low energy. Energy is a misnomer in rocketry because it is not only energy, which is important, but a low molecular mass is also important. We had observed that hydrogen and oxygen produces products with a low molecular mass, even though the energy may not be high yields high values of Isp. When we say high energy propellants, we always mean high Isp propellants. Similarly medium energy and low energy propellants imply medium Isp propellants and low Isp propellants respectively. Propellants, which have sea level Isp less than 3000 Newton second / kilogram are known as low energy propellants. The propellants having Isp between 3000 and 4000 Newton second / kilogram are known as medium energy propellants and those in excess of 4000 Newton second by kilogram are known as high energy propellants.

Well! hydrogen oxygen combination is by far the best from Isp point of view and therefore, the high energy propellants are hydrogen and oxygen. Perhaps hydrogen and chlorine would also be good. Yes, it is even more energetic, but chlorine is highly reactive and therefore, it was tried in one rocket mission and dropped thereafter. But hydrogen and oxygen cannot be used as room temperature as they are gases. It has to be liquified by reducing the temperature to low values. Hydrogen liquefies at 20 Kelvin while oxygen liquefies at 80 Kelvin. Being liquids at these low temperatures, wherein they are used, we call these high energy propellants as cryogenic propellants. This is because, they have to be kept as liquids under refrigerated conditions at cryogenic temperatures (less than about 123 K) and we call them as cryogenic propellants.

Therefore, if we want to make a missile, I cannot use a cryogenic propellant because a missile must be ready for launch any time. We cannot wait during a war. Enemy can strike at any time. Therefore, these cryogenic propellants are normally used for launch vehicles in which you can fill the liquid propellant slowly and with care as you want. You have all the time in the world, but if you want to have propellants that can be readily stored and used, we need to look at other fuels and oxidizers. Let us take a look at some of the low energy propellants first and then address the medium energy propellants.

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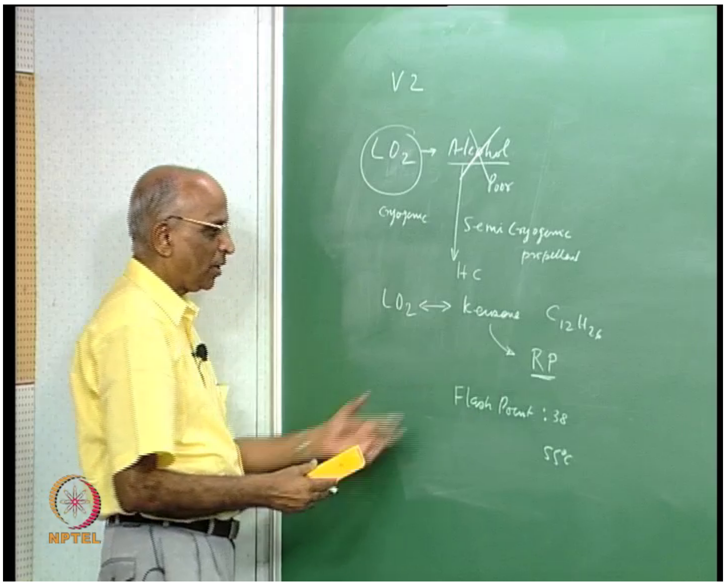

What are low energy propellants? Low energy we said those having specific impulse less than 3000 Newton second per kilogram. Let us put the names of a few propellants - few of them. All of us had have heard of V 2 rocket which was the first rocket ever made and it was by the Germans around 1945 during the second world war. It used liquid oxygen and alcohol. The alcohol is ethyl alcohol and ethane is C_2H_6. May be you remove some of the H and put OH in its place. You have ethyl alcohol. But it is very poor performing, very low in specific impulse when used with liquid oxygen. The liquid oxygen is a cryogenic liquid while alcohol is liquid at room temperature.

Therefore, you have a cryogenic oxidizer with a room temperature fuel and therefore, this combination will be a semi cryogenic propellant. It is not totally cryogenic. Why does it have poor properties? Alcohol contains oxygen also because you have OH. That means it is not a good fuel. Why not use a better fuel like hydrocarbon? Why not use kerosene? Kerosene has molecular formulas something like dodecane $C_{12}H_{26}$ as a linear chain. It is a much better fuel and therefore, the present trend is used semi cryogenics consisting of liquid oxygen and kerosene together. Kerosene forms soot and it cokes when heated. It can evaporate quite fast. It is volatile. We would like to make it suitable for rocket and the kerosene, which is modified by adding additives known as a rocket propellant.

Kerosene has been extensively used with liquid oxygen in rockets. It is also known as Rocket Propellant (RP). It is little different from the pure kerosene in that it is somewhat modified by additives. What are the changes? Flash point of kerosene is around $38^{o}C$ but you would like to increase it to something like $55^{o}C$. Therefore, you put some more additives in it and you increase the flash point. You make sure it does not gel or it does not form gum or does it coke when heated. We make it more conducting to prevent accumulation of electrical charge in it. It is used with liquid oxygen and the values of sea level specific impulse are not very high of the order of 3000 Newton second per kilogram. Therefore, it is one of the low energy propellants.

Alcohol is no longer used, but we use liquid oxygen with kerosene. It is a rocket propellant, but unfortunately there are some problems with kerosene. See kerosene is not a pure chemical. Depending on the crude, it may contain more of paraffin or of aromatics. And these influence its combustion.

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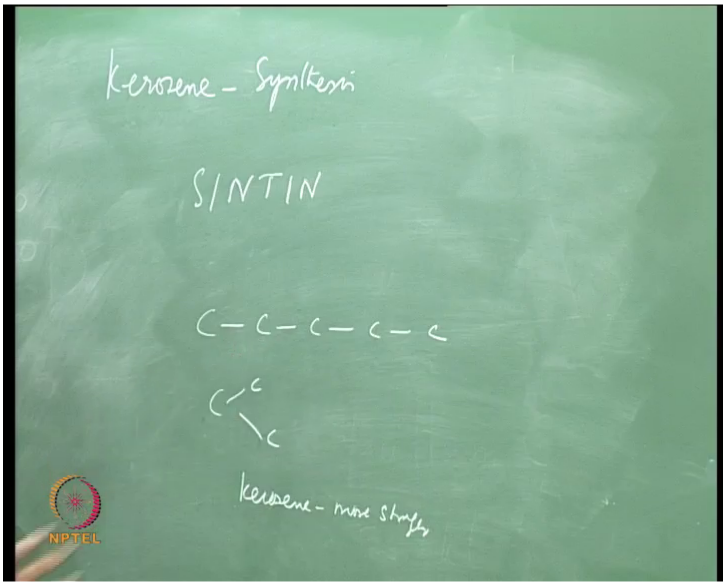

Therefore, there has been an attempt to get kerosene to be synthesized for use in rockets. The Russians have done it and called it as SINTIN. But SINTIN is costly. It is made from carbon and hydrogen at high pressure in the lab. It is not very widely used though is used by the Russians. We should have some control over the kerosene used and we say rocket propellant is something like kerosene, almost kerosene, but with some additives added to it.

If we can strain a hydrocarbon molecule, i.e., if the bond can be strained, it locks more energy and the kerosene becomes more energetic fuel. We change the bond characteristics. We can make kerosene to be more energetic. But the fuel may not be very stable.

Maybe there are a few more low energy propellants. I will go through it in the next class, but what we did today is that we looked at solid propellants, we classified them into four categories and we started with liquid propellants. We saw the high performance liquid propellants to be liquid oxygen and liquid hydrogen. Then, we started with low energy propellants and we will continue with this in the next class.