Gas Dynamics and Propulsion

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Lecture - 29
Components of the Gas Turbine Engine

So in the last class, we looked at various types of combustors. Basically, there are 3 types of combustors that are used in aircraft engine application, 1 is the can combustor, the annular combustor and then the can annular combustor that I am showing here.

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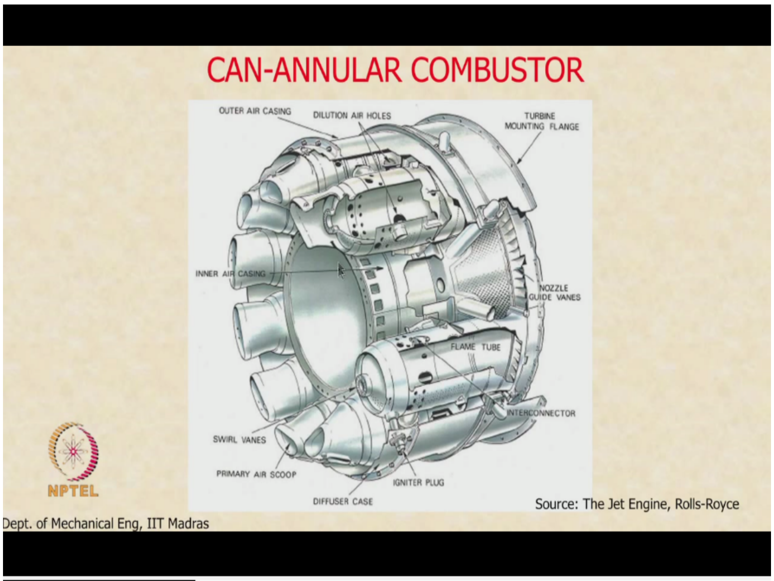

What we will do today is start with discussion of the kind of processes that take place in a single can so we are going to take a single can.

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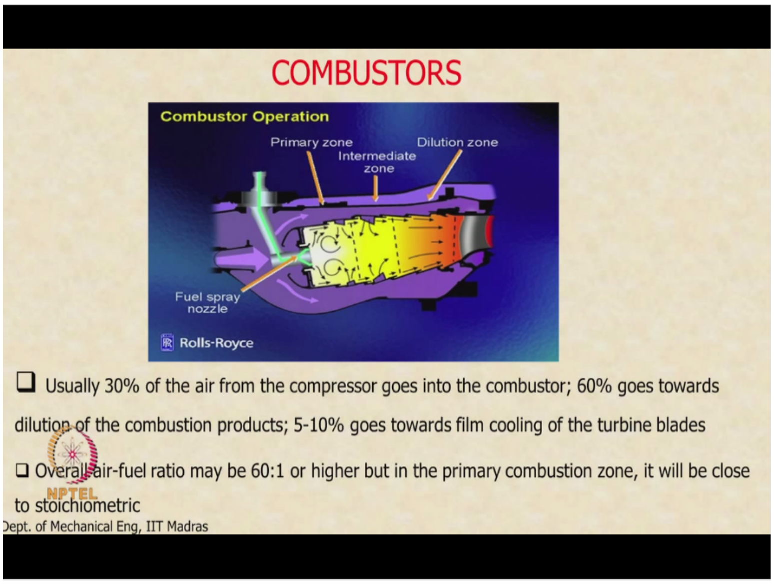

And see the thermodynamic processes inside such a can. So here we are showing the cross-sectional view of a can and the air as you can see comes in this way so that is through the air scoop, fuel is also injected. Now the amount of air that comes in here can be quite high for gas turbine engine, only part of that about 20 to maybe 25 or 30% of that air is sent through this the primary port and the remaining air is then diverted to other places, so this is the liner.

So what you see here is the liner and as we saw earlier the liner has lot of holes on its circumference. The holes allow the air to entire the combustion chamber this way as this arrow show. Air also entered, admitted into the combustion chamber through these holes. Now the combustion chamber itself can be roughly divided into 3 parts, 1 is called the primary zone where the combustion takes place.

The bulk of the combustion takes place in this zone. There is an intermediate zone where depending upon the altitude in the operating condition some of the combustion reactions may proceed okay. So the intermediate zone is provided to allow for combustion reactions to come to a completion irrespective of the altitude at which we are operating. For example, at sea level, the density of the air is higher.

So the combustion reactions will proceed faster than for example at 35,000 feet where the pressure ratio may be constant, but still the pressure of the air entering the combustor is less now right. So the intermediate zone allows for such reactions to go to a completion. The dilution zone is where the extra air is added to reduce the temperature of the combustion gases when they leave the combustor.

Unlike in an IC engine, here the temperature of the combustion gases can be very, very high. As it is they are very high and we add the air to dilute the combustion products so that the gases are at in an acceptable temperature when they enter the high pressure turbine. So here you see the vanes, which we saw yesterday right. So if you look at the previous figure you can see these guide vanes on the combustor before the gases enter the turbine.

And these guide vanes are shown here in this cross-sectional view. So if you look at the apportioning of the air we can see that about 25 to 30% normally goes here and about 60% goes into the intermediate zone and a lot of it goes into the dilution zone okay. The bulk of the air goes into the dilution zone, about 5 to 10% of the air from compressor goes for cooling of the turbine blades okay.

Because this is important to make sure that the high pressure turbine blades and also the first few stages of the intermediate pressure turbine blades do not melt because the operating temperature is well above the melting point of the blade metal, so the cooling air is essential but you must also understand that the cooling air does not generate in participation of thrust so it must be kept as small as possible.

The amount of air that is drawn for cooling should be kept as small as possible without compromising the integrity of the turbine blades okay. So the interesting aspect is for a gas turbine engine if you look at the mass flow rate of fuel to mass flow rate of air, the ratio could be as high as 1 to 60; however, wherever combustion takes place the ratio of fuel to air is closer to stoichiometric ratio okay.

So that combustion is close to being 100% complete. The rest of the air is used for diluting the combustion products so that the peak temperature if you remember the adiabatic flame temperature for typical hydrocarbon fuels will be of the range of about 2500 kelvin or 2600 kelvin.

That is not a temperature at which we can operate these devices yet based on today's technology which is why we add so much air into this, 60% is a lot you know if you think about 60%, 60% of 1000 kg per second is 600 kilogram per second right. So that much air is used to dilute the combustion products, so which brings the temperature of the combustion gases down to about 1500 or 1600 or 1700 kelvin or so which is the peak temperature at which these engines operate.

So we take it from the maximum possible temperature in these cases is the adiabatic flame temperature, which is around 2400 or 2500 kelvin. So we bring it down to about 1700 kelvin, which is where we like to operate in these things. So if you look at the combustor, the important considerations number 1 is that the combustor is exposed to the highest possible pressure in the cycle.

Because the air enters the combustor from the high pressure compressor so it has highest pressure possible and also the highest temperature okay, but the advantage is it is not a rotating component. So the stresses in the combustor material or combustor component itself is primarily thermal stress only, exposure to high temperature which brings in metallurgical issues and thermal stress.

There are no mechanical stresses other than that in the combustor, so you must take this into account when selecting materials for the combustor components and so we will take that into account. The other important aspect about the combustor is the emissions perspective okay.

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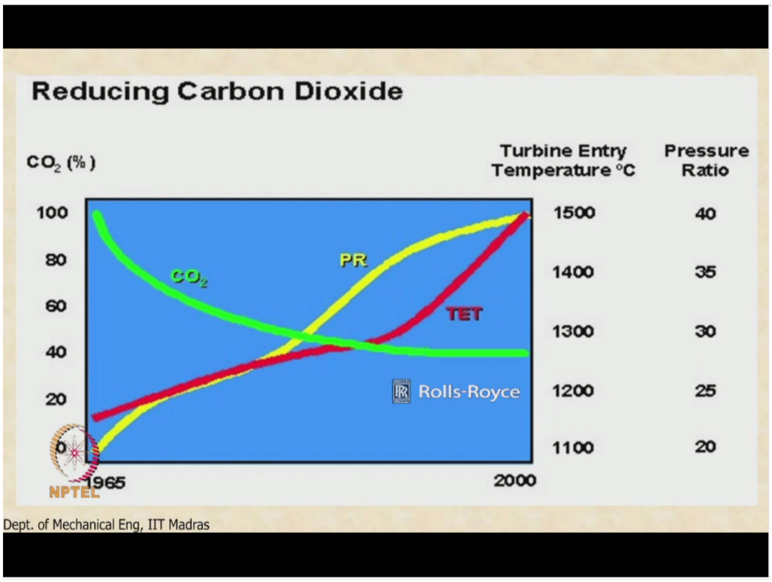

One of the major problem so we will come back to this in a minute. Let us look at emissions perspective. One of the biggest problem with aircraft engine is that because we are using so much air right. We are using 60 to 1 right. We are using so much air. There is a tendency for these engines to produce a lot of NOx. Remember the air even when it leaves the nozzle exhaust can usually be at high temperatures okay.

So there is continuous formation of NOx in these engines and remember these engines are operating at altitudes of 35,000 feet or more. So they are releasing the NOx directly into the upper levels of the atmosphere, which is a very bad thing for this you know from an emission perspective. So the push is to reduce the amount of NOx and CO2 that these engines emit. Usually unburnt hydrocarbons and other things from these engines are very small.

Because the combustion temperature is so high that you will not get unburnt hydrocarbons and so on, but CO_2 production is quite high and NO_x production is also quite high. So here we are looking at trends in 3 different aspects from a combustor perspective, amount of CO_2 over the years, turbine entry temperature over the years and pressure ratio over the years.

So you can see that the pressure ratio has consistently gone up to a value now where it is operating at about 40 or so. Most modern aircraft engines operated at pressure ratios around 40 okay. So this gives the thermodynamic efficiency of the gas turbine engine is directly dependent upon the peak temperature and the pressure ratio. Peak temperature also you can see that starting from 1100 in about 1965, it has now gone up to 1500 degree Celsius or so.

And this is about 1700, 1800 kelvin close to 1800 kelvin okay. So you can see the increase in trend over the years. The pressure ratio trend is more or less asymptotic okay. It is about 40 appears to be the value for these engines. There is no push to increase the pressure ratio beyond that so that means the scope for improvement in compressor and turbines is to reduce the weight not to increase the pressure ratio.

But for the same pressure ratio can we reduce the weight. So that is where the push is in the technology in the design of these components, compressor and turbines and also fans okay. Now turbine entry temperature however there is continuous increase in the turbine entry temperature up to this day. Now it has stabilized at about 1500 degree Celsius or so only now.

So this shows only up to 2000, between 2000 and today you will probably see that this trend is kind of flattened out about 1500 to 1600 is where it is today okay, but CO_2 levels have gone down primarily because the fuel efficiency of the devices have increased and combustors have also become better. Since the combustion temperatures have always been high, CO_2 production as I said you know will also be quite high.

Because you know combustion process is complete, but one danger with such high temperature is that when you produce so much CO_2 as such high temperatures there is also possibility for CO_2 to become CO. So we have to be very careful about the conversion of CO_2 back to CO during dissociation, we need to keep that in mind, but fortunately the gases stay in the combustor only for a certain short period of time as they move through.

So this kind of danger may be minimal but the formation of NOx is actually much more serious problem. CO2 of course is also a serious problem.

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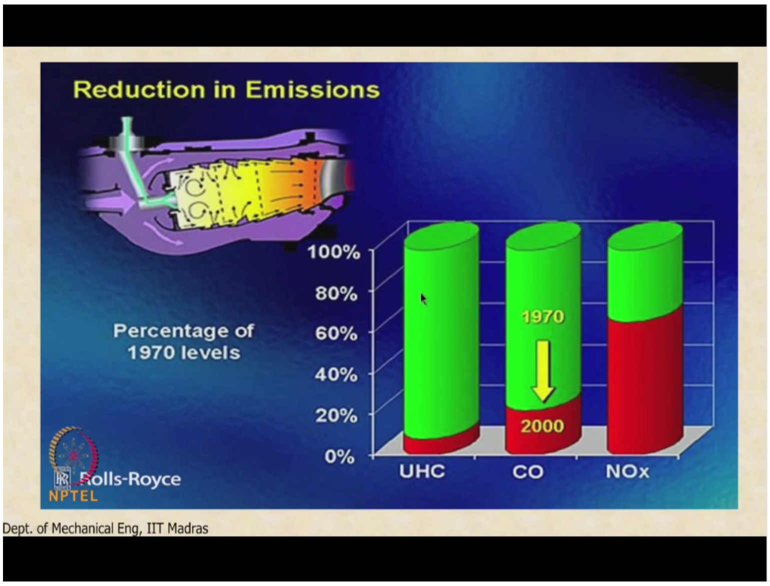

So if you look at what has been done over the years you know compared to earlier years, we can see that unburnt hydrocarbon has now come down to almost negligible level because the combustion process is complete in almost all the modern combustors, CO has come down considerably, NOx has not come down considerably because you know the air fuel ratio is more or less remain the same.

The more efficient the combustion process you know the NOx formation is also going to increase because the temperatures are continuously being increased. So the tendency in today's technology or today's environment is to see how we can minimize this. One attribute or one way by which this can be reduced is to use biodiesel and other biological alternatives, which tend to produce less NOx okay.

But getting good combustion efficiencies when using such fuels continues to be a challenge, but it is possible to do that and many airline companies are now looking at synthetic fuels, which are tailored so that emissions can be minimized. So that is being pursued we will look at that when we talk about where the industry is going today, towards the end we will discuss that.

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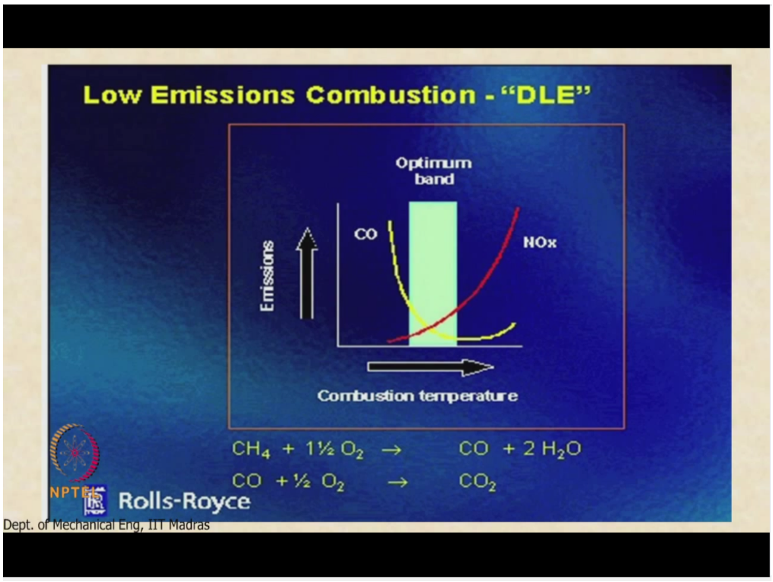

So as I said earlier if you look at emission versus combustion temperature okay you can see that you get a lot of CO and the combustion is incomplete. So the amount of CO goes down as the combustion becomes better and better. So when you have stoichiometric combustion for example, the amount of CO is minimal almost 0, but if you continue to increase the combustion temperature beyond this then the CO2 will begin to disassociate into CO.

So we need to bear that in mind that is what this curve shows beyond a certain temperature you have dissociation taking place, so the point where the CO is a minimum is where we want to operate that is close to being stoichiometric combustion, but notice that the NOx will continue to increase with combustion temperature okay. So we cannot avoid the formation of NOx.

But compromise has to be made so that you have as low value of NOx as possible and keeping CO to be the lowest possible value. So aircraft engines typically tend to operate in this range. Although, from an efficiency perspective it may be more suitable to shift this to the right, but from an emission perspective it is not better to shift this to the right okay. So these are the conflicting considerations that we must work with.

Or you need to figure out how to increase the combustion temperature while keeping the emissions also at a lower level that is very challenging and very difficult to do, but that is also a technology front that is being pursued today.

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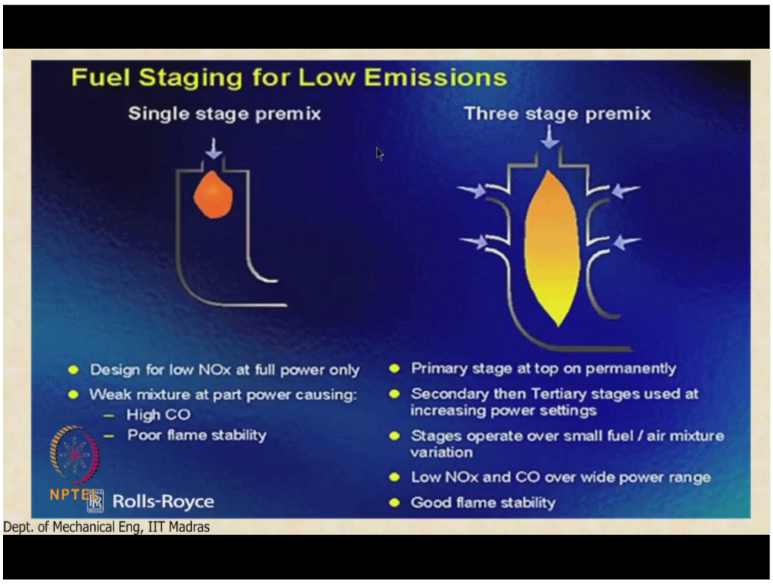

One of the strategies that is being tried for reducing emission has to do with this so called fuel staging. So normally when you allow or admit fuel into the combustor at only one location, now as the engine goes from full load at takeoff thrust to part load when it is cruising right, it is not optimized for emissions perspective. Emission is you can optimize for one operating condition but not for all operating conditions.

So under takeoff or high thrust setting you tend to use much more fuel and when you are cruising you tend to use much less fuel. The same combustor cannot accommodate such widely varying operating conditions while still keeping the emissions to a minimum. So what is done these days is to use something called as stage fuel injection. So the stage at the top is always on, fuel is always admitted from here.

And then depending upon the requirement if you want more thrust then one more stage comes on. If you want even more thrust then other stages come on and as a thrust requirement goes down, these stages are slowly turned off. So that way you are optimizing the emissions in accordance with the operating condition. There is an extremely effective strategy and it also has very good flame stability.

Plus, you produce the minimum possible NOx and CO for the entire range of operating conditions okay whereas here you really do not have a control over the amount of oxygen or CO under high fuel injection conditions. When you are injecting a lot of fuel and if the combustion efficiency is not the same, which it will not be then you tend to produce a lot of CO because combustion is not complete.

As the amount of fuel reduces the amount of CO will also go down, but here because we are using staged injection the amount of fuel in the combustion chamber is always such that it is commensurate with the load and the combustion efficiency also remains fairly high under all ranges of operating condition. So this is the strategy that is being pursued today to minimize the emissions while not compromising the performance or stability.

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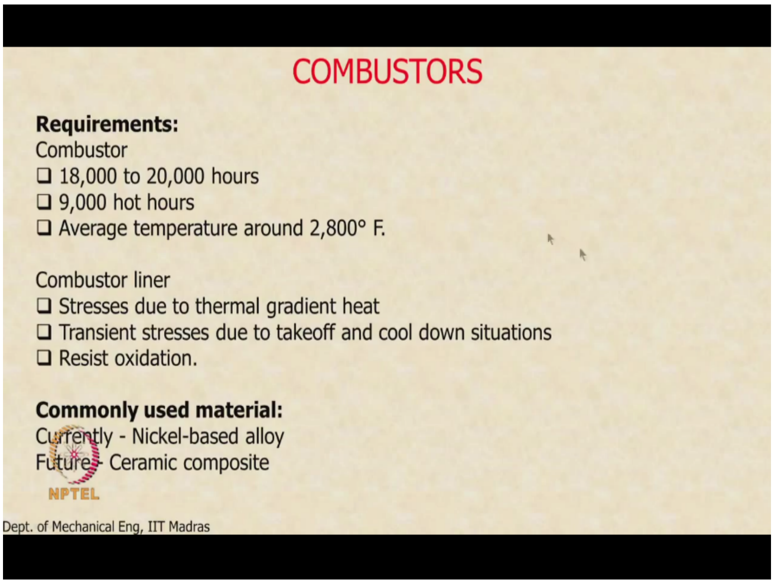

Before we go to the next component turbine let us just take a look at the materials that we are going to use in the combustors. As I said you know the primary stress in the liner is thermal gradients, it is exposed to high temperature and of course also transient stresses as I said due to the duty cycle. You have a takeoff at maximum thrust setting, cruise and then again you are coming down and then cooling down.

So this causes lot of stress from the combustor liners, so thermal stress is a major problem. Exposure to high temperature also causes oxidation of the metal, which is also a problem. Good news it is a nonrotating component, which means there are no centrifugal stresses so we are not worried on that front. So currently both the liners and the other parts of the combustors are made out of nickel and chromium based alloys, which can withstand the high temperatures and resist oxidation.

But there is a push in the industry now to coat all the liners and other things with ceramics okay. The ceramics give good high temperature protection and the nickel-based alloys underneath give good protection to transient stresses okay. So that is where we are going today.

Ceramic composites or the so called thermal barrier coating, TBC is a very promising technology, which hopefully should allow us to see a jump in the operating temperature of these engines okay.

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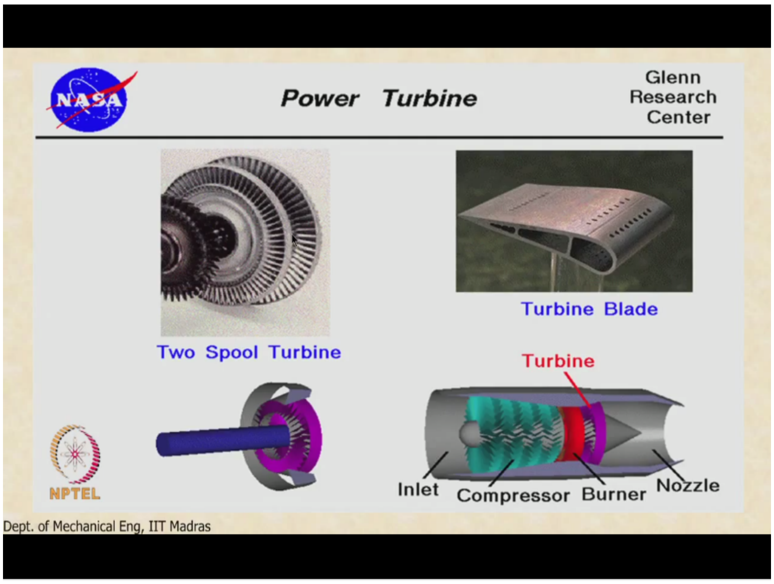

So we now move on to the next component in the engine. We have seen the inlet, we have seen compressors, we have seen combustors, now we are going to turbines. Notice that the terminology differs depending on which country you are in. Britishers call this component inlet whereas Americans call this intake. Britishers call this a combustor whereas Americans tend to call this a burner.

In fact, both mean the same thing, intake and inlet are the same okay.

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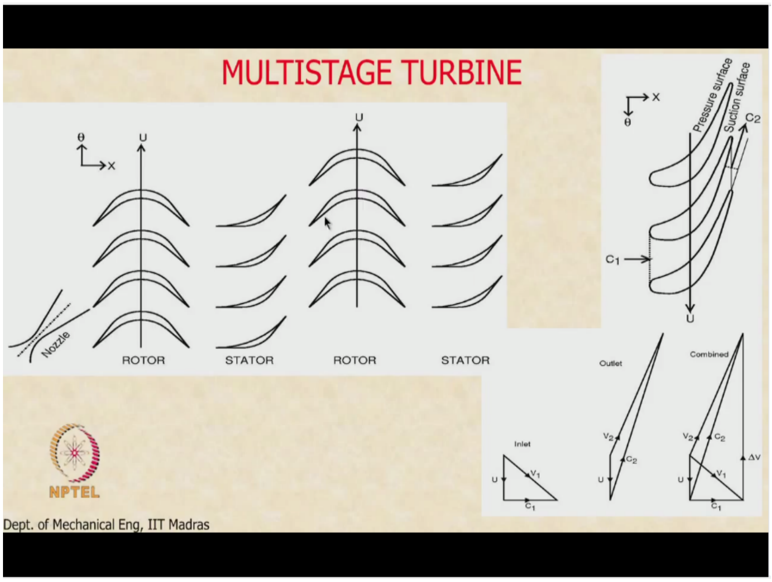

So here we are looking at cross-sectional view of a multi-staged turbine and just as we said before we have a rotor blade which is rotating, stator blades which redirect the flow on to the next set of rotor blades same as before. The biggest difference being now the pressure decreases as the fluid flows through the turbine from left to right here okay because the fluid undergoes an expansion process, the pressure decreases.

So there is no danger of an adverse pressure gradient or flow separation because of that which means that each turbine stage can probably do far more work than a single compressor stage. The single compressor stage we have limited to pressure ratios of 1.15. Consequently, the blade loading coefficient and the amount of work that I can put into a compressor blade was also very small.

Here the amount of work that I can get out of a single stage of a turbine blade can be quite high, which means that the number of turbine blades in a typical aircraft engine will be considerably less than the number of blades in a compressor stage and you can also see why. So this is the cross-sectional view of an actual turbine blade and you can see immediately it must strike you that the blades are much thicker.

And also notice the angle of turning, the flow turning that is accomplished in this blade passages. This is much higher than before and the velocity vector, this is the inlet velocity vector okay, this is the outlet velocity vector and you see the combined velocity vector. You can see that as far as the relative velocity component is concerned you can see the cross-sectional area decreasing as the fluid flows through this right.

So you can see the increase in C1 the relative velocity from inlet to outlet. Previously, this almost the same because we wanted to keep the diffusion process to be free from flow separation, but now we can see the tremendous increase in C1 to C2 and the consequent increase in delta V. Remember the amount of energy transfer is proportional to delta V right.

So the velocity change is huge which means I am extracting large amounts of work from the turbine. Also notice that delta V vector is in this direction, blade velocity is in the opposite direction. So this should tell you that this is a turbine and not a compressor okay. So because the blade loading coefficient can be so high, we can extract a lot of work from the turbine blades across all stages of the turbine blades.

So the number of turbine blades can be much less than the number of compressor blades for most of these engines.

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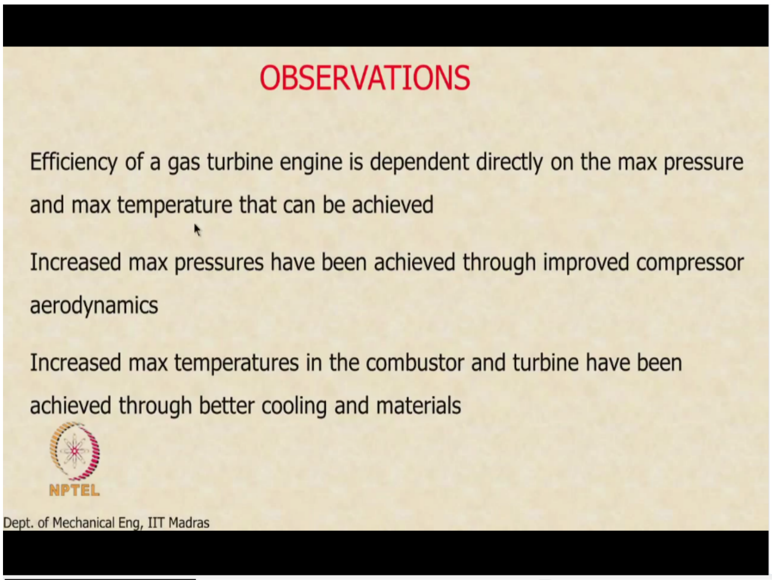

So as we said earlier the efficiency depends directly on the pressure ratio and the maximum temperature that is what the efficiency depends on and increased maximum pressures have been achieved through improved compressor aerodynamics. Even if you improve the pressure ratio of single stage of a compressor from 1.15 to let say 1.2, the number of stages can be reduced approximately by about 5.

Reduction in 5 stages as I said will work out to a reduction in the number of blades by about 700 or so. That is a considerable reduction in the weight right. So small improvements in efficiency alone are possible these days. So we are talking about improving ratios from 1.15 to maybe 1.17 okay, which is why the pressure ratio curve has more or less asymptote. We are operating now what the best possible pressure ratio.

So the technology is more or less saturated in this. Further gains have to be made only by materials maybe improved aerodynamics, but not with the view to increasing the pressure ratio but making each stage do more with less okay and increased maximum temperatures in the combustor and turbine have been achieved through better cooling in materials. Now if you think about the components in the aircraft engine let us just look at this.

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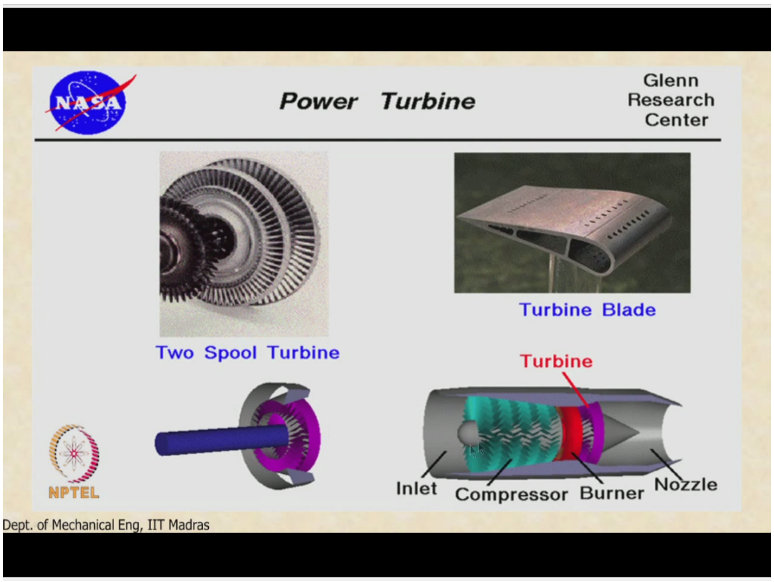

If you look at the various components, we have inlet, we have a fan, we have a compressor, we have a combustor, high pressure turbine, low pressure turbine and then the nozzle okay. Let me just quickly go back to one of the earlier slides that I had and let us take a quick look.

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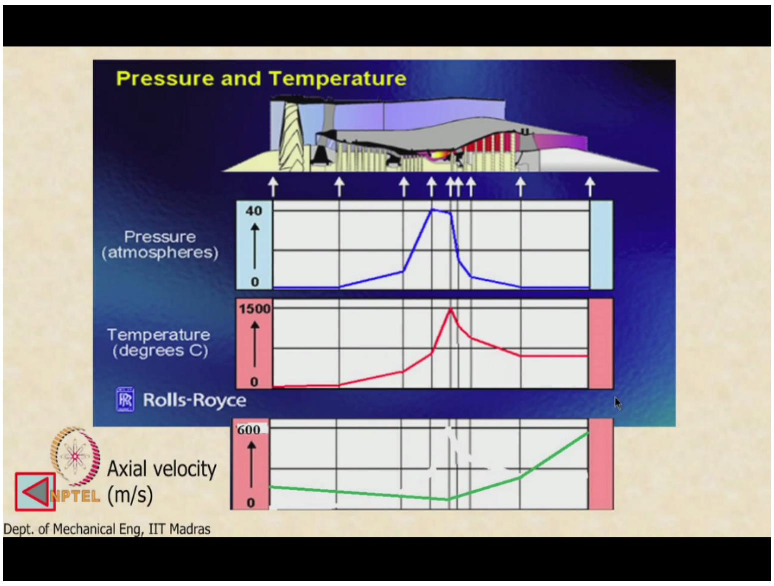

So if you look at this diagram, it shows the pressure, temperature in velocity variation across the engine. Judging from this diagram which component will you say is the most critical component in this engine? So we have fan, the low pressure compressor, high pressure compressor, combustor, high pressure turbine, low pressure turbine and nozzle. Which is the more stressed component?

"Professor - student conversation starts." High pressure turbine. The high pressure turbine is the most stressed because it is a one component which sees the highest pressure, highest temperature and highest RPM okay. The combustor sees the highest pressure and highest temperature, but it does not rotate. **"Professor - student conversation ends."** The fan also has challenges.

The fan is equally challenging if not more challenging then the high pressure turbine, but the high pressure turbine sees the highest pressure as you can see, the highest temperature and the highest rotation speed. Here we are showing only the axial velocity but if you look at RPM the high pressure turbine typically spins at 10,000 RPM so it also sees very high centrifugal stresses.

Not the highest centrifugal stress, but very high centrifugal stresses. The highest centrifugal stress is seen by the fan and we will look at that next okay. So that means we need to really give special protection to the high pressure turbine blades.

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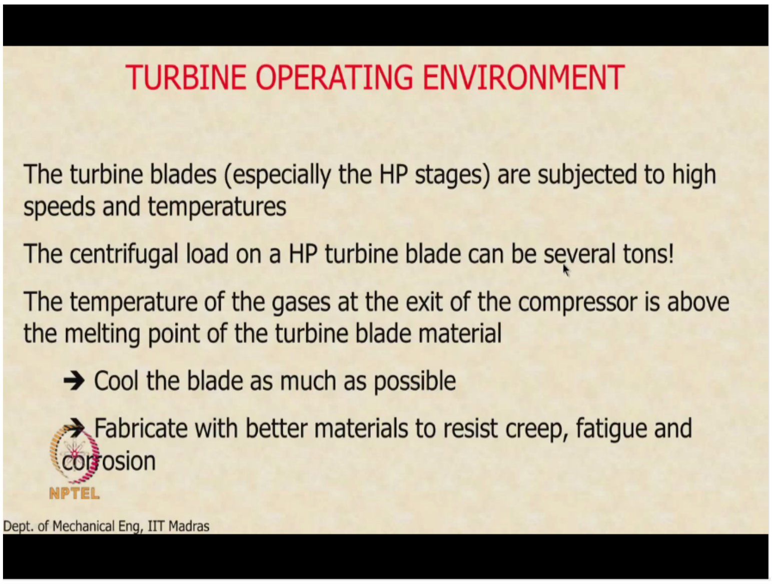

The blades have to be manufactured very carefully, so the high pressure turbine blades are subjected to very high speeds, temperatures, and pressure. The centrifugal load on a typical high pressure turbine blade is usually of the order of few 10s of tons okay. So the stresses are very high, which means that what we need to do is we need to have a multipronged strategy, usually a 2 pronged strategy or 3 pronged strategies to make sure that the turbine blades can operate in this environment without breaking down without failing okay.

So what is done is this, of course we need to keep in mind that the temperature of the gases when it enters the high pressure turbine stage is about 400 degree Celsius above the melting point of the blade metal okay. For the blades to continue to operate in such an environment, we do 2 things, number 1 we cool the blades and number 2 we make sure that we fabricate them with good materials to resist other metallurgical problems.

They must also continue to operate; we cannot change the blades once every week or once every fortnight or once every month. Each one of this special turbine blade cost about 50,000 dollars per blade okay and the typical high pressure turbine stage will have about 100 blades or so, it is a lot of money okay. So we need to make sure that they can operate as long a period as possible okay.

But we also should bear in mind that these are the most critical components of this.

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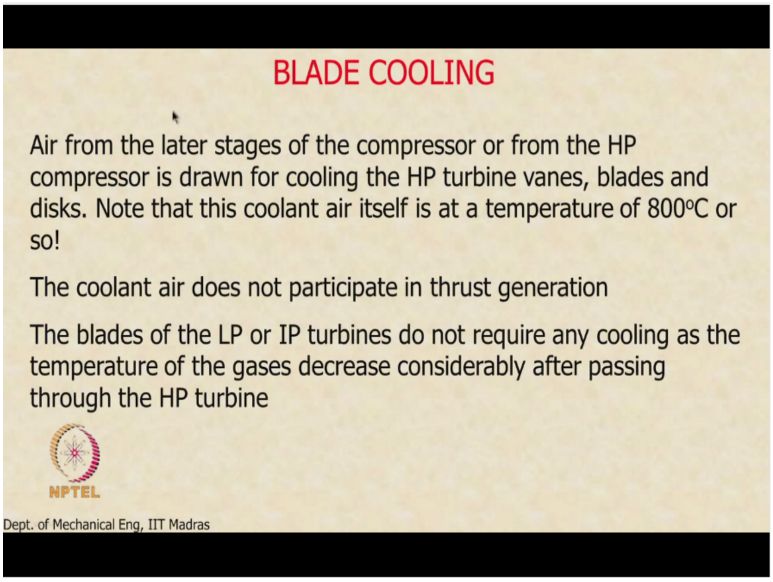

So how do we do this? As I said we do blade cooling. Blade cooling what is done is we take the air from the high pressure compressor and we use that for cooling the high pressure turbine vanes. We also cool the blades and disks and the combustor liners are also cooled in the same way. We have film cooling for the combustor liners also to make sure that the hot gas does not come in direct contact with the liner material okay.

Because the liner is also exposed to very high temperatures so we have a film of cool here around the liners to make sure that the hot air does not come in contact to this and remember the liner itself ensures that the hot combustion gases do not come in direct contact with the air casing. So the liner separates the casing from the gases and we need a film of cool air around the liner to make sure that the hot gases do not come in direct contact with the liner.

So coolant air is used for this, but remember the air at the end of the HP compressor itself is at 800 degree Celsius, but that is cool compared to 1700 or the gases or at temperatures around 2400 or maybe even less so they are cooled down to these values once you mix with the cool air in the combustion chamber and then you provide this film cooling okay. The LP or IP turbine does not require cooling.

Because as we said the blade loading factor in a turbine is very high, so the fall of temperature is also very high across the high pressure turbine blade, which means that you know these blades can operate without cooling, it is only the high pressure turbine blades which requires special cooling. How is this done? So here is the cross-sectional view of HPT rotor blade from the GE CF6 engine.

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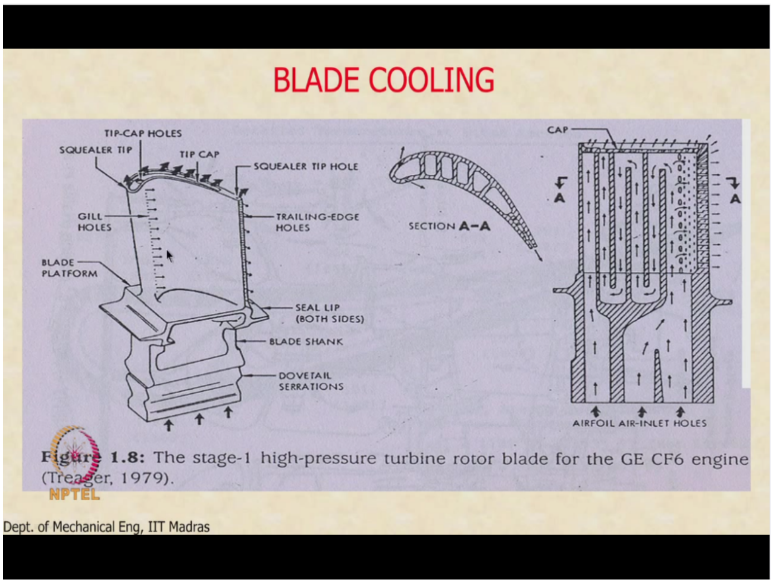

So you can see many different things being done so the air enters from the bottom, there are passages for the air to enter. So you see holes on the surface of the blade from which air comes out. So the blade itself is very hollow, this you can see here. So the air enters likes this through these hollow passages and then you can see that the air goes through a very circuitous passage to provide maximum amount of cooling across the entire section of the blade.

So the air comes out like this, goes back in, comes out like this, goes back in, so it goes through a circuitous passage to cool the entire height of the turbine blade and also entire length of the turbine blade okay and then it leaves through holes at the trailing edge also through holes from the leading edge of the turbine blade. So this air when it goes out through these holes it flows along the blade surface and forms a protective film or barrier.

So this air film will be at a temperature of about 800, but outside of that the gas is at a temperature of about 1500 to 1600 degree Celsius. So the air actually acts as an insulator between these two and keeps the film cool. It continuously carries the heat away. It is not stationary. The heat is removed continuously so that the blades do not heat up and start melting okay.

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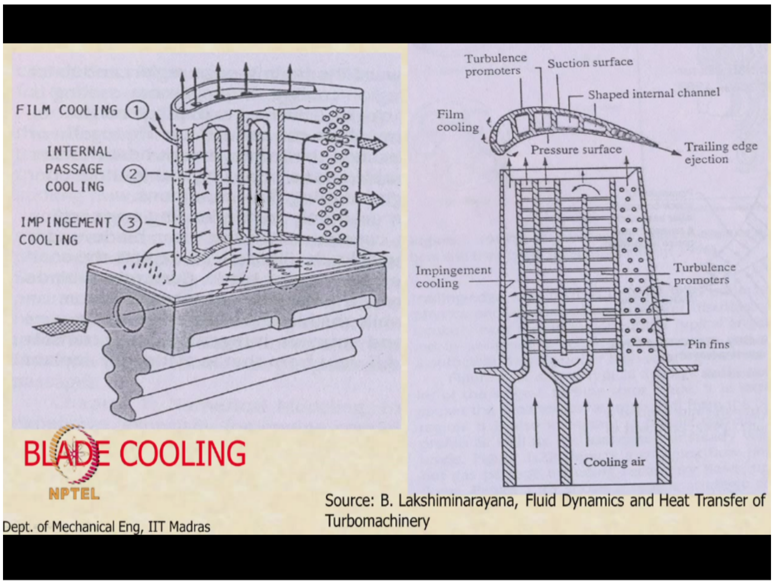

Of course, this cooling technology has improved tremendously over the years what I showed was one of the earlier generation blades okay. Notice that there is no cooling of the leading edge.

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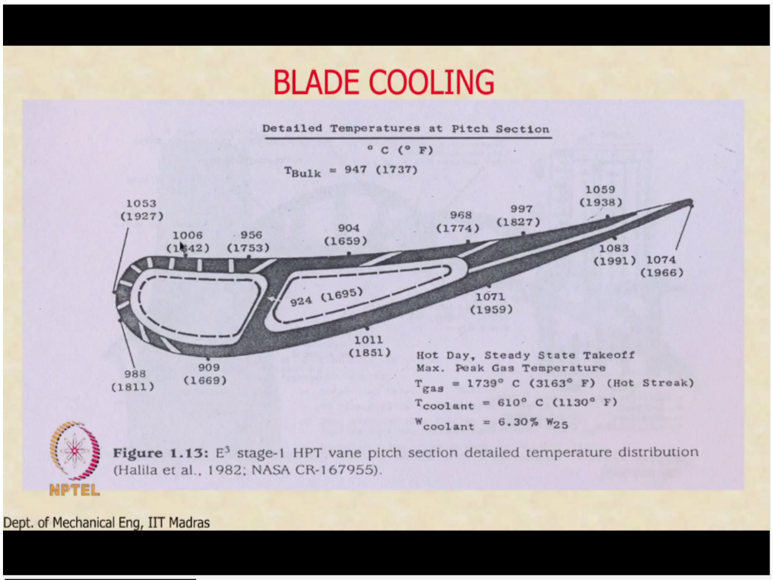

As I will show next, if you look at that blade and look at the variation of temperature. You see that the highest temperatures are seen near the leading edge and the trailing edge. The leading edge is a stagnation point, which is why the temperature is there and the heat transfer coefficients are very, very high. So it gets heated up a lot. The trailing edge gets heated up a lot because there is simply not enough metal near the trailing edge okay.

The amount of metal that is present there is a smallest possible so it gets heated up quite a bit. So we need to provide special methods for cooling the leading edge of the turbine.

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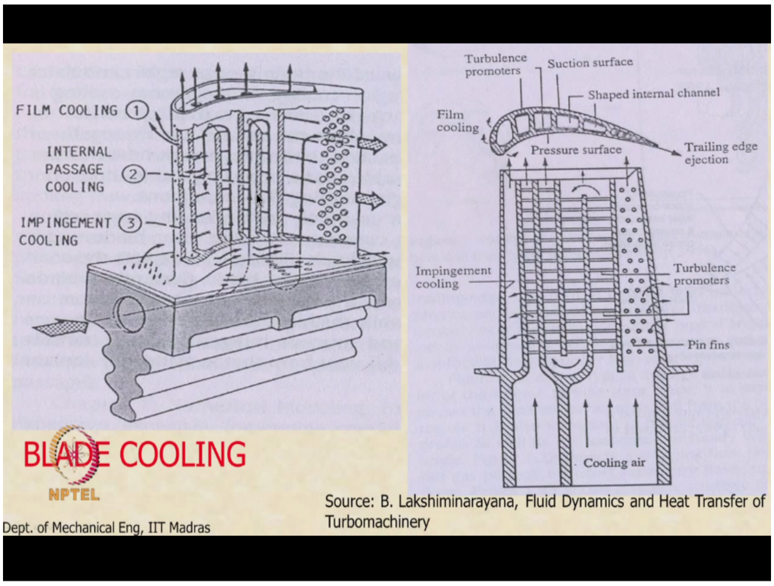

In the newer versions of this turbine blades, you can see something called impingement cooling. So the air that comes through here is made to impinge directly upon the leading edge of the blade. Remember stagnation flow gives you the highest amount of heat transfer. So the impingement cooling does exactly that. So if the blade surface is curved like this, the cooling air heats the blade surface directly.

So you have stagnation heat transfer here and as much of the heat is removed as possible. So it takes care of the leading edge by having impingement cooling. So impingement is a very important technology okay. Then you also notice that in these cases, we have given lot of additional small obstructions or protrusions like this which promote the flow to become turbulent.

And turbulent heat transfers as you know is much higher than laminar heat transfer so these things promote turbulence and increase the amount of heat transfer that is possible. So you can see that in this design the high pressure air enters this way and then flows upwards through the blades and then comes out through the holes like this and again these protrusions are provided near the outer surface.

So that the heat transfer can be very high near the trailing edge also okay. So it is this film of cool air around the turbine blade, which prevents the blade from melting. We do other things to make sure that it can continue to operate at this temperatures and pressure, but that is a different thing. The film cooling is what prevents the blade from melting okay, but remember even if it prevents it from melting that blade temperature is still quite high.

As you can see from here, the temperature of the blade in terms of degree Celsius, which is given on the outside here is as high as about 1100 degree Celsius that is still very high. So there are going to be metallurgical issues related to continuous operation at such high temperatures, pressures and RPMs. So we need to worry about that also and that is what we are going to see next.

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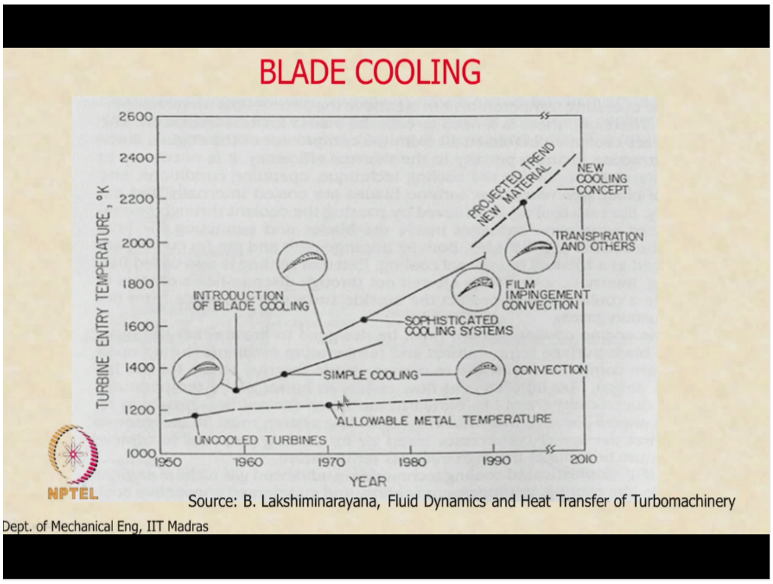

So we can see how the technology has evolved in terms of blade cooling so uncooled turbine blades can operate only here because the allowable metal temperature itself is only around 1200 kelvin okay. So you can see with introduction of blade cooling, there is a big jump in the temperature and then simple cooling, sophisticated cooling, film cooling, convection cooling keeps increasing.

Now we are using transpiration cooling, some engine manufacturers are doing that and where this will go we do not know, but this is where it is going okay. So we can see now that we are operating at temperatures this is about 2200 kelvin, this will allow us to operate a 2200 kelvin. This is where we are today. We are operating at about these kinds of temperatures 1800 kelvin is where we are.

So that is about 400 to 500 more than the allowable melting point of the blade metal. So next time you fly in an aircraft you must remember this, not feel nervous. It works fine, no problem. So we talked about continuous operation at such high pressures, temperatures and RPM so that brings in certain metallurgical issues into consideration, which is what we have to look at next.

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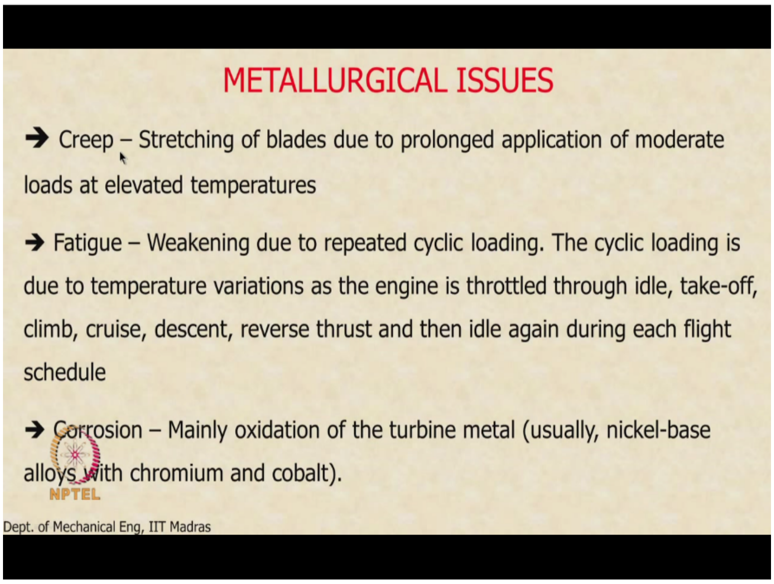

First and foremost is creep, now when you look at creep and fatigue, the blade metal can fail due to these 2 effects creep and fatigue, but the interesting part is the load that is applied in creep or fatigue is not more than or higher than the yield point of the blade metal. See normally all metals will have yield point okay. So they will fail if you apply a load which is higher than the yield point of the blade metal.

But what is interesting is in both creep and fatigue, the load is never above the yield point, it is not even close to the yield point, but they can still fail because of the nature of the loading. It is not direct tension or compression loading, but loading at elevated temperatures or cyclical loading can lead to this kind of failure.

For example, the stretching of the blades due to prolonged application of moderate loads at elevated temperature, not loads above yield point but moderate loads at elevated temperatures. Probably the most common example of creep is what happens to pressure cooker gaskets. Have you seen the rubber pressure cooker gaskets? When you buy them they are very stiff, but you continue to use them.

After about 2 or 3 months of usage, you can see that the rubber has creeped, it can no longer be used, it is no longer stiff, it no longer acts as a seal, it cannot seal the steam from escaping that is creep, but the rubber gasket has not been broken that is just creeped. So that is the difference between moderate load at elevated temperatures and yield point load okay.

So that is also dangerous and these turbine blade materials are exposed to loads at elevated temperatures that is why we have to be worried about them. Fatigue happens due to cyclical loading. Cyclical loading comes because as I said the duty cycle itself is like that right. So when it is in idle that is when the engine is at the best possible situation, takeoff means takeoff thrust maximum, it is stressed the maximum during takeoff okay.

And then climb again moderate levels of thrust, cruise minimum level of thrust, right next to idle in terms of desirability okay. Then reverse thrust, climbing down reverse thrust and then idle again gives you a cycle. So it is all cycle through this way and the components are exposed to these kinds of fatigue and if you think about fatigue, the best possible real life example is how you break a paper clip.

And if you take a paper clip and if you constantly do this way that way you can break it very easily correct. The same paper clip if I try to pull it apart, will I be able to do it? I cannot do it so if I pull it apart that is when I am applying a load which is more than the yield point of the metal, but when I do this way that way I am able to break it very easily because I am fatiguing the metal and then breaking it okay.

So that is the difference between breaking something apart and the fatiguing it to failure. So fatigue failure and creep failure are dangerous because they arise even when the loads are nowhere close to being the yield point of the metal that is why they are very dangerous and we have to be aware of that. Creep as I said comes because we are exposing it into elevated temperature.

Fatigue is due to cyclical load. The other danger is corrosion and oxidation. Corrosion comes mainly because of oxidation of the turbine metal when it is elevated to high temperatures. As you know, metals at high temperatures are very prone to oxidation. Oxygen has a great affinity or metal has a great affinity to oxygen at elevated temperatures okay. In fact, if hot metal is exposed to water, then the oxygen in the water will preferentially oxidize the metal leaving the hydrogen behind.

And if it is in a confined space, the hydrogen can cause an explosion. "Professor - student conversation starts." Where did this happen? Fukushima. That is what caused the Fukushima accident. The hot metal took away the oxygen from the cooling water and then it created a cloud of hydrogen gas inside the reactor, which then exploded. So oxidation is a serious problem with metals exposed to high temperatures.

And usually these are made out of nickel-based alloys with chromium and cobalt added to them because chromium and cobalt both provide very good oxidation resistance at elevated temperatures. These are the metallurgical issues. There are also other things that we can do.

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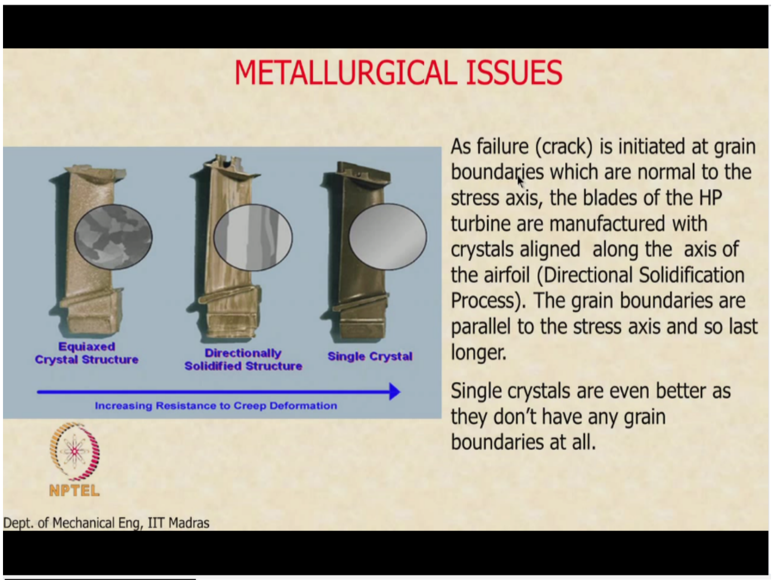

If you take a close look at how failures starts in a turbine blade, a failure or a crack if you look at a normally cast turbine blade okay. The normal casting will produce lot of grain boundaries. There will be lot of grains and lot of grain boundaries. The grain boundaries where the metal is the weakest.

So when you apply a load remember these are blades which are spinning this way. So the load is acting in this direction, centrifugal load is a tensile load which acts in this direction. So any grain boundary, which is oriented normal to the stress axis, remember the stress axis is like this so any grain boundary which is oriented normal to the stress axis is pulled apart and that is where the crack is initiated and then the crack propagates.

One way out of this dilemma that aircraft engine manufacturers have done used to cast the metal in such a way that all the grain boundaries are parallel to the stress axis. So if they are perpendicular to the stress axis they will be pulled apart. So cast all of them parallel to the stress axis, then they are much higher strength and that is what is called directional solidification process that is what you see here.

All the grain boundaries are parallel to the stress axis. That is called directional solidification. Probably, the best thing would be not any grain boundaries at all, that is to use something called a single crystal. Most modern high pressure turbine blades rotor blades are made with single crystals today. There is no grain boundary which is why they cost 50,000 dollars (()) (39:39) okay.

That plus the exotic cooling this and other things. What are the other things that we are talking about?

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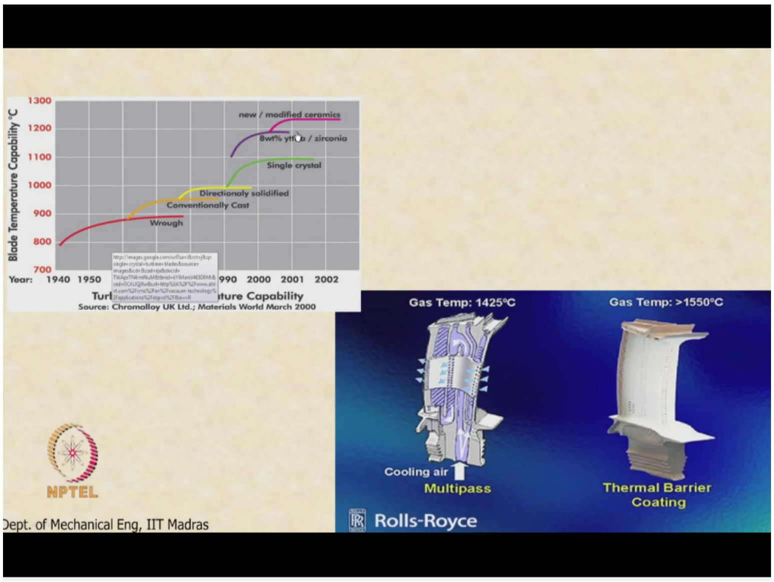

So you can see the trend in the technology with the years in terms of blade materials okay. So this is blade material and increase in temperature over the years. This is not talking about cooling, just blade material versus possible turbine temperatures so you can see that conventionally cast, then we went to directionally solidified, now we are operating with single crystal okay.

This is without cooling so cooling will add another 300, 400 degree Celsius to the operating margin right and then if you go to ceramics, you can go to even higher temperatures. So here you are looking at high pressure turbine blade coated with ceramic which is called a thermal barrier coating. So this has a thin coating of ceramic on the outside as you can see from here, which allows further margin of about 70 to 100 degree Celsius.

Here it is called TBC, but there are lot of issues involved with using ceramics in these types of situations, but remember it is only a coating so it is not exposed to any loads you know this is a very safe way to use ceramics for these kinds of applications okay. So this is the latest and probably the greatest available in the engine industry today, fully cooled turbine blade made out of single crystal with ceramic thermal barrier coating that is the state of the art today.

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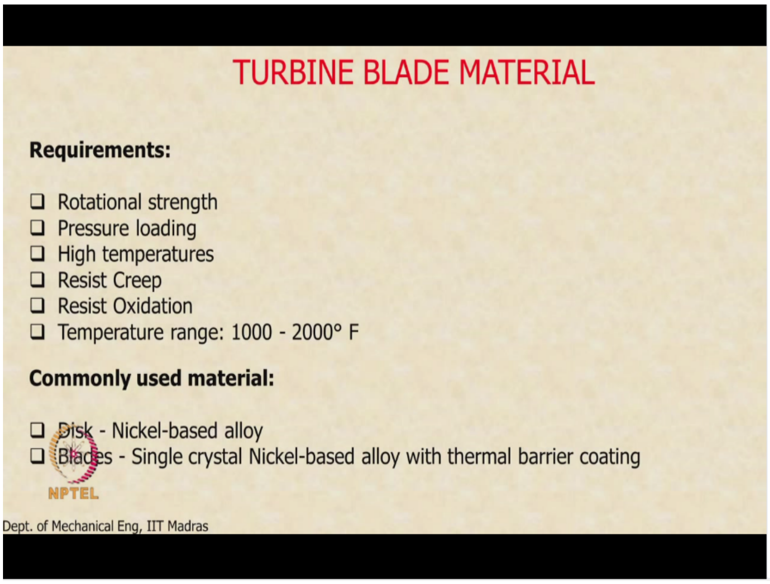

So we have already discussed these requirements as we said the disks are made out of nickel-based alloys, they are not specially cooled, but any of the disks are hollow so cooling air can be sent there, that is not an issue. The blades require single crystal I mean they are made out of single crystal nickel-based alloys with TBC and with special cooling.

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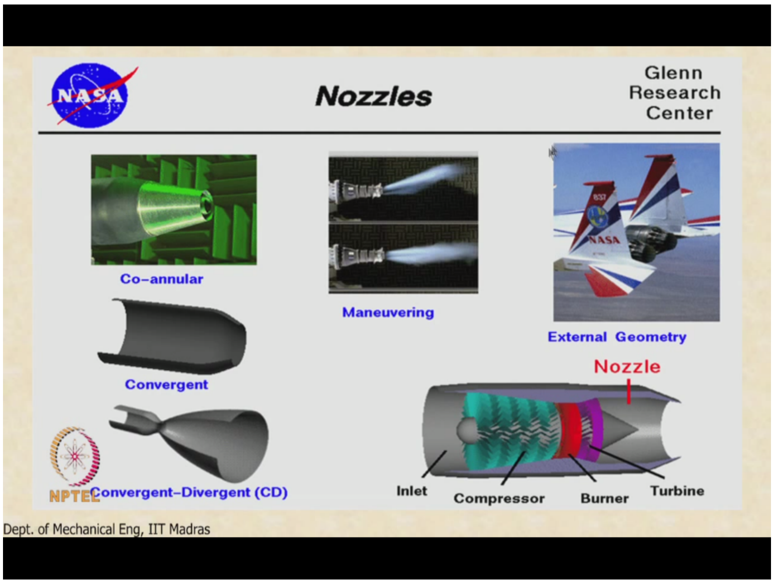

The next component that we will look at is nozzle and the purpose of the nozzle in these devices that is the last component in the engine.

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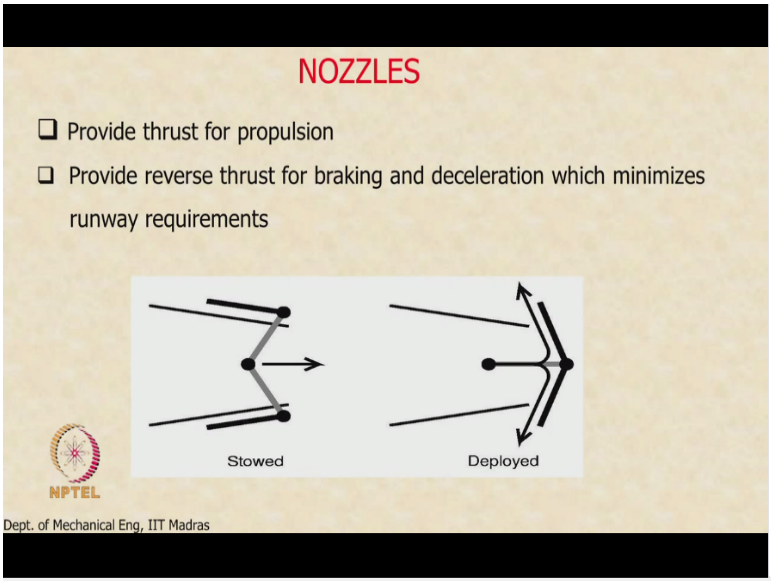

The purpose of the nozzle in an engine is to do 2 things, 1 is to provide thrust for propulsion, next it is also suppose to give reverse thrust for breaking and deceleration because without reverse thrust the runway requirement would be about 3 to 4 times what it is today. Today if you thought the runways were long, without reverse thrust they have to be 3 to 4 times longer.

It will take that kind of distance to bring the plane to a complete halt. So reverse thrust is very essential for breaking and bringing the aircraft to a halt. So these are the 2 things that the nozzle must provide. We are talking about commercial aircraft engines not fighter aircraft where other means are used for breaking the aircraft not this but other means okay. They may use parachutes or they may use arresting cables, arresting wires and so on for bringing the aircraft to a halt.

They normally will not have reverse thrust in those types of high performance nozzles. Here we are talking about nozzles used in commercial aviation applications okay. Now a simplest possible means of reverse thrusting an aircraft is shown here. So you have this type of thrust reverser, which is called the clamshell reverser. So under normal operation the clams are like this and the air simply goes through without any difficulty produces thrust.

But when you want the thrust to be reversed, you bring the clams over this way and the air is then halted and then taken to the other sides as you can see from the arrow here the clamshells are open here and then they close and they redirect the air this way producing the revers thrust okay.

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So here we actually see a clam thrust reverser in operation. So you can see these 2 clams, so normally when it is not used through the central mechanism, these 2 things will be like this and the air will go through. When you want reverse thrust, you bring them forward like this and the air then goes out through them, so you can see the clams thrust reverser being used in the turbojet engine here.

This is a rare picture, very difficult to get because you do not see so many turbojet engines today. So I have to (()) (44:06) for this picture, it is very rare to see. Interestingly enough I have actually seen this in operation when I flew many years ago, but I could not find a picture of it. This is a very nice picture okay.

Modern turbofan engines do not do this, they use a slightly different means for thrust reversing an engine and we will see that when we talk about turbofan engines. This type of clamshell reversers can be used only on turbojet engines, which have a single nozzle. So you can do this to a single nozzle propulsion device not to a dual nozzle propulsion device. So turbofan engines try to do something different.

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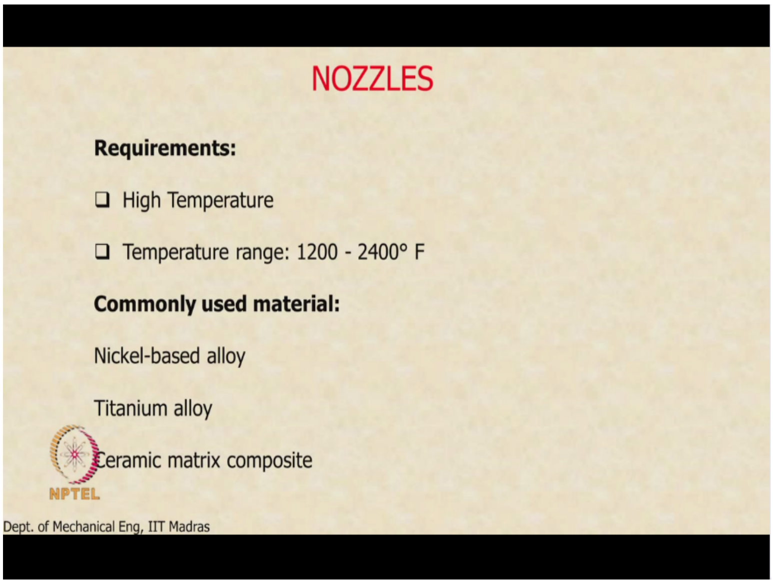

So designing of a nozzle for operation at this temperature again we must be concerned about high temperature. The temperature can be quite high in these types of situations. Once again it is not a rotating component, so the stresses are primarily thermal stresses. So nickel-based alloys even titanium alloys can be used.

Remember the high pressure stages of a compressor is exposed to similar kinds of temperatures, which means it is safe to use titanium in these types of situations, ceramic matrix composites can also be used for this because there are no stresses. The only stress is thermal stress where ceramics can operate quite well under these circumstances okay.

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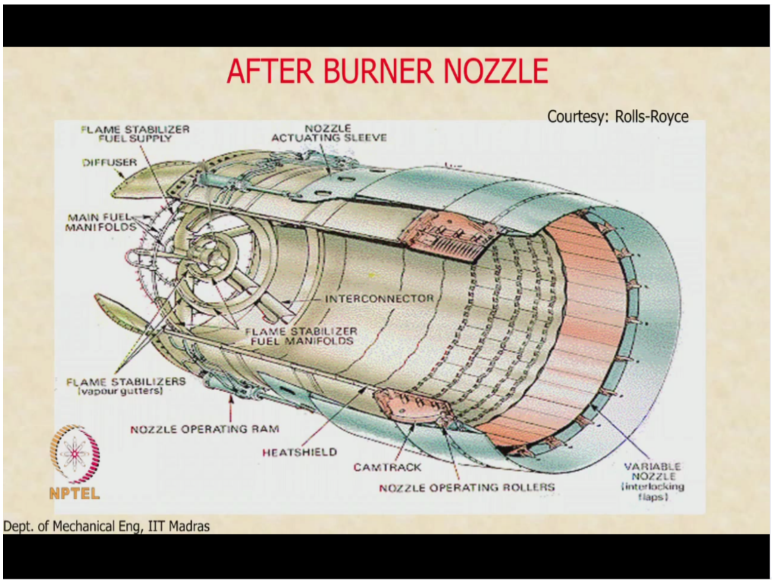

So we will take a look at after burner nozzle in the next class and then move on to turbofan engines okay.