Gas Dynamics and Propulsion
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Lecture – 36
Calculations for Thrust and Fuel Consumption/Emerging Trends

In the last class, we did thrust calculations and fuel flow rate calculations for a turbofan engine.

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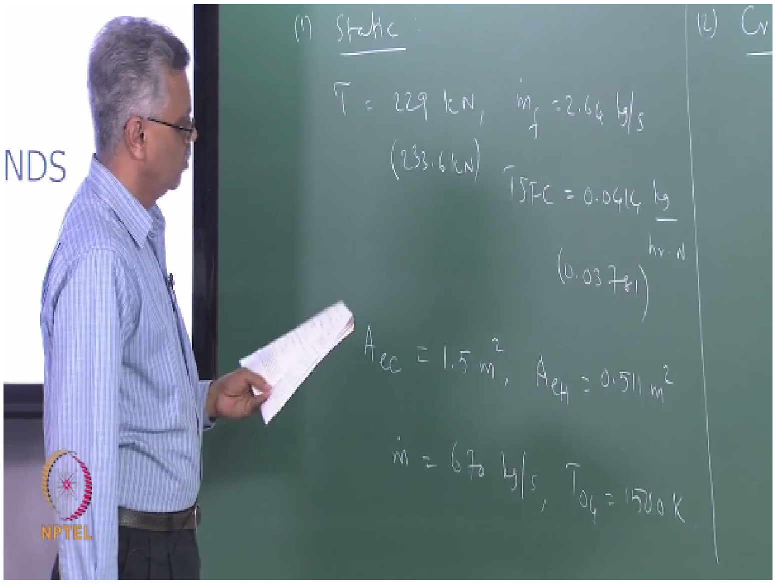

Let us summarise what we have done so far for this problem. We looked at two operating condition, one was static (()) (0:25) condition in which we calculated the total thrust T of the engine to be 229 kN and we calculated the mass flow rate of fuel, mf dot to be 2.64 Kg per second which corresponded to a TSFC of 0.0414 Kg per hour N and we compared with the manufacturer coated value for this.

This was 233.6 kN for the total trust and for the TSFC, the manufacturer coated value is 0.03781. So, the values seem to compare reasonably well and based on this we calculated the area of the cold nozzle to be 1.5 metre square and we calculated the area of the hot nozzle to be 0.511 metre square. So, this was done for the static conditions.

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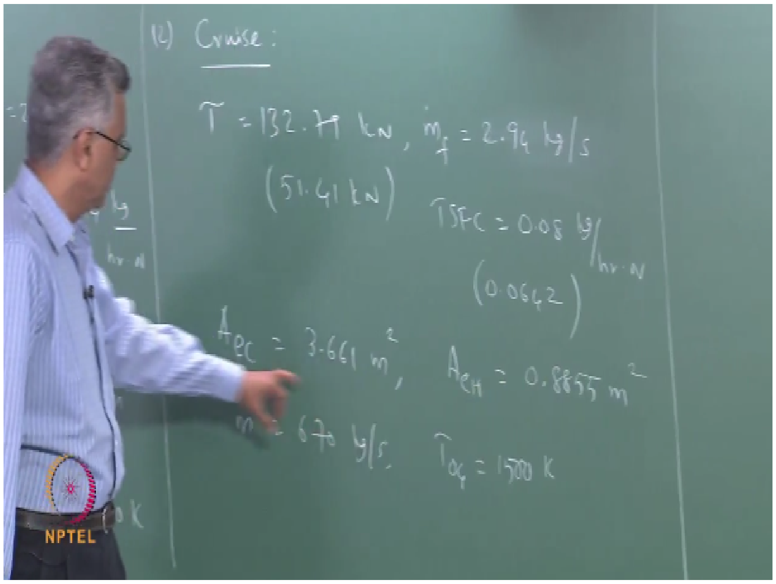

Then, we moved on the cruise conditions and for the cruise condition or initial calculations, let me also add one more thing here. We assumed the mass flow rate for this case to be, it was given to be 670 kg per second and the turbine entry temperature was given to be 1500 K. Now for cruise, we assumed same mass flow rate and we calculated the total thrust to be 132.79 kN which compares very poorly with the manufacture coated value of 51.41 kN.

And the TSFC is 0.08 kg per hour N and the mass flow rate of fuel was calculated to be 2.94 kg per second and the manufacture coated value for this is 0.0642. So, the comparison for TFSC is also quite poor and we calculated the areas of the nozzle for the same mass flow rate. When we did the calculation for the areas, we obtained the areas to be 3.661 metre square and the hot nozzle area to be 0.855 metre square for the same mass flow rate.

So, we once again took the mass flow rate to be 670 kg per second and we took T04 to be 1500 K. We concluded quite rightly that this is the source of the discrepancy. This is what is causing the discrepancy. The area of the nozzle in a commercial a turbofan engine has to remain the same. It is not a variable area nozzle. So, what we can do. The first thing that we can do is try to adjust the mass flow rate.

Now what you must remember is if I change the mass flow rate, how many of the quantities that I calculated is going to change.

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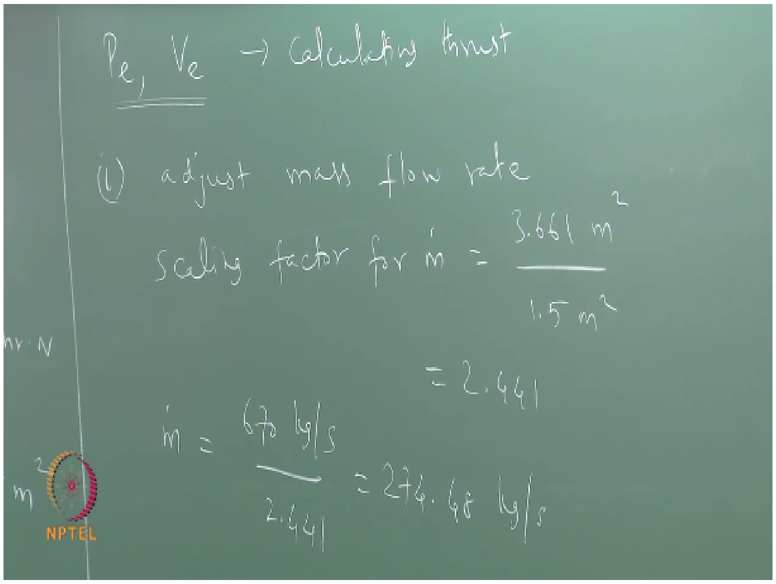

Pe, Ve → Calculating thrust

(i) adjust mass flow rate

$$\text{scaling factor for } \dot{m} = \frac{3.661\ m^2}{1.5\ m^2} = 2.441$$

$$\dot{m} = \frac{670\ kg/s}{2.441} = 274.48\ kg/s$$

Remember, we said we finally wanted to evaluate the exist static pressure and the exit velocity. These are the two quantities that are used for calculating the thrust. So, these are the two quantities that are used for calculating thrust. So, if I change the mass flow rate, will these quantities change. Now, if you go back and look at your calculation procedure, you will notice that evaluation of any of the thermodynamic state properties; stagnation pressure, stagnation temperature, static pressure or velocity did not involve use of any mass flow rate.

We use the bypass ratio but not the mass flow rate. So, as long as you do not change the bypass ratio or T04 or any other thermodynamic properties, we can actually quite freely change the mass flow rate that is passing through the engine, right. So, we can adjust. So, there are two things that we can do. The first thing that we are going to do is adjust mass flow rate. So, I can adjust this without changing my Pe or Ve, both should remain the same.

So, if I do that. Now, what I need to do is passing this mass flow rate through the nozzle under cruise conditions required this kind of area. What if the area available is only 1.5 metre square, what should the mass flow rate be, that is how we scale this and yesterday we saw that the scaling factor is going to be for m dot should be 3.661 metre square/1.5 metre square which gives me 2.441.

So, m dot now has to be adjusted to 670 kg per second/2.441 which gives me 274.48 kg per second. So, the mass flow rate has to be reduced from 670 kg per second to approximately 274 kg per second, okay.

“Professor - student conversation starts” Any questions, yes. As we are changing area, it will also change choking condition. It will also change upstream conditions. How will it change upstream condition, that is why I said before I started this, I told you that we did not use the mass flow rate in the calculation of any other thermodynamic state properties; P01, T01, P02. You can go back and check your calculation, you will notice that we have used the bypass ratio but not the actual value of the mass flow rate itself, okay.

So, I can freely change mass flow rate without changing Pe or Ve, that is permitted. Even if you change Ae, remember when velocity is the same, right velocity is the same. So, now I am passing less mass flow rate through this, stagnation pressure remains the same, so my thrust is going to be scaled accordingly. The thrust we have to recalculate now, okay. What you are saying is true for the thrust but thrust uses a slow rate.

So, all I am saying is V will not change but other quantities will change. For example, thrust will change, fuel flow rate will definitely change, correct. Sir, if intake is same and exit is change. If mass flow rate, inlet mass is same. No, what I am saying is the compressor showed round out a speed, which is such that it takes in only this much mass, okay. So, you throttle down the engine, so, the compressor RPM goes down, fan RPM goes down. So, the mass flow rate that goes through the engine also goes down, okay.

So, an engine does not always operate at the same mass flow rate. Mass flow rate through the engine can be changed by adjusting the speed of the compressor and fan, that is quite possible. That is what we are proposing here that the engine should take in less mass flow rate. But engine is cruising at same speed. Correct. The engine is cruising at the same altitude. Va is the same, but if you go back and check your calculation, you will notice that this was calculated without using m dot, that is the most important point.

These two quantities are calculated without using m dot. So, when I change m dot, these two will remain the same, there are no issues, okay. **“Professor - student conversation ends”.** So, this then tells me that Aec now will revert back to it, so for the adjusted mass flow rate and for the exit velocity we have calculated Vec. The area of the cold nozzle can now be 1.5 metre square, there is no problem. Now, we have to see what the area of the hot nozzle is for the new mass flow rate. So, we have changed the mass flow rate like this.

So, mass flow rate through the hot nozzle is going to be 1/B+1*m dot and if I substitute this value for m dot, I get this to be 51.69 kg per second. So, this is the mass flow rate now through the hot nozzle, okay. So, for the calculated value of Vh what is the area that is required to pass this mass flow rate.

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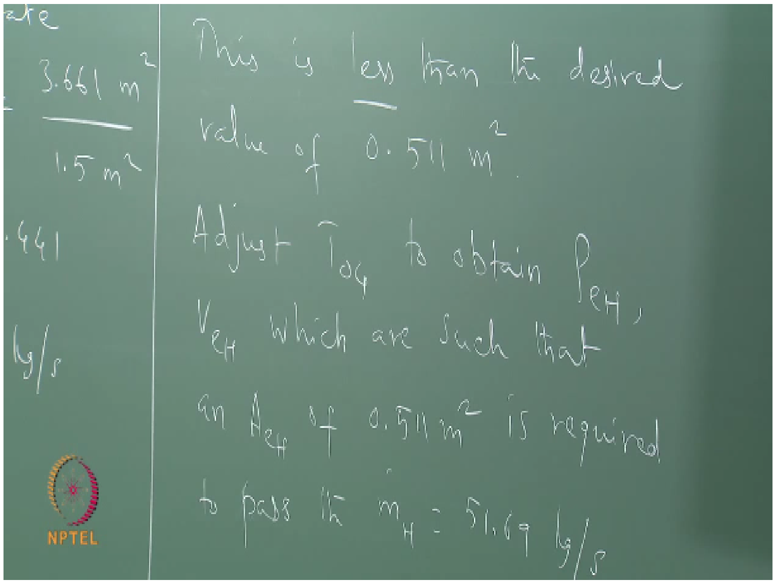

ate

$3.661\ m^2$

$1.5\ m^2$

.441

kg/s

This is less than the desired value of $0.511\ m^2$.

Adjust T_{04} to obtain ρ_{eH}, V_{eH} which are such that an A_{eH} of $0.511\ m^2$ is required to pass the $\dot{m}_H = 51.69$ kg/s

So, Aeh now can be calculated. So, Aeh is going to be m dot h/rho eh*Veh and if I substitute the numbers, I get this area to be 0.363 metre square. Whereas the desired value for the hot nozzle area is 0.511 metre square, okay. Now, I cannot play this same trick again. If I adjust the mass flow rate now, the mass flow rate through the cold nozzle will also change. So, this can be done only once, okay. So, I need to adjust something else to take this effect into account.

How do I adjust the condition so that the required amount of mass flow rate m dot h can be passed through a nozzle which has a area of 0.511. This means that I have to change these conditions, okay. The only other quantity that I can play with is the turbine entry temperature, right. This is the only other quantity that I can play with. So, what we are saying now is as the flight gains altitude, you are throttling back on the engine which means you are reducing the fuel flow rate and the stagnation temperature at entry to the turbine.

So, we have to determine a value T04 which is such that the mass flow rate is fixed at 551.69, right. So, we have to find a stagnation temperature which will give me rho eh and Aeh which are such that when I substitute m dot h= 51.69, I get the area to be 0.511 metre square, okay. Now, we have to start changing thermodynamic properties, okay. So, let us summarise this. This is less than the desired value of 0.511 metre square.

So, what we need to do is adjust T04 to obtain rho eh and Veh which are such that Aeh of 0.511 metre square is required to pass m dot h which is 51.69 kg per second. So, when I changed T04, my rho eh and Veh are both going to change. I have to keep changing, I have to keep it rating until I get a value of T04 which is such that and I plug it in here for this value of m dot h, I get the area to be 0.511, okay. This has to be done iteratively. It cannot be done in one go, okay and if you iterate then you have to do this a couple of times and let us see what happens.

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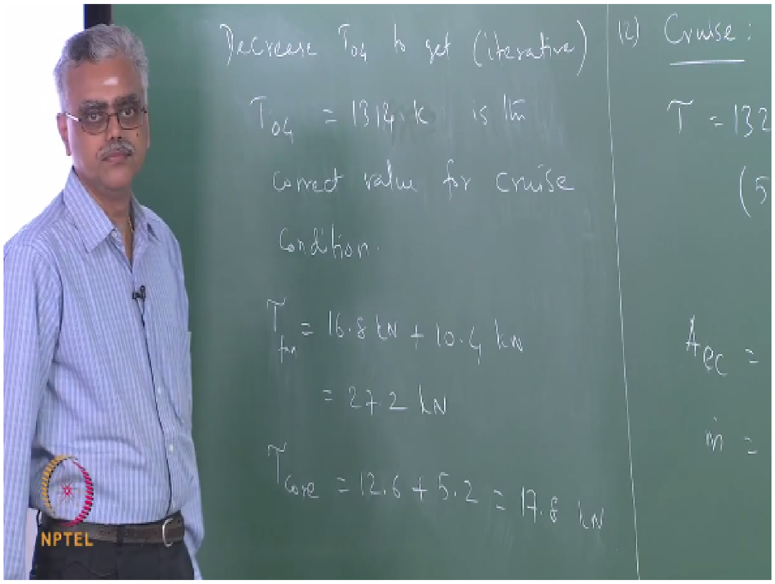

Decrease T_{04} to get (iterative)

T_{04} = 1314 K is the correct value for cruise condition.

T_{fan} = 16.8 kN + 10.4 kN = 27.2 kN

T_{core} = 12.6 + 5.2 = 17.8 kN

(2) Cruise:

T = 132

(5

A_{ec} =

$\dot{m}$ =

You can already guess which way we are going to change the temperature. Are we going to increase T04 or decrease T04. We have to decrease T04, so that is understandable. So, we decrease T04 to get and again this is iterative. For the cruise condition, it turns out that T04 of 1314 K is the desired value for the cruise condition.

So, if you this the thrust comes out to be after adjusting the T04 this way and the mass flow rate this way, the thrust comes out to be 16.8 kN from the fan+10.4 kN momentum thrust and pressure thrust respectively which gives me 27.2 kN of thrust from the fan and the core engine is = 12.6 kN+5.2 kN which gives me 17.8 kN of thrust. So, that the total thrust now comes out to be, I am going to erase this and substitute this value here, okay.

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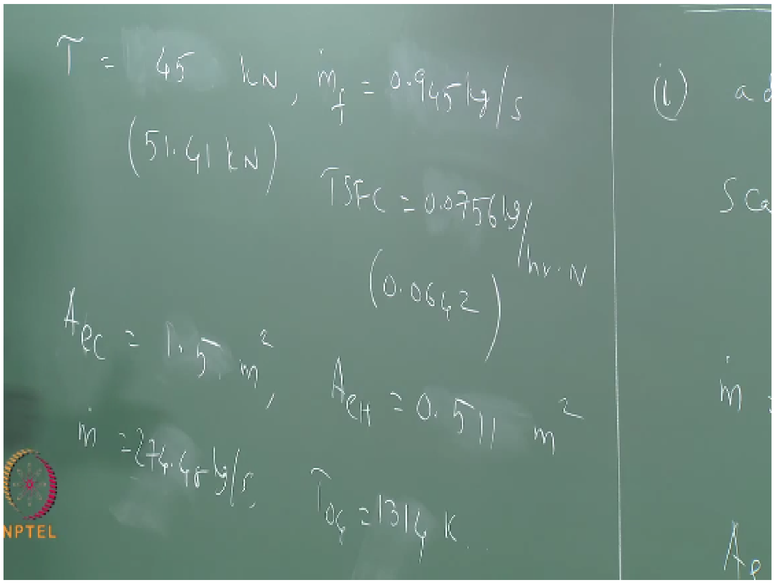

$T = 45$ kN, $\dot{m}_f = 0.945$ kg/s

(51.41 kN)

TSFC = 0.0756 kg/hr·N

(0.0642)

$A_{ec} = 1.5\ m^2$, $A_{eH} = 0.511\ m^2$

$\dot{m} = 274.48$ kg/s, $T_{04} = 1314$ K.

So, the total thrust comes to be the sum of these two which is 45 kN. Now, you can see that the comparison of the manufacturer coated value this much better, okay. Mass flow rate of fuel for this T04 works out to be about 0.945 kg per second, instead of 2.94, this has now become 0.945 which then gives me TSFC of 0.0756. You cannot expect better match of TSFC than this. Thrust can probably be reasonably well, but matching TSFC requires much more information about the engine most of which is actually going to be proprietary information.

So, we really cannot get even more realistic predictions than this with the information that is available in the public domain. Now, of the cold nozzle now we have adjusted this to be 1.5 metre square. The area of the hot nozzle based on this procedure comes out to be 0.511 metre square. We have adjusted that also nicely. The mass flow rate through the engine has now been adjusted to be 274.48 and the stagnation temperature is now 1314.

So, you can see that our calculation procedure actually allows us to adjust conditions. It is able to not only predict values correctly for static conditions but we are also able to adjust the thermodynamic quantities, the area is another thing for predicting thrust correctly under cruise conditions also. So, the procedure is actually a very consistent procedure. What you must remember is that there are only two factors which are at our disposal.

Remember, when we did this, we assume that the bypass ratio is fixed which is always going to be fixed. When you takeoff and then go to cruise, you are not going to change the bypass ratio because the bypass ratio changes only with the diameter of the fan, that cannot be changed. We kept that the fan pressure ratio also fixed, okay which is reasonable. There are some engines which can actually operate with adjustable fan pressure ratios, but assuming fan pressure ratio to be fixed is a reasonably good assumption.

We also assume that the pressure ratio is fixed across the compressor which is usually reasonable assumption to make also. Generally, the engines are designed to operate at fixed values of pressure ratios and fan pressure ratios. They are usually not changed, although there are designs available which do that, these are reasonable things to assume. So, the parameters that are available in the (()) (19:32) law as we said earlier, pressure ratio, turbine entry temperature, bypass ratio and fan pressure ratio, these are the four parameters.

So, we kept three of them constant. Only thing we changed was the turbine entry temperature which give us the kind of results that you are looking for. Mass flow rate can be adjusted without changing any other values for the thermodynamic property, that is what we did here, okay. So, the calibration procedure is very evolved but it is very powerful, allows you to make very good predictions for both static as well as cruise conditions and the exercise involves lot of problems which are actually engines which are in service today.

So, you can go through this calculation procedure for the problems given in the exercise, compare the values and then see how things go, okay. Are there any questions, okay? So, that actually concludes our objective of what we set out to do for aircraft engines, okay. So, turbofan engines and turbojet engines, we wanted to do thrust calculation and thrust specific fuel consumption calculation.

So, we are completed that now. What we are going to see next is emerging trends in the industry for turbofan engines or commercial aviation engines. Then, we will move on ramjets and scramjets.

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EMERGING TRENDS

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So, let us look at some of the emerging trends that are being seen in the commercial aviation industry today with respect to aircraft engines. We are not really talking about changes in fuselage or structures and so on or aerodynamics. We are only looking at emerging trends in engine technology, that is what we have been talking about.

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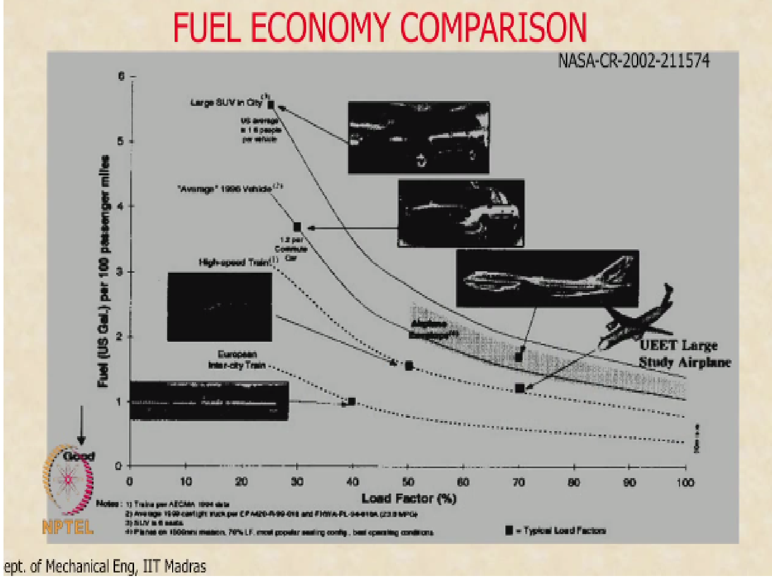

FUEL ECONOMY COMPARISON

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So, this is a little bit of dated plot but it is actually very revealing. The plot allows us to compare fuel economy of various modes of transportation, okay. Starting from sports utility vehicle to passenger sedans to aircraft to high-speed trains and intercity trains. This is probably not graphic that one would like to present when teaching a course on aircraft engines because these shows aircraft engines in a very poor light in terms of fuel economy for number of passenger miles, okay.

So, you can see that aircraft actually are better than sport utility vehicles. So, aircraft lie here. The most efficient aircraft is expected to lie perhaps over here. This is a concept plane that is being studied, ultra efficient engine technology airplane. So, this is located over here. But you can see passenger trains which transport a lot of people have probably the best fuel economy curve, okay. This is at a load factor of 70 and if you think about typical Indian trains, they carry approximately 1700 passengers or more per train.

So, the load factors for trains in express trains in India will be close to 100% if not more than that. If you discount people travelling on the roofs and things like that, the load factor will be about 100 for the Indian trains. So, in terms of fuel economy and emissions probably the goal standard will always be passenger trains or express trains. Use of the airline industry probably should do a lot to meet these types of goals and standards.

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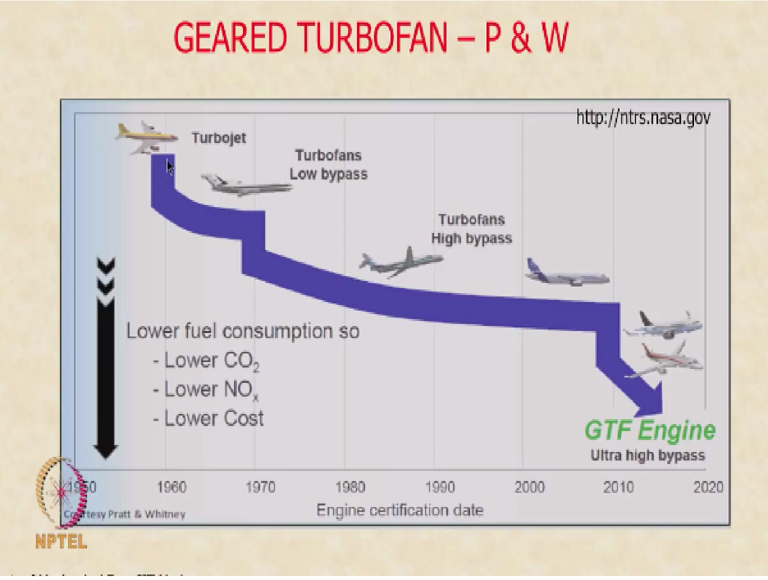

GEARED TURBOFAN – P & W

So, what we are going to do in this module is to see what kind of technologies are being attempted to bring this operating point closer to or if not competitive to passenger trains, okay. So, this is how the technology has been evolving over the years starting from 1950s to about 2010. Then, we moved to turbojet engines and turbojet engines are not really very fuel efficient. The big advantage that they gave was that you could fly at high subsonic flight Mark numbers but fuel economy was not one of the things that was proposed for turbojet engines.

You must also bear in mind that in the 1950s and 1960s, price of oil was relatively very low. Oil was very cheap, so fuel economy was not a major concern in those days. The speed of flight was much more of a driving concern than fuel economy cost of fuel, but today as I said earlier more than 50% of the operating cost of any airline in the world is fuel cost. So, now fuel cost is the driver for the technology changes the industry.

So, you can see from turbojet, we went to turbofan engine. These are the introductory low bypass turbofan engines and as you can see from here, there is an improvement in the fuel economy and it is a kind of a tapered out in the 1970s with low bypass turbofan engines. Then, the high bypass turbofan engines were realized. Remember, it is not a big jump to go from turbojet is to low bypass turbofan engine because a low bypass turbofan engine will have reasonably small fan diameters.

It is not going to be a transonic fan. It is only when you increase the fan diameter, that you run into the problems of transonic fans and as the diameter increases, if you remember we also said that we need to spin the fan down slower, otherwise the centrifugal stresses will be very high. So, the higher bypass ratio engines bring in those kinds of challenges, transonic fans as well as differential speeds, multi-spool technology and so on.

So, the low bypass turbofan engines do not present a challenge. So, it was a little easy for the industry to migrate from turbojet to low bypass turbofan engine but it took a while before they could migrate to high bypass turbofan engines and we looked at these technological challenges and how they were overcome in our earlier lectures. So, over the years the high bypass turbofan engines, technology relating to that are more or less stagnated as you can see from here.

This is a long span, okay. This is we are talking nearly 40 years. So the technology has matured and it has stalled. So, no more gains in fuel economy or efficiency or emissions appear to be possible in the current technology, which means we are looking for a paradigm shift. If you will forgive me for using this cliché, we need a paradigm shift to realise bigger changes in fuel economy and the paradigm shift appears to be the gear turbofan engine which probably will be rolled out later this year.

So, that is a technology that will start flying in the skies later this year. This is a gear turbofan engine and it is expected to give a big boost about 15% to 20% savings in fuel and a considerable amount of reduction in noise also in addition to other things. Of course if you have 15% to 20% reduction in fuel consumption, naturally you are going to reduce the amount of CO2 and amount of NOx okay.

Cost will also go down, operating cost will definitely go down if you have a 15% to 20% savings in fuel, that is what is being projected for the gear turbofan engine. Let us see what is being done now.

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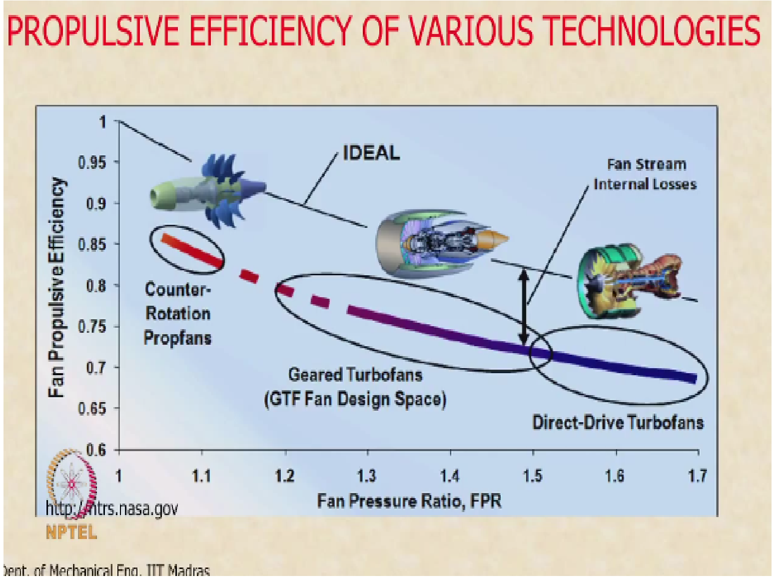

PROPULSIVE EFFICIENCY OF VARIOUS TECHNOLOGIES

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So, here is where the current technology is. This is the direct drive turbofan engine. By direct drive what we mean is the fan directly coupled to the turbine and this is one of the key barriers that we discussed earlier, because the fan is directly coupled to the turbine and the turbines have to be run at a certain minimum speed to keep the flow moving through the blade passages.

We were forced to run the fan at a speed of 3000 RPM which brought in its own challenges, centrifugal stresses, multi-spool technology, transonic fans, so those were the challenges which were brought about because these are direct drive turbofans, the fan is directly connected to the turbine, okay. Because the diameter is large and the fan speeds are also larger, these fans typically operate with fan pressure ratios around 1.6 to 1.7, that is what we used in our calculations also just now but we want an example.

So, this is the space in which direct drive turbofan engines operate with propulsive efficiency around 0.8 or so and you will remember that we had a chart earlier which compared the various propulsion technologies, right. Starting from the propeller which had a bypass ratio of infinity to the pure turbojet which had a bypass ratio of zero; and if you remember, we pointed out that the high bypass ratio turbofan engine has an efficiency which is better than the peak efficiency of a propeller engine, okay.

So, we are talking about efficiencies of the order of about 0.8 or so, but the bigger tumbling block in improving the efficiency further has to do with this direct drive. If you can allow the fan to spin at a lower speed, then efficiency of the fan will increase even more, but in order to do that you cannot have a direct fan anymore. So, the trend is to go to gear turbofan engine. So, you place the gearbox between the fan and low pressure turbine.

So, the gearbox allows the fan to run at a lesser speed and at its optimum efficiency point. So, you can see increases in efficiency to about 0.85 or so. This may not mean much, an increase of 0.5 or 0.05 may not seem much, I mean it may not seem to be much but in terms of fuel economy, this can be quite a lot and from a noise perspective also this can be quite a significant shift, we will look at that next, alright.

Now, the best technology as things stand today appears to be the counter rotating prop fan. We showed a picture of this in the early part of our lecture, you can go back and take a look at that. This is a technology that GE is pursuing. The gear turbofan is a technology that both Rolls-Royce and Pratt & Whitney most notably, Rolls-Royce also seems to be pursuing this technology. GE is pursuing the counter-rotating propfan technology which supposedly has efficiency at least on paper close to 0.95 or so.

Very difficult to realise in practice but that is very the GE is going. Okay. Now, if you notice you can see that as we spin down the fan, the pressure ratio at which you have to operate also goes down, right. As you spin it down, the relative Mark number of the flow that approaches the fan blade goes down. So, the fan can also operate at a lesser pressure ratio where its efficiency can be higher. So, you can see that the pressure ratio goes this. The pressure ratio is decreasing this way.

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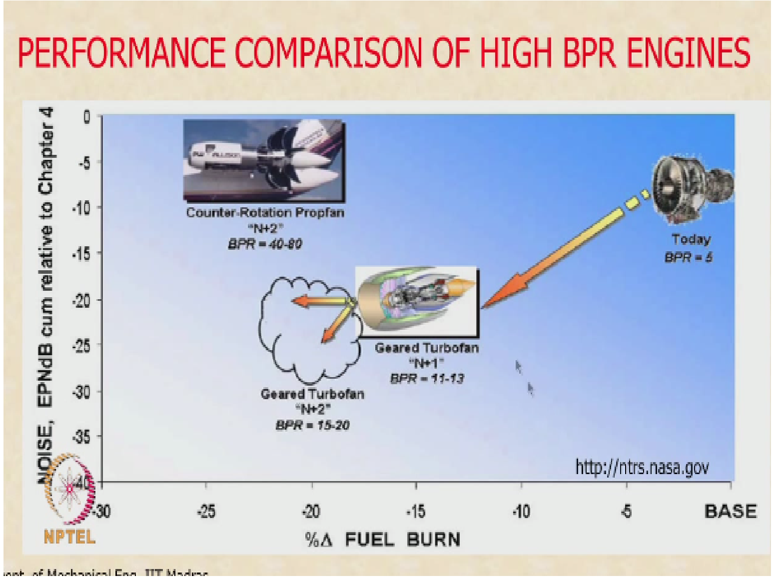

PERFORMANCE COMPARISON OF HIGH BPR ENGINES

So, here we are looking at benefits of the proposed technology. So, this is where we are today bypass ratio around 5 to 6 or so. So, if you take that as your baseline for noise, okay. Here on this axis plotting noise benefit from the baseline perspective, okay. So, here we are talking about effective perceived noise level in decibels, okay. You can see that the current engine stands here with a gear turbofan fan with the projected improvement in fuel efficiency.

We are looking at a fuel efficiency improvement of about 15% to 20% with increased bypass ratio. Even with the same bypass ratio, you can realise substantial fuel savings, okay. The counter rotating propfan is supposed to give reduction in fuel flow rate of 25% but there is not a noise benefit but there is not a noise disadvantage either. It appears to have the same noise level as the current family of engines but with a 25% improvement in fuel consumption, okay. So, this is where the industry is heading today in terms of propulsion technologies.

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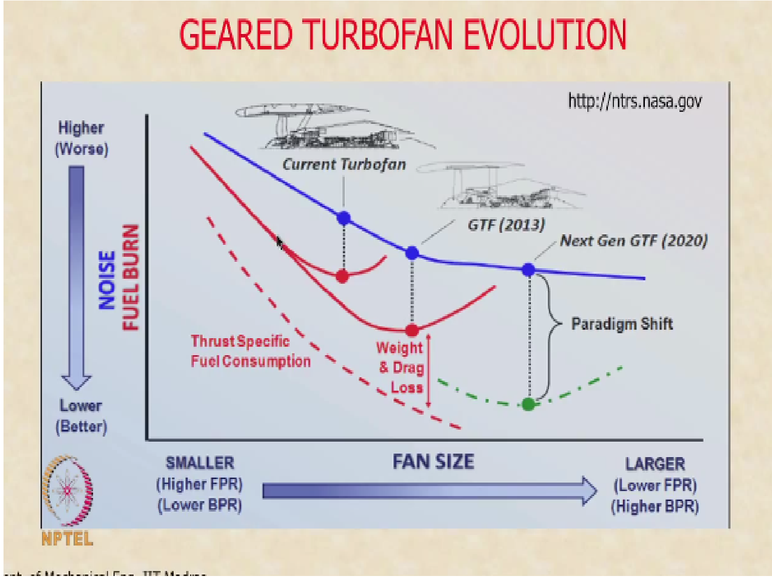

Now, if you look at the gear turbofan itself, we are talking about two important matrix; one is noise, another one is fuel burn. This has to do with efficiency, this has to do with compliance with noise standards. So, the blue line here pertains to noise and the red line here pertains to variation in fuel burn with increasing fan size, okay. So, as you can see the current family of turbofan engine sit over here, this is their operating point, okay.

Here, as we increase the fan size, we are going from a lower bypass ratio to high bypass ratio and as you increase the bypass ratio, I can relax the fan pressure ratio. Remember, the thrust produced by the fan nozzle is dependent on two quantities; one is mass flow rate through the fan nozzle, the other one is the pressure rise across the fan. So, generally what is done is for a fair comparison as I increased the bypass ratio, we will decrease the fan pressure ratio which improves the efficiency considerably, right.

So, as you can see from here, the current technology turbofan engine in terms of fuel consumption sits as the best point possible, the lowest point in this curve, which is why I said that this technology has matured and it is very unlikely to see significant improvements in this technology. Even if you increase the bypass ratio, you can see that there is actually an increase in fuel consumption due to certain other issues which we will talk about later, okay.

So, the only way to improve fuel economy is to move away from this curve, jump from this curve to another curve. So, this is the curve corresponding to gear turbofan engine. So, you can see that gear turbofan engine if you increase the bypass ratio definitely we get a much higher fuel consumption benefit. If you operate at the same bypass ratio, even then get a good amount of benefit in terms of fuel consumption, okay.

Noise may not improve significantly but you get a good amount of improvement in terms of fuel consumption even if you operate at the current bypass ratio, okay. Now, the green one here is supposed to be either the next-generation gear turbofan or the propfan, okay. Next-generation gear turbofan is supposed to address some of the issues with that you have when you increase the bypass ratio to such large values.

Currently, the gear turbofan operating space is in this region of bypass ratios about 10 to 11 or 12 which is the highest bypass ratio engines that are in service today, that is the design space that we are looking at for gear turbofan. Increasing the bypass ratio beyond that will require the industry to work on certain other tech technology obstacles which we will talk about, okay. So, this is what we are talking about. This is why it makes sense to move to the gear turbofan that the industry is moving to today. It is driven by fuel economy, cost of fuel.

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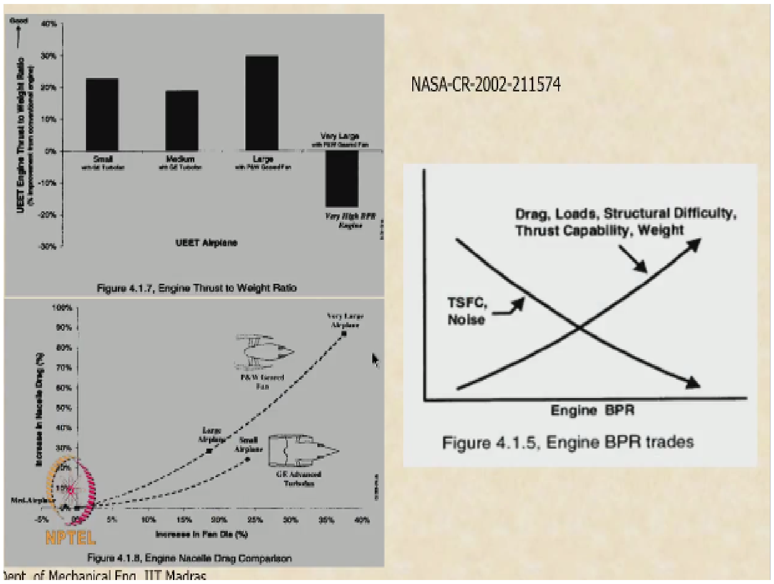

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Figure 4.1.7, Engine Thrust to Weight Ratio

Figure 4.1.8, Engine Nacelle Drag Comparison

Figure 4.1.5, Engine BPR trades

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Now, as you can see from here, if I increase what we are seeing on the Y-axis here is the thrust to weight ratio. Remember, we said the thrust weight is the critical requirement for an aircraft engine technology, right. So, as you can see from here as I increase the bypass ratio, with large bypass ratios with about 10 to 12 that we are operating with today, we definitely get good thrust weight metrics but if you go to very large bypass ratios that actually becomes a distinct disadvantage.

We lose all. So, here we are looking at increment of thrust to weight. So, from the previous technology when I to a small bypass ratio gear turbofan, I get some benefit. Medium bypass about the same benefit. Large bypass ratio I get good amount of benefit in thrust to weight, about 30% benefit in thrust to weight ratio. So, per unit weight, the same engine produces 30% more thrust with the gear turbofan for bypass ratios around 10 to 12.

However, if I become greedy and go to very large bypass ratios, then the same engine for the same weight it produces about 20% less thrust than the previous version, okay. So, there are some significant technological obstacles that need to be overcome before we can migrate to very large bypass ratio engines with gear turbofans. The propfan does not appear to have an issue here but it has its own technological challenges, okay. This is only for the gear turbofan engine, okay.

You can see what happens when I increase the bypass ratios. So, as I increase the fan size from the baseline to a larger value, you can see that the very large bypass ratio engines, the (()) (37:59) drag because the frontal area increases so much, the nozzle drag increases quadratically with fan diameter, okay. So, you can see that very large bypass engines have much higher frontal drag. So, the increase in thrust that you are realising is being not only offset but also being negated by the increase in the nozzle drag.

So, it is actually becoming a disadvantage. We are producing less thrust than before when you go from large bypass ratio to very large bypass ratio. This slide summarises very nicely the trade-offs when you increase the bypass ratios. So, as I increase the bypass ratio from left to right, you can see that the thrust specific fuel consumption reduces, noise also reduces.

However, the nozzle drag continues to increase, weight increases, the structural difficulty meaning integration of the engine with the airframe becomes more difficult. The very large bypass ratio engines cannot be mounted below the wing. So, they have to be mounted above the wing or on the tail or the fuselage, that becomes a challenge in itself because the engine is much heavier than the large bypass ratio engines, okay.

So, that posses a lot of structural challenges. So, these are the disadvantages as I keep increasing the bypass ratio. These are the advantages. So, what we needed is this appears to be the sweet spot. This is where we would like to operate. So, improved technology will perhaps bring this rise a little bit down, so that we can enjoy the same benefits even at higher bypass ratios, that is what we have to see, okay.

So, if the sweet spot could be shifted, let say to the right, meaning this curve become shallow, then if it goes like this, then we will be in good shape. So, that is where the technology is trying to go but right now what we will look at is what is going to be offered later this year, that the latest technology.

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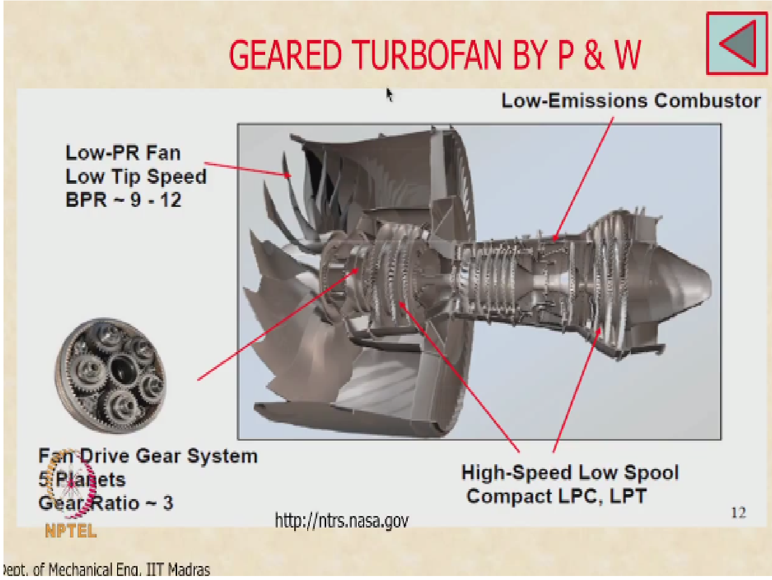

GEARED TURBOFAN BY P & W

Low-Emissions Combustor

Low-PR Fan
Low Tip Speed
BPR ~ 9 - 12

Fan Drive Gear System
5 Planets
Gear Ratio ~ 3

High-Speed Low Spool
Compact LPC, LPT

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That is the gear turbofan by Pratt & Whitney, okay. If you remember, let us just quickly go back and take a look at the motivation for doing this.

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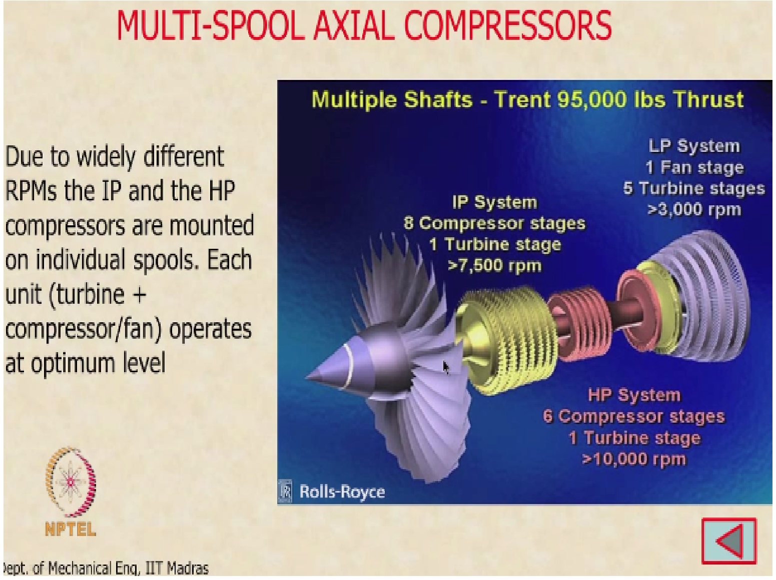

MULTI-SPOOL AXIAL COMPRESSORS

Due to widely different RPMs the IP and the HP compressors are mounted on individual spools. Each unit (turbine + compressor/fan) operates at optimum level

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This is a direct drive turbofan that we saw earlier and we emphasized the fact that the fan has to run at speeds around 3000 RPM or more because it is directly coupled to the turbine. The turbine cannot run at speeds lower than this. We actually allow different parts of the engine to run at different speeds again for the same reason because the fan was really quite large and the centrifugal stresses would have been very large.

So, we said that fan has to spin at a slow RPM whereas the high-pressure compressor has to spin at a much higher RPM. So, then we segmented the engine and mounted them on different shafts, that this ran at a very high speed, this ran at an intermediate speed, this could run at the lowest possible speed but that was 40 years ago. The time has come to allow this to run at even slower speed which means that we still have the multi-spool technology but now we place the gearbox between the fan and the turbine shaft which will allow this to spin at even lesser speed and be more efficient.

As the speed reduces, the efficiency of the fan increases because the pressure ratio can be brought down. So, that is the motivation for the gear turbofan technology but the biggest challenge was in realising the gearbox which would work. As I mentioned some time ago, the amount of power that this gearbox has to transmit is of the order of about 30,000 HP, okay. For high bypass ratio turbofan engines about 30,000 HP.

So, to design a gearbox which can transmit this power, be lightweight should not add significantly to the weight and also produce much less mechanical noise. Remember if you are going to add a gearbox, mechanical noise is the major problem. So, this is a major challenge in terms of turbology and gear design and strength and lightweight. So, this is a challenge which (()) (42:26) presumably as overcome.

So, they are utilizing five and a gearbox with the gear ratio of three which allows the speed to be step down by a factor of 3. So, this has bypass ratios as I said in the high bypass ratio range, 9 to 12. Low pressure ratio fan, okay. Low tip speed because we have stepped it down by a factor of 3. We have stepped down the RPM by a factor of 3. The tip speed also go down by a factor of 3. So, we do not need presumably the controlled diffusion aerofoils.

Very likely the tip speed may not even see supersonic relative Mark numbers. So, double circular arch may itself be sufficient. So, a lot of things become simple. If you could realise this critical piece of technology. So, that is what the Pratt & Whitney is using today.

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GEARED TURBOFAN BY P & W

	Projected Based on Demonstrated Technology
NOISE (cum margin to Ch4)	-20 EPNdB
LTO NOX (below CAEP 6)	-60%
FUEL BURN (relative to 737/CFM56)	-15%
MAINTAINANCE COST	Significant Reduction

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So, here you see the experimental engine being mounted on an aircraft and this is being test flown as we speak today and it has noise advantage of reduction of 20 decibels in effective perceived noise which is actually a lot. A 20 decibel is actually quite a lot. As I said earlier, decibel scale is a logarithmic scale and human ear has only a fidelity of +/- 2 dB; however, if you reduce the noise by about 4 dB or 5 dB, 50% of the people would perceive that to be a 50% or most of the people would perceive that to be a 50% reduction in noise.

Remember, noise is a perceived quantity. So, majority of the people would feel a 4 decibel reduction in noise to be a 50% reduction in noise, although their hearing itself only has a fidelity of +/- 2 dB, okay because it is a logarithmic scale. So, 20 dB is a big reduction in noise and fuel burn supposedly is around 15% or so, okay because you have kept the bypass ratio the same as existing engines, high bypass ratio not very high bypass ratio.

You will see 20% to 25% reduction in fuel burn only when you go to very high bypass ratios. So, here we are staying with a high bypass ratio so there is a saving of about 15% in fuel burn or 60% reduction in NOX for a 15% reduction in fuel burn does not seem to make sense unless there are some other things which have been done in the combustor, okay. But a 15% reduction in fuel consumption will definitely reduce the amount of NOX and CO2 that you are producing, there is no doubt about that. So, this is what presumably will be offered.

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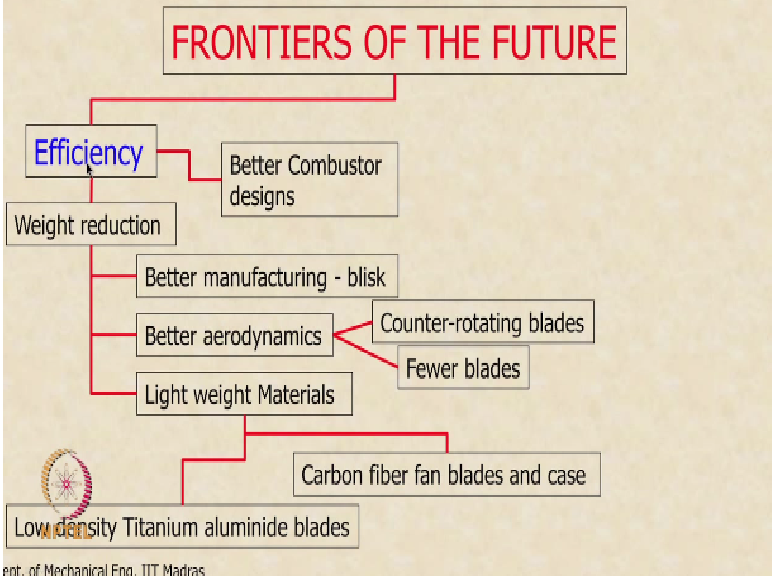

FRONTIERS OF THE FUTURE

Efficiency

Better Combustor designs

Weight reduction

Better manufacturing - blisk

Better aerodynamics

Counter-rotating blades

Fewer blades

Light weight Materials

Carbon fiber fan blades and case

Low density Titanium aluminide blades

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It is being test flown and this will be offered towards the end of the year. So, we should be able to see these in the skies probably towards the end of 2014 or beginning of 2015. Hopefully, that will make flying cheaper, somehow I doubt it, okay. So, we have seen the kind of things that are in the offering in the immediate future. What we are going to see next is how the benefits are going to be accomplished.

There are two frontiers in which engine technology is evolving today, okay, one is from the efficiency perspective. The other one is from compliance perspective. How do you comply better with emission norms and noise norms, right, that is the other perspective. So, more efficiency is being pursued in two different directions or two different fronts, one is better combustor design because fuel economy is going to give better efficiency, that is one line of pursuit for improving the efficiency.

The other line of line of pursuit is the weight reduction, produce more thrust per unit weight of engine. Now, the weight reduction target itself can be pursued in many different directions, let us see. Better manufacturing practices. If you remember, we said that the compressor blades are mounted onto discs and the discs are mounted onto the shaft, okay. Now, new manufacturing technologies allow the blade and the disc to be manufactured as one single piece that is called the blisk.

This is the blade plus a disc through better casting and manufacturing practices, we can now blade integral with the disk which results in considerable weight advantage, okay. So, there are improvements in better manufacturing which can result in weight reduction, better aerodynamics for the compressor and turbines will definitely improve the weight perspective. If the same blade can do more that means I can reduce the number of blades.

If I can make the same blades stage do more, then the number of stages can be reduced. If I reduce the number of stages, then the number of blades also go down significantly which can result in significant weight advantage. So, that is how we are pursuing better aerodynamics what is being done in better aerodynamics of turbo machines. Number #1, counter rotating blades. If you remember we said that the straighter blade does nothing but redirect the flow from one rotor stage to the next rotor stage, that is all it does. It is not doing anything more useful for me.

Can I make it do something more useful? If I allow the straighter blades to spin in the opposite direction to a rotor blade, then that can also participate in work interaction. So, if it is a compressor, I can transfer work to the blade because now that has become a rotor. So, I can cut down the number of stages by a factor of 2. So, the straighter now is doing more for me. So, counterrotating blade is a technology that is currently being used in GEnx engines and other engines which are offered with the latest aircraft.

So, the straighter blades are now doing more. They are not only redirecting the flow, but they are also participating in work transfer, and fewer blades. As I said if I am able to better aerodynamics, I can reduce the number of blades which can also reduce the weight for the engines, so the weight reduction can be pursued through better manufacturing, better aerodynamics and obviously lightweight materials. If I can make the material lighter, then I can lose the weight.

What are some of the technologies that are being pursued, the fan blade and the fan case are now being manufactured with carbon fibers instead of the titanium that we talked about, now they are being made of carbon fibers which actually results in significant amount of weight reduction and the compressor blades are being made out of low-density titanium aluminide material, okay. So, this allows the weight to be reduced substantially.

Even if you are able to reduce by 10% considering the number of blades that are there in the engine. This can result in a significant weight advantage, okay. So, these are the frontiers in which improved efficiency is being sought in engine technology. In the next class, we will look at what is being done in terms of better meeting norms, right, compliance with norms, then we will move on to the next module.