Jet Aircraft Propulsion

Prof. Bhaskar Roy
Prof. A. M. Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Lecture No. # 32
Engine Off-Design Operations

We are talking about jet aircraft engines. Now, one of the duties of the engine is to make the aircraft fly and when it flies, it has to fly under various operating conditions. For an aircraft to fly, it has to takeoff; it has to climb to certain altitude; then it has to cruise; it may have to do some maneuvers, if it is a military aircraft and then it has to descend and finally, it has to land back safely to the ground from where it had taken off. Now, all these flight regimes require different kind of engine operations. So, when the engines are used to make an aircraft fly, they have to ensure that they provide sufficient power or thrust to the aircraft during all these various flight regimes.

Now, the requirement for thrust during takeoff, during climb or during cruise or various maneuvers are quite different from each other. You see one of the reasons an aircraft flies to very high altitude and cruises there. Most of the passenger and transport aircraft do that or even military aircraft going to long distances quite often fly to high altitudes and then fly to the destination. And one of the reasons they do that is because at high altitude, the air density is very low; the thrust is very low. And as a result, the engine would have to do much less work; create much less thrust for the aircraft to fly.

The same aircraft to fly at a much lower altitude near the ground would have required much more thrust and that is the reason, aircraft is made to fly at a very high altitude. Now, which means that the engine has to provide thrust during takeoff, where the thrust requirement would be quite high. And then it has to provide thrust during cruise, where the thrust requirement would indeed be quite low. And this requires that the engine is able to operate under various operating conditions. At high altitude, the air density is low; the pressure is low; the temperature is low. At low altitudes at sea level for example, your density is high; the pressure is high.

And in hot countries like India and many other tropical countries, the temperature also would be quite high. And as a result, the engine is now asked to create thrust under various kinds of operating conditions and to do that, the engine has to operate differently. Now, this different kind of operation requires the engine to act differently and as you have seen through various lectures in this lecture series, engine has a number of components. It has an intake; it has a compressor; it has a combustion chamber; it has turbine and then it has a nozzle and all these components together make up the engine.

When we are asking the engine to create different kinds of thrust different amounts of thrust under different operating conditions, all these components would have to now operate under different working conditions in illusion together in a coordinated manner and then create different kinds of thrust under different working or operating conditions. Now, this means that the engine per force needs to have its intrinsic capability to work under different kinds of operating conditions. And all the component should work together to create thrust with reasonable degree of efficiency reasonable amount of efficiency.

Because at the end of the day, you want an engine which is reasonably fuel efficient take in over the entire flight spectrum. And this efficiency as we know translates to overall fuel efficiency of the aircraft. In case of transport aircraft, it translates to operational efficiency of the aircraft itself. And as a result of which, it is necessary that we have an engine that under various operating condition operates reasonably efficiency. And as a result, the overall fuel efficiency of the engine working at various operating conditions is quite good.

Now, this is a requirement under which aircraft needs to be created or designed. So, when an aircraft is designed, it has to take into account all these operating schedules or conditions for creation of the engine. Now, typically an engine is designed for what is known as a design point. Now, this design point is normally very close to one of the highest thrust making conditions at which the engine is expected to be operated on. And then the load thrust making conditions, under which the aircraft has to operate; the engine has to operate would be called off-design operating conditions.

What is necessary now is to ensure that even while creating less thrust, it operates at a reasonably good efficiency. If it has to work under various operating conditions, it is quite possible that some of the components could work under very poor efficiencies. At the time of design, this has to be factored in. Because once the engine is made and once the engine is installed, there is no other way the engine efficiency can be improved. So, the improvement and ensuring that it works under various operating conditions efficiently has to be done a priory during the process of design of the engine.

And hence we say that an engine has what is called a design point, at which all the components all the various geometrical components of the engine; the intake, the compressor are geometrically shaped and sized to give the maximum performance, which is quite often in the thrust at very good efficiency. And then under various other operating conditions, all these components which are already sized and geometrically shaped. They also give very good efficiency even while creating different amounts of thrust. This is what, the engine designer has to ensure by design. Let us take a look at various factors that go in to this consideration.

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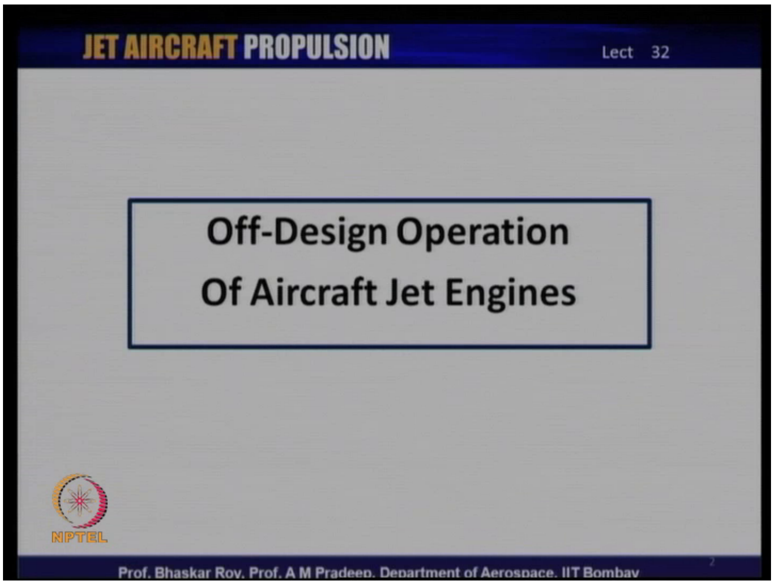

Let us try to understand what it is off-design operation of aircraft jet engines. You see an aircraft is designed on the basis of a cycle, which you have done in quite a great detail in the earlier lectures.

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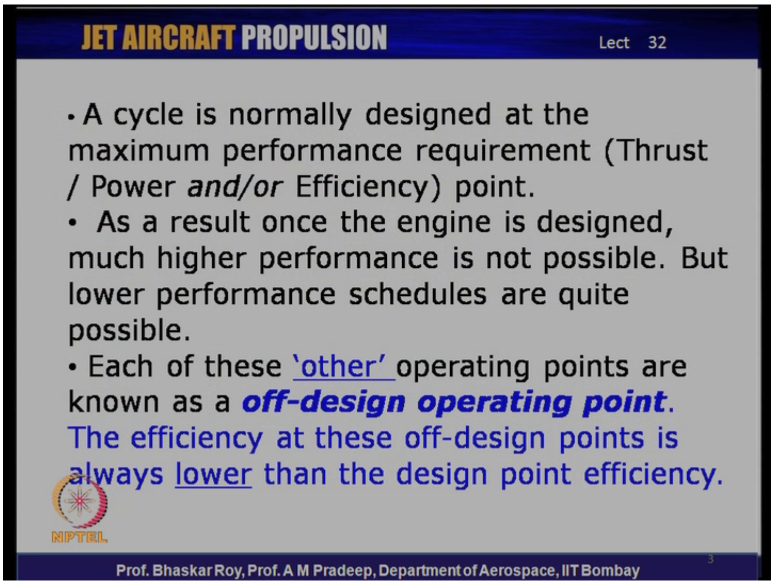

Now, this cycle is normally designed at the maximum performance requirement. So, the design of the cycle itself is for maximum performance requirement or pretty close to maximum performance requirement. So, once an engine is designed and created, much more performance out of it than the design point is normally not possible. You may get about 5, 10 percent more; but anything more than that is normally not possible. So, what you get is engine design for very close to its maximum performance requirement. As a result of this, it is necessary that the engine noise now able to give thrust or lower performances, which are required for various other aircraft operations.

And all these other operating points are known as off-design operating points. Now, what happens is since they are off-design points; they are not the point at which all the geometry of the components have been designed, it means that these components each of these components will work at a slightly lower efficiency than its design point. And all of them together would invariably then work at a efficiency engine as a whole lower than the design point efficiency. What is needed to be done is to ensure that give efficiencies do not go very low.

If they go very low, then ofcourse it will finally reflect on the overall fuel efficiency of the engine and the fuel efficiency of the or the fuel economy of the aircraft operation. So, by design it is needed to ensure that under off-design operating conditions, the engine continuous to give good performance at a reasonable efficiency. We understand that the efficiencies are going to be slightly lower than the design point efficiency. But we have to ensure by design that they do not go too far low. So, that the overall fuel efficiency of the engine is still quite good. Let us try to understand a little more about what is a design point operating condition.

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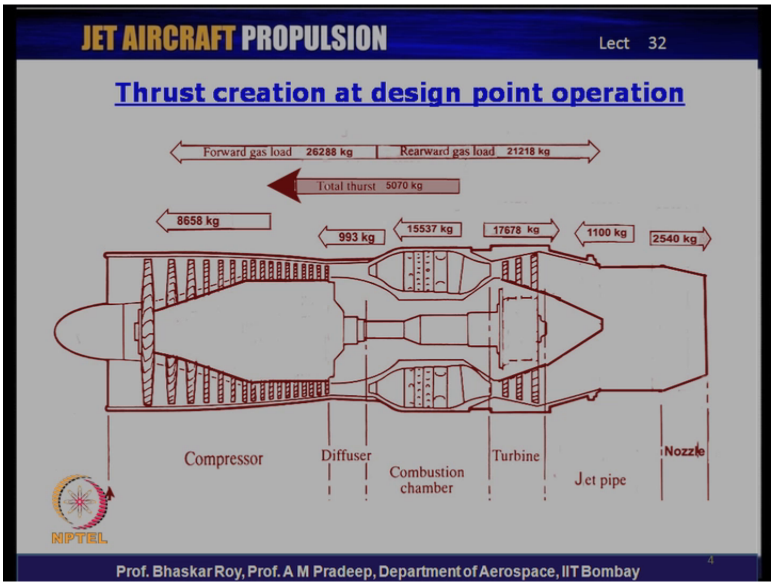

If you look at this diagram, we see that every component of an engine actually participates in creation of thrust. A compressor creates certain amount of thrust; the combustion chamber creates certain amount of thrust; the turbine creates a certain amount of negative thrust; the jet pipe creates certain amount of thrust and it is possible that the nozzle may create positive or negative thrust by itself. When you put them all together, you have certain amount of forward thrust and certain amount of rearward thrust and the combination of the two give us the total forward thrust. So, all the components put together, we get a forward thrust.

Ofcourse, the way we calculate the forward thrust is simply subtract the momentum at the exit from the momentum at the entry and the change of momentum is what we call thrust. But what we see here now is that every component actually participates in the process of creation of thrust. Now, this means that when we create an engine at the so called design point, each of these components is created to ensure that they participate in the process of thrust making exactly in the manner that is required for the particular design point. Now, what happens at the so called off-design point that we are trying to understand now. Under off-design point, each of these components will again operate in their own way at certain off-design operating point.

And then again they will try to create their own amount of thrust, which again as we see could be positive or negative. And as we see, the compressors normally make positive thrust;

the turbines normally make negative thrust; the other components may give positive or negative thrust. So, under off-design conditions, it is entirely possible that some of these other components may start giving more of negative thrust. Or in some other conditions, the compressor may start giving less of positive thrust. Now, all these things put together finally give us the positive thrust or the forward thrust. We have to ensure that under off-design operating conditions, the participation of each of these components which are spaced out over the engine continued to give us thrust that is required.

For example, an aircraft if it is designed for takeoff and creates high thrust during takeoff, we have to ensure that during cruise when the thrust requirement is very low indeed. All these components put together still give you enough thrust for the aircraft to fly at cruise condition economically and safely. Now, this is something which has to be ensured at the time of design of the engine. So, the off-design operating point has shown a great importance during the design of the engine itself. And we have to ensure that participation of each of these components in creation of thrust continues to be exactly the way we would like them to be, even though they are shaped and sized for the design point to begin with.

This is more important when we are having a military engine, where it has to do all kinds of maneuvers. And during the maneuvers, it has to do very fast acceleration and deceleration of the engine in coordination with the acceleration and deceleration of the aircraft. And during this process, it has to create very fast thrust acceleration or thrust increase or thrust decrease during deceleration to match with the aircraft maneuver requirement. Now, this has to be ensured again that it happens exactly the way it is required for the aircraft operation and this has to be built in to the capability of the engine at the time of the design. And so, we see that the off-design operating conditions are often as important as the design point operating conditions.

And most of the modern engines are nowadays designed or let us say optimized to give good operation not only at design point; but at almost all the off-design operating conditions. So, modern aircraft engines are designed or optimized to give good performance at design point at various off-design operating conditions. This optimization procedure taking into account the requirements at off-design operating conditions is the hallmark of the modern engine designs. And as a result, the shape and the size of the component that we are seeing here is quite often optimized for off-design operating conditions or good off-design efficiencies.

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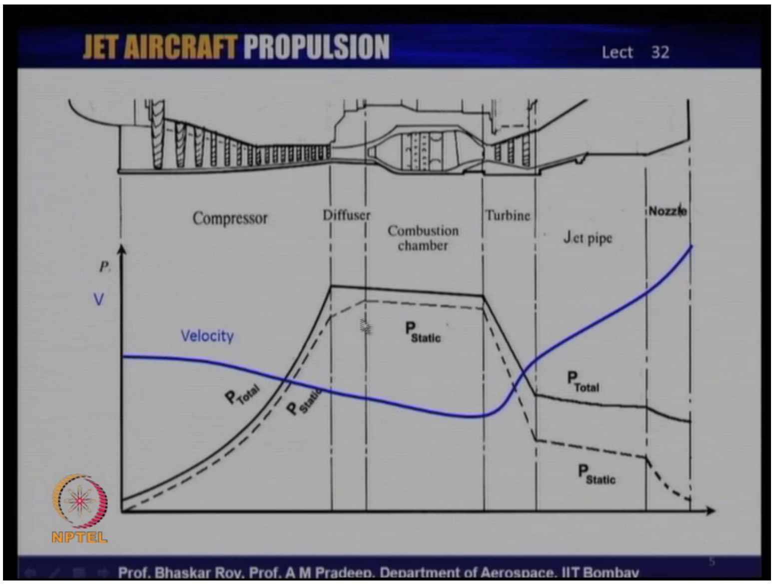

Let us see what happens a little more. In a typical engine, you have variation of pressure and velocity through the engine. The black lines tell you the pressure variation; the total pressure variation and the static pressure variation through the engine. The blue line gives us an approximate idea about the velocity variation through the engine. Now, again at design point, you have a certain pressure variation and based on which, the engine is designed; based on which, the engine cycle is designed. Under off-design operating conditions, both the pressure variation through the engine and the velocity variation through the engine would be quite different from this one.

And this variations of pressure, temperature and velocity; the three primary parameters through the entire engine under various off-design conditions would have to be considered, during the process of analysis of the engine and the design that goes into creation of the engine. And as a result of which, it is necessary that we have a very good a priory notion of the variation of fundamental parameters; the pressure, the temperature, the velocity through all the components of the engine in as much detail as possible. So, that the engine components are indeed configured sized and shaped in a manner. So, that under off-design conditions, they give very good performance.

How it go so far as to say that under certain modern engine design schemes, the design point performance may be slightly slightly compensate compromised or sacrificed to get better off-design operating condition. This is something which the operators, the engine designers have learnt over the years that sometimes it is necessary may be to sacrifice a design point performance just a little to get a much better off-design operating condition performance, which needs to be done under various operating conditions. Now, this is become a necessary thing at that time of design to optimize the various components of the engine in a manner such that its off-design operation and performance is very good.

Now, you see this is something which really is not a very big sacrifice or a very big compromise. Because the design point as I mentioned earlier is essentially the maximum thrust making operating point. The maximum thrust making operating point for most aircraft engines is indeed during the takeoff. Now, takeoff as we know actually requires the engine to operate for a very short period, which may be few seconds or may be half a minute or so. After which, the takeoff is over and the aircraft is flying. Now, during the process of flying, the thrust requirement is slowly going down and as it goes to high altitude, the thrust making requirement is lower and lower and it is going in to the so called off-design operating condition.

So, the design point requirement in terms of how long it is required is actually very small. So, if an aircraft or transport aircraft or a passenger aircraft or even a military aircraft makes a small sacrifice of the design point efficiency, it is not really a big sacrifice. And if this sacrifice is for the purpose of getting better efficiency during the off-design operating condition, it is a sacrifice worth making. So, that off-design compromise or the off-design optimization that I was shocking about is very much a done thing in the modern engine design and as a result of which, it is necessary that we understand very well what the off-design requirements are. Let us take a little more closer look at what various off-design operating conditions would indeed require.

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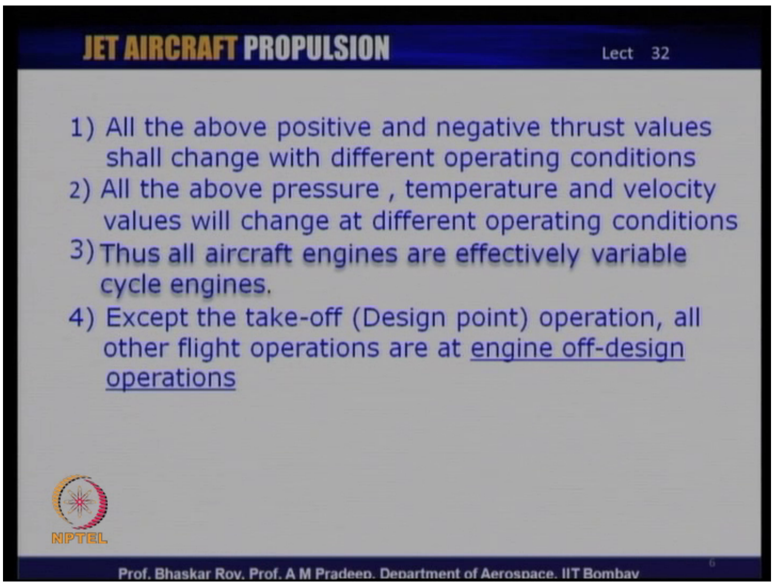

As we see now that off-design operating conditions require that you have flight operations at which the thrust requirements are more; operating pressure, temperature, velocity through various components are different. And we can thus say that an aircraft engine is effectively operating under different cycles during the various times of its flight. So, when the aircraft takes off under design point, it is operating at a design cycle. Once it is climbing, it goes; its cycle operation changes and then when one it is cruising, all the operating conditions are quite different from the design cycle operating condition.

And hence, it is operating at a completely design different cycle. So, one can say that an aircraft engine per force is actually operating as a variable cycle engine during the flight of the aircraft. It starts off with one cycle thermodynamic cycle. It assumes another slightly different thermodynamic cycle during the climb operation and once it reaches cruise, it settles down to a completely different operating cycle through the entire engine. And then ofcourse, if it is a military aircraft; if it is doing all kinds of maneuvers, each of these maneuvers would require essentially a different kind of cycle to operate through the engine.

So, when we talk about thermodynamic cycle, we have to quickly understand that engine per force has to operate under all these cycles during its actual operation and hence, an engine any engine in any aircraft is effectively a variable cycle engine. It has to operate under variable cycles during its entire operating schedule of the aircraft. And hence, we see that all these cycles have to operate efficiently under the so called off-design cycling operations and all of it together ofcourse gives us the overall engine efficiency. So, all these off-design operating conditions need to be then factored in to the engine design during the optimization process.

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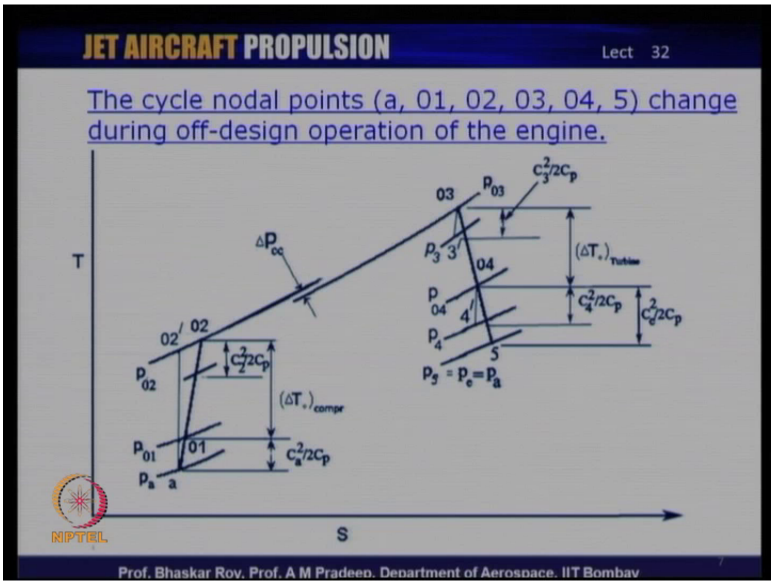

Let us see let us take a quick look at what we mean by cycle changes. When we have a cycle this is something which we have done in some detail earlier, we have the cycle operating condition 01, 02, 03, 04 and then 5. Now, this is what the engine is designed for; this is the cycle the engine is designed for. Now, what we understand under various operating conditions right in the beginning, the first point itself will be different; a will be different. Correspondingly, it is flying at a different altitude; it is flying at different operating speed flying speed. So, 01 will be different; correspondingly 02 would be different and 03 would be different and 04 would be different and 5 would be different.

So, all the nodal points of the cycle would be different under various operating conditions and it stands to reason then that the cycles that you have done before. All the intervening kinetic energy or the velocity values in between the C a, the C 2, C 3 and C 4 would be different under various cyclic operating conditions. So, when we see off-design operating conditions, we are talking about all the values shown in the cycle diagram completely different from the design point. So, under off-design conditions, all these values would be quite different from the design point operating condition.

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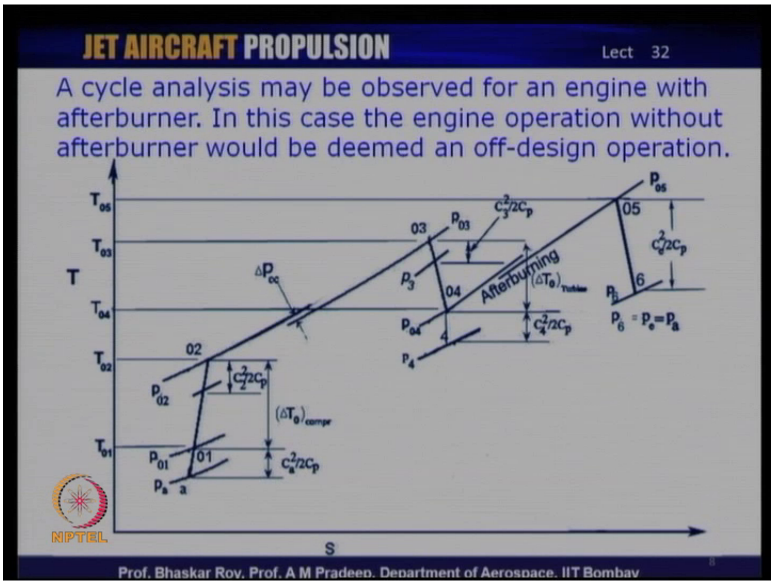

If you take a different kind of engine let us say a turbofan engine or to begin with an afterburner engine, now this afterburner engine is designed for operation of afterburner and we have an afterburner showed here in the cycle. Now, again not only all the nodal points 01, 02, 03, 04, 05 and 6 are different, it is entirely possible that in many of the afterburning engines. You may not have the afterburner at all; which means a non-afterburning operating point essentially is an off-design operating point. And the engine needs to be reasonably efficient during this off-design non-afterburning operating point. So, all the nodal points would be a quite different from the so called design point at which all the nodal points are designed for and the engine is shaped and sized for those nodal points.

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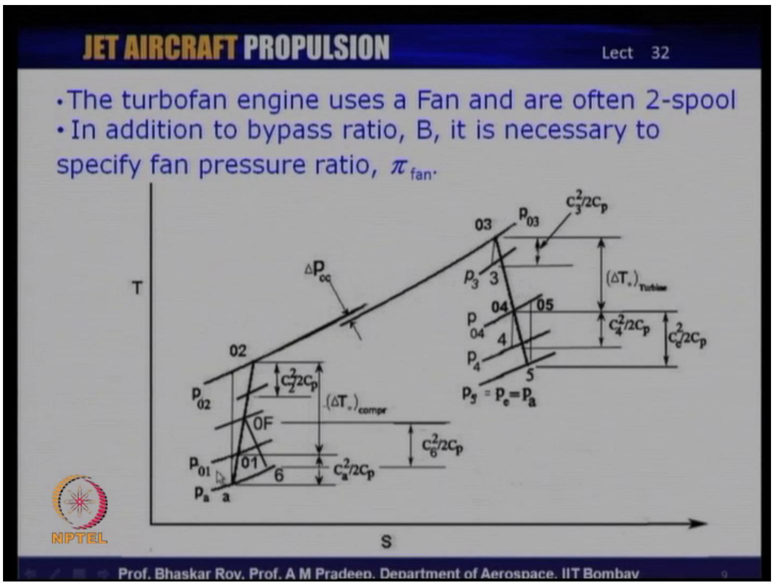

Let us take a look at a turbofan and here you have a fan which operates a big fan and then it has a nozzle of its own. Under various other operating conditions for example during cruise, the fan would have a completely different operating schedule. 01 to 0F would be quite different from that design point and 0F to 6 would be quite different nozzle operation from the so called design point, which could be the takeoff. And ofcourse as we said before, the main engine 02, 03, 04 and 5 would be quite different from the design point. So, we see that any kind of aircraft engine that you take whether it is a pure jet, afterburning jet engine or a turbofan engine, it has to per force operate under various kinds of cycle during its flight. And we have to ensure during the cycle design, during the engine design that its off-design operations are good.

So, as I was talking about, we have an engine that has to operate under different operating conditions. I was talking about shaping and optimizing the shapes and sizes of the components. So, that you may make a small sacrifice at the design point to get a much better off-design operating conditions. Now, we see that even the cycle that you design for may need to be optimized such that you may make a very small again compromise or sacrifice at the design point cycle. So, that you get a much better operating cycle under the various operating conditions at off-design. So, the cycle design the engine design quite often is optimized such that under various off-design operating conditions, you continue to get very efficient operation of the engine and of the aircraft.

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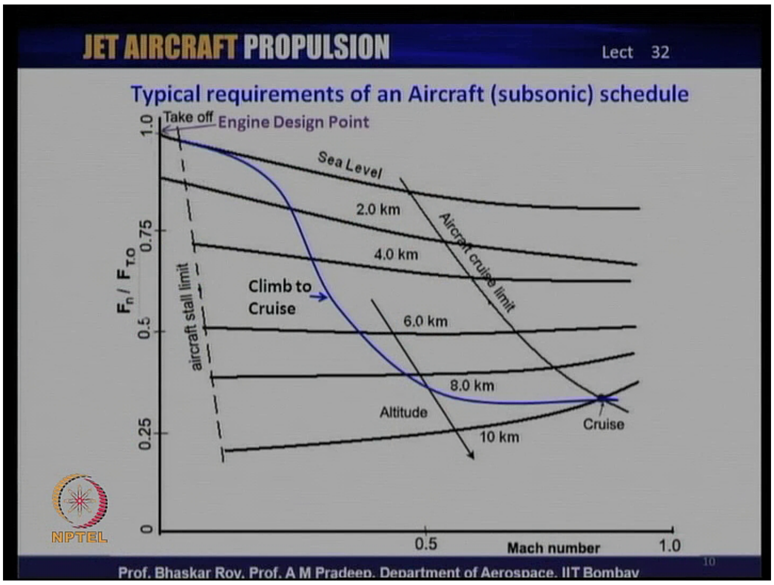

Let us move forward and see what the off-design also means with reference to the aircraft. In an aircraft, typically if you look at the thrust to mach number plot; a typical plot which you may have done in your other courses, it starts off with a takeoff at sea level and then climbs through various altitudes and finally, reaches a cruise at which it cruises let us say to very long distances. Normally, the cruise is somewhere around 9, 10, 11 kilometers altitude and it it goes through various climb procedures to reach that cruise altitude. Now, this entire flight spectrum starting with takeoff to climb and then reaching the cruise requires that the engine gives a matching amount of thrust under various flight conditions. And as we have seen, all these other operating conditions are the off-design operating conditions.

So, takeoff is normally the engine design point and all other operating conditions as we see here are off-design operating conditions for an aircraft to very quickly climb from sea level or ground level takeoff to its cruise, where its thrust requirement is very low. A very fast climb would ensure that you reach the cruise very quickly and operate at a low thrust requirement condition and to do that, this entire climb procedure needs to have matching thrust making capability of the engine matching with the thrust requirement of the aircraft. And as I mentioned, these are all off-design operating condition. This has to be built in to the capability of the engine and then the engine is shaped and sized. Let us take a look at what are the other demands of these off-design operating schedules.

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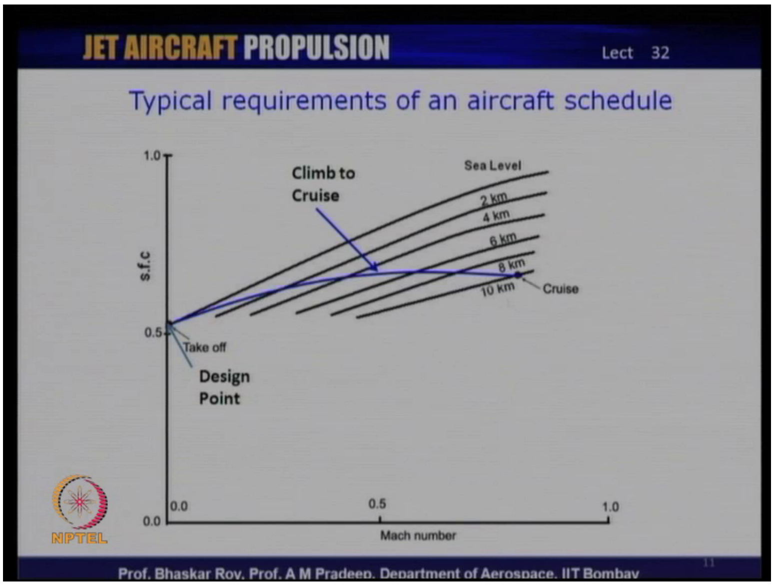

This is the SFC requirement. Under SFC requirement of a typical aircraft, SFC versus Mach number plot tells us that when the aircraft takes off, its SFC is some value; it goes through various climb procedures through various altitudes and reaches the cruise. And at the cruise at is let us say 10 kilometers, it has reached a straight and level flying condition at which it is now supposed to create very low thrust. Now, as we can see here in terms of SFC, the value of SFC at cruise could indeed be a little higher than that at takeoff. At takeoff, it is creating a huge amount of thrust; at cruise, it is creating a very small amount of thrust comparatively much lower amount of thrust and this entire flight from takeoff to cruise is the climb procedure.

An aircraft has to operate reasonably efficiently through this entire procedure in the process of reaching the cruise and then through the entire cruise operation. As we know, all engines especially the transport and the civil aircraft operations have become extremely sensitive to the economy of operation. And as a result, the requirement for the aircraft to provide very high fuel efficiency means it its cruise operation quite often requires that you have a fuel specific fuel consumption there. As low as possible, the demand is the specific fuel consumption at cruise should be lower than that of takeoff. Now, which means that engine has to be designed to ensure that you have a low SFC, even during the cruise operation; even if your thrust requirement is low.

We understand that if you you know convert SFC to actual fuel consumption, multiplying it by thrust. The actual fuel consumption at cruise is always much less than that at the takeoff; because at takeoff, you are creating a huge amount of thrust. But the requirement in the modern days is that the fuel consumption at cruise, which is for a very long period. It could be for 10, 15, 20 hours of long distance flights; it is extremely important. Whereas takeoff is for a very short period of may be 10, 20, 30 seconds. So, even if the fuel consumption at cruise is shown to be lower than that at takeoff taken over a long time over 10, 15, 20 hours, the fuel consumption during cruise is indeed very high.

So, the modern engine requirement is that at SFC requirement, at cruise also should be as low even preferably lower than that at takeoff. Now, as we have seen, the engine is designed for takeoff; because that is what the thrust requirement is high. The engine has to be sized for that high thrust requirement. You cannot have an engine that is sized lower than that; because then it will never give you thrust for takeoff and if you cannot takeoff, you cannot fly. So, it is necessary that engine is designed for takeoff; but it is also necessary it gives very good performance during entire cruise operation. And in most modern jet airline operation, the economy of the flight is hugely dependent on the economy of the cruise operation.

And as a result of which, the engine designers are working towards creating engines that has very low SFC during cruise and during various other operations other than takeoff. And this ofcourse requires that, as I mentioned optimization of the size and the shape of the engine which means optimization of the size and shape of various components of the engine; the intakes, the compressors, the turbines, the nozzles. All of them are to be shaped and sized in an optimized manner. And as I mentioned earlier, this optimization may mean a very small sacrifice at the design point, which is the takeoff point. Let us take a look at what are the other operational requirements or schedules that demands an aircraft to take care of its off-design operation.

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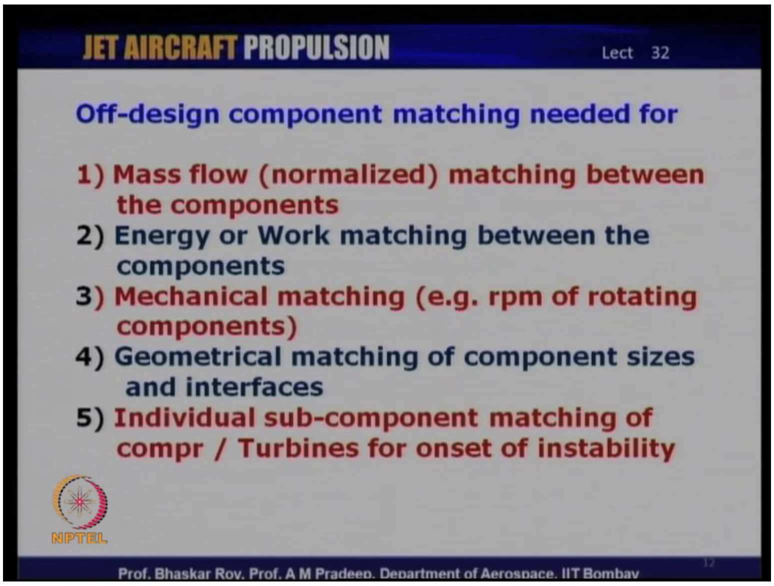

The other requirement is that under off-design operating condition. All these components are to be matched. See, all these components are part of an engine. They are supposed to work in a coordinated manner and this matching requirement is extremely important under various off-design operating condition. Let us take a quick look we will do the matching a little more in detail in the next class. But let us take a quick look at what this matching requirement means. It means that the mass flow flowing through various components need to be matched to each other. You see once the air which is the working medium has entered the engine, the same amount of air more or less will go through all the components; compressor, combustion chamber, turbine.

And hence under various operating conditions off-design operating conditions, all these components must work with same amount of mass flow and this matching is extremely important. Next is the energy or work balance between the components. Under off-design condition, the turbine has to supply work to the compressor for the compressor to do its work. So, there must be a continuous work matching between the turbine and the compressor under various off-design operating condition; during the time when the aircraft is climbing; during the time when an engine in aircraft is accelerating or decelerating; doing various kinds of maneuvers. During all the time, the turbine must supply exactly same amount of work that is required by the compressor.

And the compressor and turbine should do exactly same amount of work that is required to produce certain amount of thrust. So, this matching is extremely important at every instant; every second of working of the engine. The third requirement is the mechanical matching. The r p m of the rotating components of compressor and turbine which are on the same spool or shaft. So, the LP compressor must be matched with the LP turbine. They must operate at exactly same r p m and they must ofcourse be matched in the work schedules; that is the number 2 that we discussed. The turbine should do same amount of work as that compressor required and that must be done while working at exactly the same rotational speed or r p m.

The fourth point is the geometrical matching of the component sizes and this is what I was saying earlier, the sizing of the engine is done taking into account the design requirement the design point requirement. The same size of the components of the intake very importantly the intake, the compressor, turbine, combustion chamber and then nozzle must operate under operating conditions, when your mass flow is much lower. When your flow is quite different from the design point and the geometrical size that you have created at the design point must cater to all these operating other operating conditions. At which, the mass flow is different; the flow velocities are different and they have to do under different kind of work schedules.

So, the geometry that you have created for various components must also cater to all the other off-design operating schedules. So, while creating the geometry, it is necessary that you take that into account and this is what I meant. That while creating the geometry, the modern aircraft designer the engine designer ensures that the geometry also takes into account the off-design operation to the extent as I mentioned sacrificing may be a little bit at the so called design point. So, the geometry is created to sacrifice a little bit at the design point. So, that your all your off-design operations are very efficient and very smooth and matching with the aircraft requirements.

And then ofcourse, we have the conditions that individual sub components of the engine. Now, you see the compressors in the turbine that we have are multistage. You have 5, 10, 15 stages of a compressor; you have 2, 3, 4, 5, 7, 8 stages of a turbine. So, which means these are the sub components of compressor and turbine. And during the operation under off-design condition, they must be matched to each other; they must be working in a coordinated manner. So, all the components of a compressor; all the components of a turbine under off-design operating conditions also must be matched with each other. Otherwise, you will not have a compressor working properly; you will not have a turbine working properly within the engine.

So, off-design matching of the sub components is also extremely important and this also must be done during the process of design. And quite often again, the sub component matching quite often may require that at the design point, you make a small sacrifice of efficiency or operating performance of the design point to ensure that under off-design condition, their matching is very good; the subcomponent matching is very good. And to ensure that it may be necessary at design point, you make a very small sacrifice in your design at the so called design point. Now, these are the requirements under which the modern aircraft engines are designed or to be designed. Let us take a look at some of the other off-design requirements.

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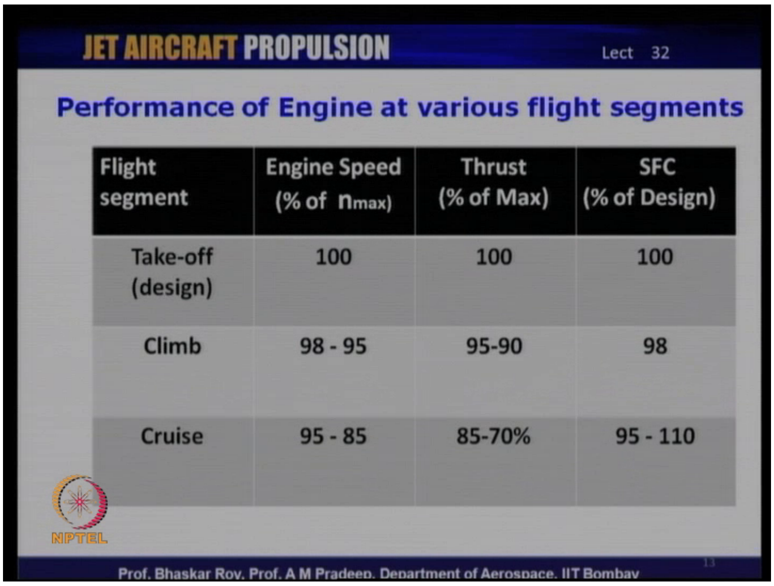

Flight segment	Engine Speed (% of n_{max})	Thrust (% of Max)	SFC (% of Design)
Take-off (design)	100	100	100
Climb	98 - 95	95-90	98
Cruise	95 - 85	85-70%	95 - 110

You see under various main operating conditions if we take the takeoff, normally as I mentioned takeoff could be the design point. Engine speed is 100 percent; thrust is 100 percent and SFC let us say is 100 percent. During climb what will happen is your engine speed is now getting slowly reduced; your thrust requirement is slowly getting lower and your SFC is also getting slowly lower. Once it reaches a cruise, an most aircraft try to reach the cruise as quickly as possible; as quickly as it is possible to coordinate the engine with the aircraft. Once it reaches, the engine speed is substantially lower now; it could be working at 85 percent speed. The thrust is substantially lower; it could be as low as only 70 percent of the maximum thrust. It could be even lower than that under certain certain aircraft engine combination.

Now, SFC of the engine now could be actually higher. Now, this is where the problem is that many of the early designs, the SFC at cruise used to be higher than the takeoff or the design point. The modern requirement is that the SFC at cruise should preferably be lower than the design point, which is the takeoff and the reason as I mentioned; because many of the modern engines are designed for very long cruise. Cruise of the order of as I mentioned 10, 15, 20 hours of operation of the engine flying over may be 10000 miles or 15000 kilometers. Now, that means the SFC there becomes a very stringent requirement for the airline economy of operation and that is where, the engine designers are now asked to design engines, where the SFC at cruise is as low as possible even lower than the design point efficiency. So, the fuel efficiency at cruise demands to be lower than the design point fuel efficiency.

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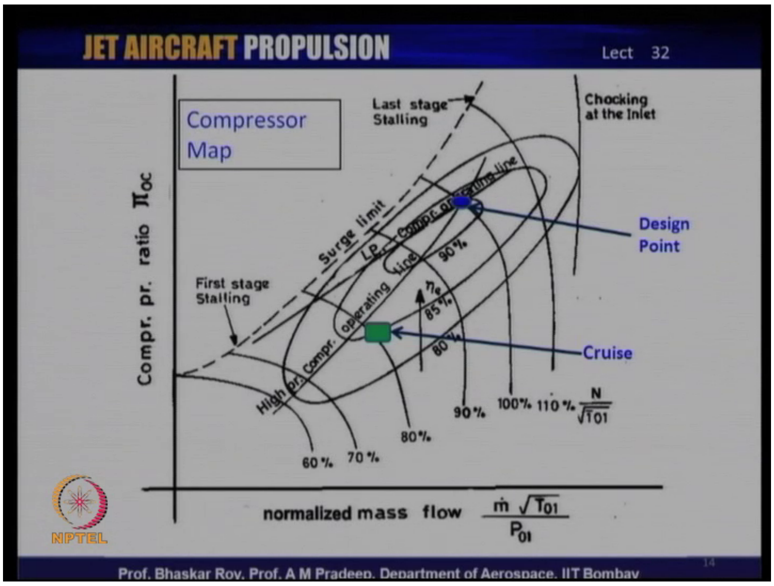

Now, let us look at the various components that has to work under various off-design operating conditions. The compressor map which you are familiar with and you have done in detail earlier. You will simply look at the map and see that the design point is at one particular operating condition, which caters to the engine design point. And it gives you certain pressure ratio, certain efficiency at certain 100 percent operating speed. The cruise is at a completely different compressor operating condition, at which your speed is probably 80 percent or 85 percent. And you are working at a efficiency which is may be slightly lower than the design point efficiency of the compressor. And all the other operating conditions are falling within this map are the off-design operating conditions and as you can see and as you have done before, these are at lower efficiencies.

They produce lower pressure. They work at lower speeds and quite often they work at lower efficiencies. If you are within this 90 percent efficiency loop, you are still working at high efficiency. Once you are outside that, you are working at a lower efficiency. So, the engine designer has to look at this compressor map and try to figure out what are the off-design operating conditions. So, what are the main off-design operating conditions? Cruise for example is a main off-design operating condition and he needs to ensure that you have a compressor within the engine, which produces the necessary amount of compression at certain efficiency. So, that the overall engine efficiency is maximized and the fuel consumption is minimized.

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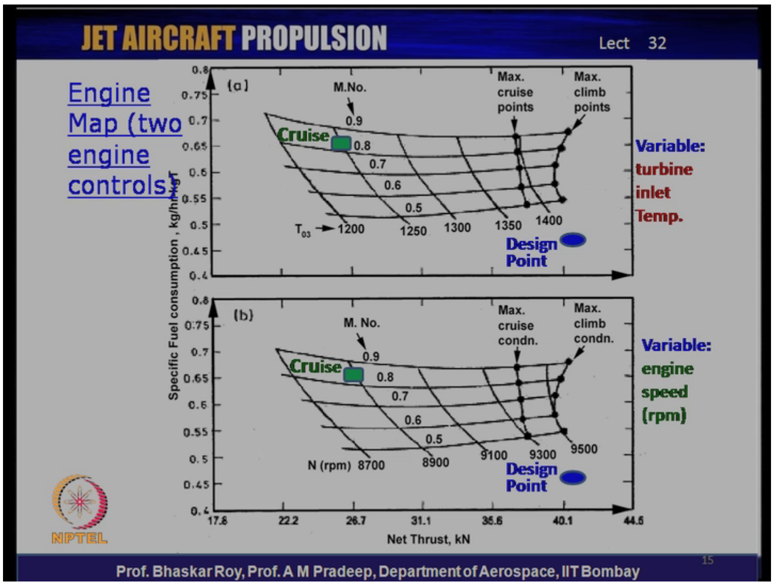

Let us take a look at the engine map. Take an over the whole engine if you look at the engine map which is SFC, the specific fuel consumption versus the net thrust. Now, if you see here, the top map actually gives the variation with Mach number and the turbine inlet temperature. We know the turbine inlet temperature is a primary parameter in the engine operations. And as we see here as it goes towards higher and higher engine operating temperature, it has to also operate at close to the design point which operates at a very low Mach number and this is why, let us say the design point is most likely to be. From there onwards, it moves towards cruise altitude and it moves towards cruise climb through the climb various cruise operations climb operations to the cruise altitude.

And finally reaches the cruise Mach number, which could be mach 0.8 or 0.85 let us say for a typical civil aircraft and it will reaches a cruise point. So, in the engine map as you can see here, the cruise operation is quite different from the design point operation. What the modern engine designer would like is in terms of SFC, this cruise SFC should be as low as possible. So, this map should get flattened and flattened. So, that the cruise SFC could become as good and the demand is indeed that the cruise SFC could actually be lower than the takeoff SFC. If you look at the lower map, it has engine rotating speed as the variable in the over here as a third variable and the design point rpm is normally one of the highest r p m.

So, that is where you have the design point and the cruise r p m is one of the lower r p m and that is where you have the cruise at a high mach number. And as a result of which, again you are variation from cruise to design point and design point to cruise is normally quite large. So, the modern engine designers are now asked to bridge this gap in terms of SFC which is the y axis here. That even if they are operating at vastly different operating condition; vastly different intake condition; compressor operating condition; the turbine operating condition; the entire engine operates at a different operating condition, still the SFC value should be competitive. So, that the overall fuel economy of the aircraft is very good and and competitive in terms of economy of operation.

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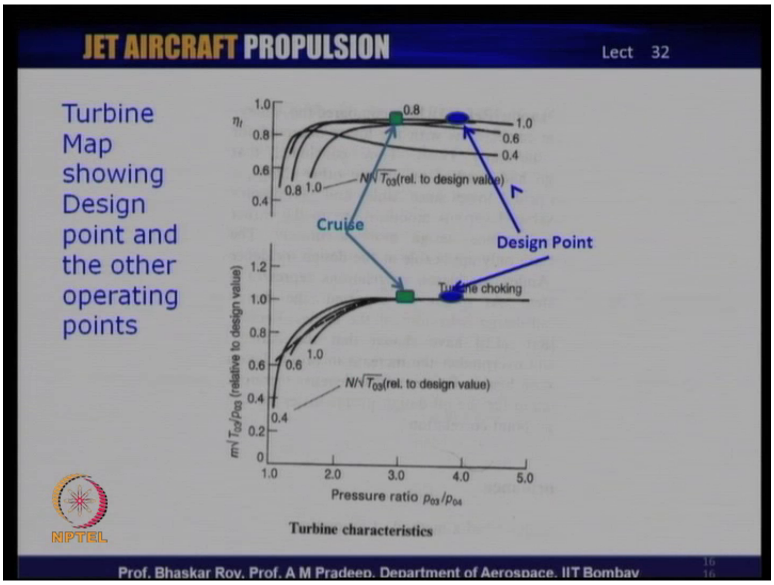

Let us take a look at the turbine which is one of the important components. The design point typically operates at certain condition, where the turbine is likely to be chocked and this is where, you have a very good efficiency. And it is in the modern aircraft design, you could have the cruise operation which is far away from the design and it is entirely possible that at cruise, your turbine could still be chocking. Now, this has to be ensured by design; because that is where, you get the maximum work output out of a turbine. And it is necessary that by design, you ensure that the cruise operation is also under turbine chocked operating condition, where you also continued to get very good efficiency from the turbine. So, the turbine which is the work producing element and supplies work to the compressor always works under various under various operating conditions; but at the highest efficiency and preferably under chocking condition.

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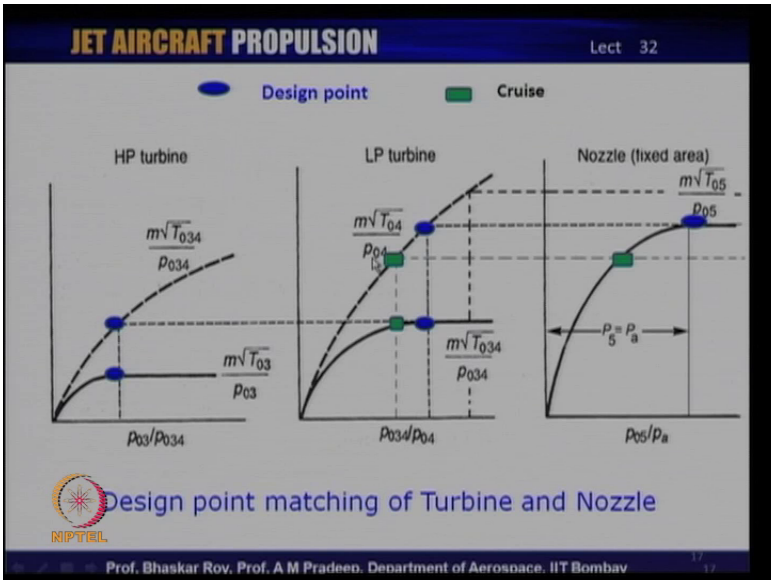

If we take the turbine to nozzle operating condition, nozzle is something you have just done. You see here if you have a fixed area nozzle, the nozzle matching with the turbine gives you that this is where the nozzle which operating; this is where, the turbine exit would be and that this where, the turbine design point would be and then this is where, the HP turbine design point would be. So, if you go through the blue points over here which are the design points from HP to LP and then on to the nozzle, you have the fixed area nozzle design point and you can fix your nozzle area at that design point.

Under off-design operating condition let us say under cruise, your turbine as I mentioned could LP turbine could still be very close to chocking. The HP turbine could indeed be indeed still chocking. But your nozzle now is operating under a different operating condition and as a result, it is now incumbent. It is now necessary that you render the nozzle a variable geometry capability. Because if it is fixed area, the nozzle as you can see now is a mixed mismatched to the turbine schedules and hence, all aircraft today have engines which are variable geometry nozzles. You do not have fixed geometry nozzles anymore in any aircraft whether it is transport or military aircraft.

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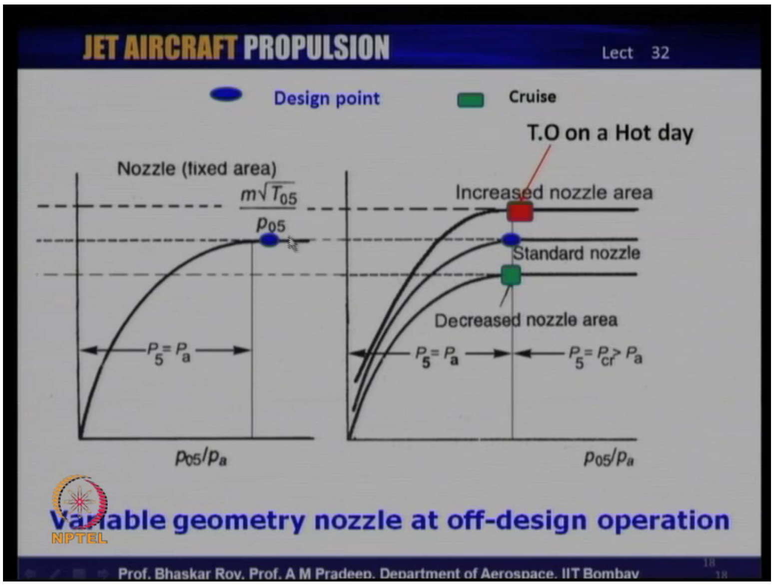

This is what we see here that this is what you get out of variable geometry nozzles. If you have a standard nozzle, it matches with a fixed geometry nozzle. But if you have a variable geometry nozzle, it has a very important task that at the operation itself if it is operating under hot condition as it is in tropical countries like India, your nozzle area requirement is higher; your intake area requirement is higher; but intake is normally fixed geometry. So, by varying the nozzle, you can vary the engine mass flow capability; that is very important requirement for creation of thrust. So, you can decrease the nozzle area under off-design operating condition say during the cruise operating condition, when thrust requirement is low and the engine could operate with low mass flows. But when you need to operate under hot operating condition, you can increase the nozzle area to allow more mass flow to come in to create more thrust.

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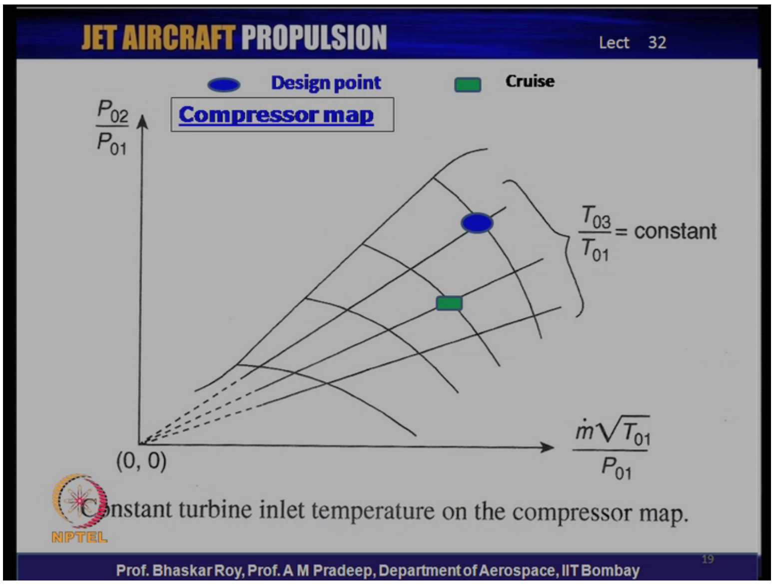

So, various engines engines have components or components are created to cater to these off-design operating condition. Again if you look at the turbine operating condition with variable turbine temperature and this is a compressor map with variable turbine temperature and the blue point asusual is the design point and the green point is the cruise operation. So, on the compressor map as we see it is operating at at a different pressure ratio at the design point, it is operating at a different temperature ratio at and pressure ratio at the cruise point. And it is necessary that the engine is designed to take into account these various operating conditions, the main operating conditions, atleast the cruise operating conditions, other maneuvers that need it needs to do. So, that it is shaped and sized to give very good efficiency under those off-design operating conditions.

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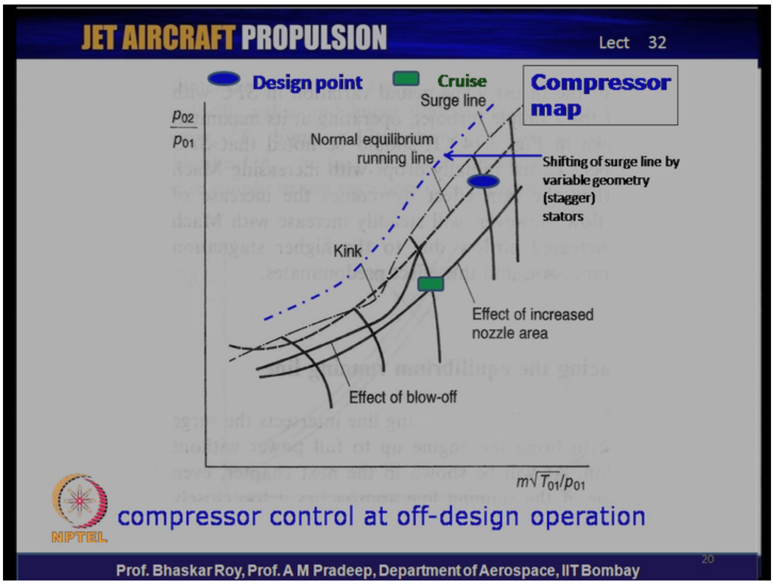

If you look at the compressor map, a very important issue comes up that compressors are amenable to surge. Now, what you can do is under various off-design operating conditions, compressors amenable to move in to stall and surge operating condition. However, if you have variable geometry or what is known as variable stagger stators, you can shift the surge line under off-design operating conditions. So, that the compressor does not move in to stall or surge zones as it is quite possible for it to happen, if you do not have variable geometry stagger or variable geometry stators. The normal operating map point as we see here in this point in this curve could move in to this surge line. However, by shifting the surge line through variable geometry stators, you can avoid that catastrophic possibility during off-design operating condition.

So, modern engines especially the transport aircraft and many of the military aircraft do have variable geometry stators; because under off-design operating conditions, you can get out of the surge or stay out of the surge altogether by operating the variable geometry stators in addition to variable geometry nozzles. These are the things that the modern aircraft designers have done to take in to account the various off-design operating conditions. So, as we see here that various engine operations need to be brought in to the picture during the process of the design itself. And if you do that, then you have an engine that is very good not only at the design point but at various off design important off-design operating conditions.

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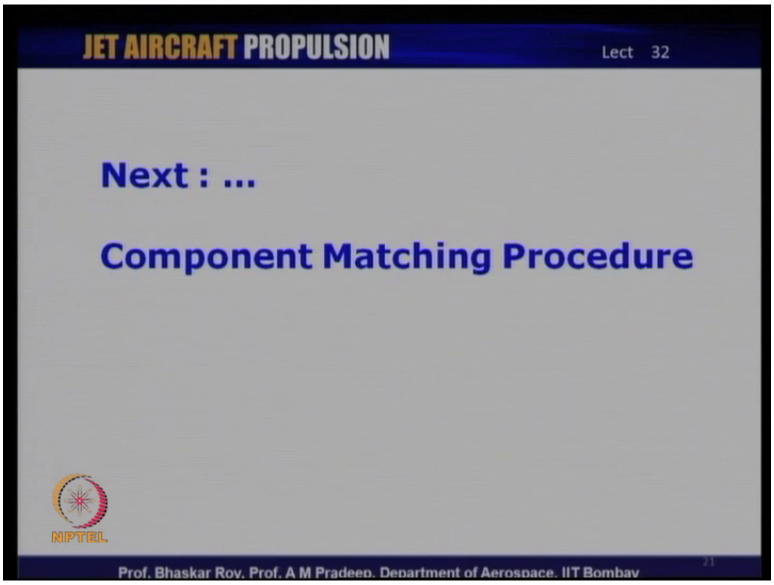

In the next class, we will look at the component matching. If you are to do off-design operation of the engine, it is necessary these components are also matched during the various off-design operations. And we shall look at this matching procedure in the next class; the component matching, the sub component matching; how it is done in the modern engine design; that is what we will do in the next class.