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

Lecture No. # 04
Turbojet, Reheat Turbojet and Multi-Spool Engines

We are talking about the jet engines; jet engines for aircraft. Today, we will be talking about the basic version of the jet engines; that are used for aircraft. This is the kind of engine that of course, first came into being for flying aircraft, and this is of course the simplest of all the jet engines. The various variants that has been talked about a little in one or two lectures in the past would be dealt with later on in the course of this lectures. But today, we will talk about only the basic version of the jet engine that is used even today for flying of aircraft.

It is simple in the form of a mechanical engine; it is also simple or simpler as thermodynamic entity; it is also a simpler version in terms of aerodynamic machines. As we have talked before, a typical jet engine is of course, a mechanical machine it is of course, a thermodynamic entity, and it contains lot of components, which are fundamentally aerodynamic machines; as I mentioned, we will be talking about all those facets of a jet engines as we go along in this lecture series. But let us, take a quick look at what are basic jet engine contains, what it is composed of and how we can measure the performance of such a basic jet engine, in terms of the basic performance parameters, which we talked about in the last class.

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So today, we will talk about these basic jet engines, which are used for flying aircraft. Now, you see a basic jet engine that we know of is composed of a number of components. These components have been introduced to you; we will look at these components again. And then try to figure out, how the performance of an engine as a whole can be derived from all these components put together into a jet engine

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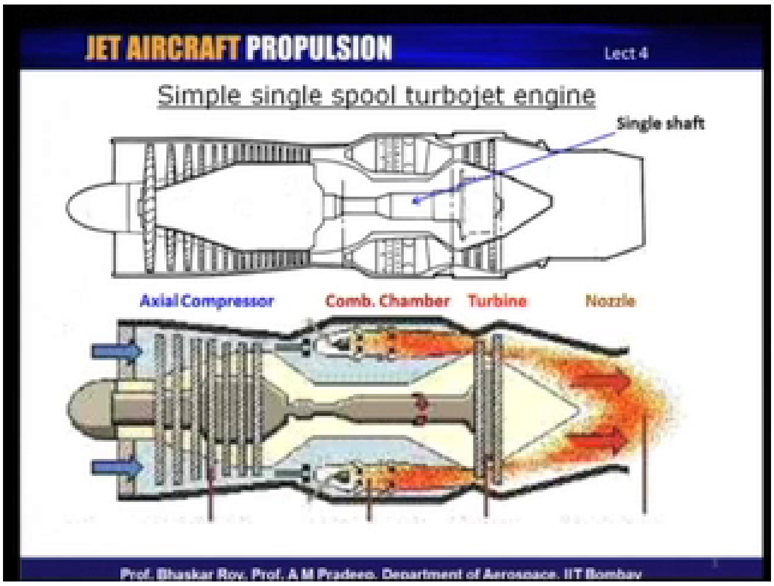

If we look at a basic jet engine; we shall see that it has components, which to begin with our compressors. In this particular diagram, you would see component of compressor, which is generally called axial compressor. We will see in the next picture; a diagram of a centrifugal compressor followed by axial compressor. There is a combustion chamber then there is a turbine, and then a flow exits through the nozzle.

Now, what happens is in a typical jet engine each of these components have a function. These functions are also thermodynamically laid out in a cycle; and each of those components of the cycle as you would see lectures, which should be followed very soon. That each of these components actually perform a certain thermodynamic function. Now here in this particular kind of jet engine. These happen in a sequential manner for example, in a i c engine or a piston engine which is also me kind of a heat engine they often happen simultaneously.

Over here, they happen in a spaced out manner so, in a axial compressor or a compressor. The compression is performed followed by the compressor. The flow or the working medium goes into different space, where the combustion is performed. Then it moves on to another space, whether turbine extracts work essentially to run the compressor, and then after the turbine has done its work the working medium. Now, a gas or hot gas is exhausted through a nozzle. So, the various components that comprise a jet engine are spaced out in the space of an entire jet aircraft engine as isolated components, and the various incidents that we talked about happen in a sequential manner one after another.

So, the flow comes in as we see here in this arrow flow comes it from the front. There would be an intake, which varies from one kind of aircraft to another same engine actually mounted on different aircraft may have different kind of intake. But those intakes, we will be talking about later on in the course of this lecture series. So, the flow comes in through this intake system, and gets into the compressor, and it gets compressed. And then after the compression process it goes into the combustion chamber normally between the compressor, and the combustion chamber. As you would see in the upper diagram there is a small duct, which is normally used to slow down, the flow substantially essentially to aid the combustion process.

And then, once the combustion has been performed that means the fuel has been burnt; and the air has been raised to a very high temperature; that high temperature, and compressed air is then released to the turbine. Now again, you will see there is a small duct over here; which is the releasing duct from the combustion chamber to the turbine. And once, it is released to the turbine the turbine essentially extracts work out of this high energy gas, which has high pressure, and high temperature, both in the form of essentially potential energy.

So this potential energy is then extracted in the form of mechanical work, which then this turbine essentially uses to run the compressor through the shaft. So, in this particular basic engine, we have a single shaft. And this single shaft runs the entire compressor; that is shown over here; and as we see here. It has a series of compressors really speaking; we will be talking about this series of compressors. As we go along more and more. So, this turbine runs this entire compressor and having done its job, releases the high energy gas. It still has very high energy, very high pressure, and very high temperature, it releases that gas through this nozzle.

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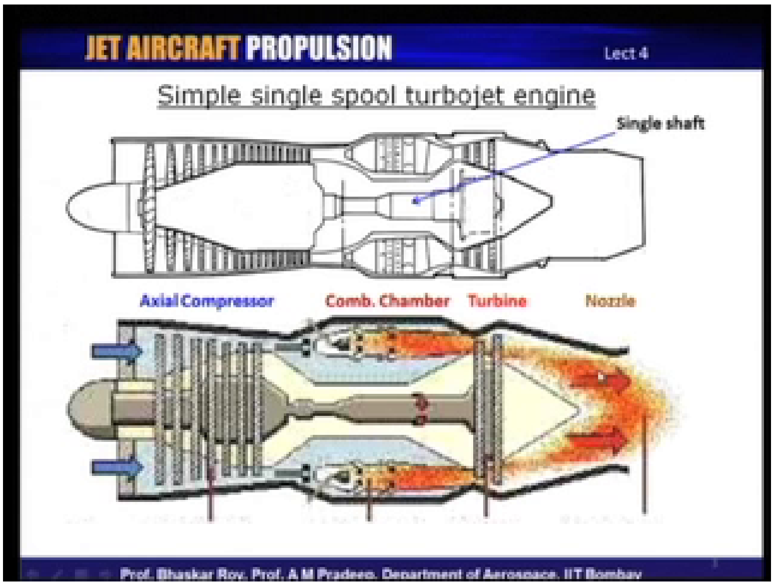

And the nozzle is appropriately shaped for every particular engine; it needs a particular shape, and it is released through that nozzle into the atmosphere through a exhaust system whereby the exhaust velocity is very high certainly much higher than the intake velocity with which it came in and of course, this change of velocity manifest itself in the form of production of thrust.

Now this is a simple basic jet engine that has been in existence for little more than fifty years used for flying aircraft of course, similar kind of engines we do not call them jet engines. Similar kind of basic engine comprising of compressor combustion, chamber, and turbine have been evolved to create power for land based gas turbine engines. They are often much bigger produce much more power. And of course, we do not call them jet engines. Jet engine is typical of aircraft variety, which produces a jet for production of thrust.

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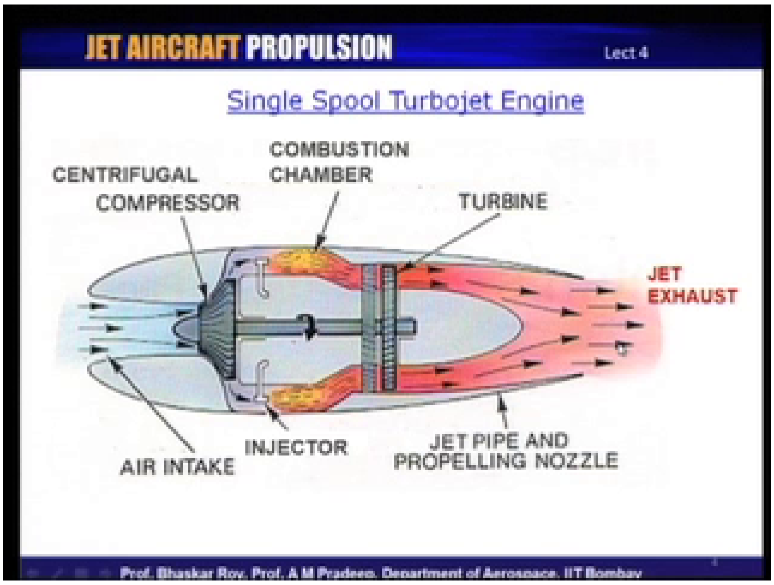

Let us take a look at another variant of this single shaft or often as it is called single spool basic turbojet engine in which for a compressor. You have a centrifugal compressor; now, as you see it looks quite different from the earlier one.

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In the earlier version, you had a series of compressors; they are actually individual compressor units lined up one after another literally lined up in a sequential manner, and the compression process happens one after another in a sequential manner. So, that he compression is built up over a number of compressors literally.

Now, in a centrifugal compressor it produces compression in one go fairly high amount of compression can be achieved through a centrifugal compressor. And then, this is delivered to the combustion chamber, where again you have fuel injection you are burning a fuel, which raises again the temperature of this gas, which of course has already been compressed to high pressure. So, again this high temperature, and high pressure gas is released through the turbine. And this turbine extracts work to run this compressor, and releases the high energy gas into the jet exhaust for creating the high velocity jet.

So, the process of creating a jet exhaust is very similar, whether you have a axial compression process or whether you have a centrifugal compressor to do the compression process. We shall see later the pros, and cons of axial, and centrifugal compressor, where and how they are used at this moment. I can probably tell you that the first jet engine that appear actually had a centrifugal compressor. Because centrifugal method of compressing was already very well understood, and the technology of that was very well known the axial compressor process actually developed a little later however most of the engines, today are axial compressors.

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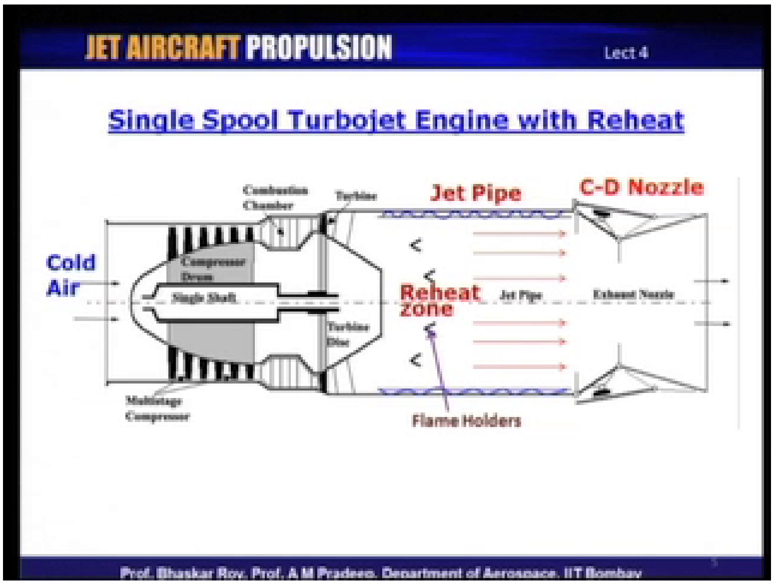

Now let us, take a look at another version of jet engine slightly beyond the basic jet engine in which a long reheat pipe has been added, and this reheat pipe or a jet pipe actually contains, what is can be called a reheat zone in which we have a number of flame holders. Now, these flame holders are also there actually inside the combustion chamber. We do not see them in this particular diagram, but there are certain versions of flame holder normally used in any combustion chamber.

Now here, the entire exhaust or jet pipe here is used for the combustion process; and in this combustion process. We have large flame holders in which the fuel is in injected, and the gas is again raised to high temperature. Now let us, start from the beginning all over again, and see how this is actually introduced into a basic engine, and convert it to what we call a reheat engine or more popularly known as after burning engine. The cold air comes in into the compression process. And then it goes into the combustion chamber, and again we have a turbine with extracts work essentially to run the compressor with the help of a single shaft.

And this is a mechanical loop between turbine and compressor as we have talked about before. And once the turbine has done its work; this high energy gas is released into this long jet pipe. Now, this long jet pipe is then used to raise the gas temperature to even higher level. Now, one of the advantages of this is, we shall talk about these things more in detail later on.

Now, one of the advantages of introducing a reheat here or the primary reason for introducing the reheat here is you do not have any turbine anymore. Now, since you do not have a turbine the temperature of the reheat or introduced by the reheat can be much higher than, what you can do through a normal combustion process. Because they are the temperature that you can raise it to is somewhat limited by the capacity of the turbine blades or turbine blade material to withstand high temperature.

Now, since these are made of metal alloys. There is certain limit to which the temperatures can be raised to at the turbine inlet. So, turbine inlet temperature is quite often a limiting factor in turbojet engine. Once you have a reheat, and there is no turbine afterwards that limit is kind of gone; and you can indeed, if you want reheat the gas either to the same temperature or to even higher temperature depending on your engine design. And once you do that high energy gas is now exhausted through the jet pipe into the exhaust nozzle; and you can create a high velocity jet.

Now let us, let us look at this jet pipe a little more what you are doing here is you are raising the temperature to very high values all over again. Now since, the gas temperature is going to be very high. And you create a process through flame holders and other process. Let us say, very cleverly so that you have uniform temperature profile a little later after this reheat zone, and this temperature is quite high.

So, what you need to do is you need to create a situation here, where the jet pipe or the outer shell of the jet pipe is protected from this very high temperature inside so, what you have here this annulations, that you see over here are essentially liners that are created to protect this body of the engine from high velocity jet. So, what happens is this gas, which is coming from the turbine a little bit of it goes into this liners; those are also very hot gases anyway, but the body of the jet pipe is indeed designed to withstand those kind of hot gases, but not the very high temperature.

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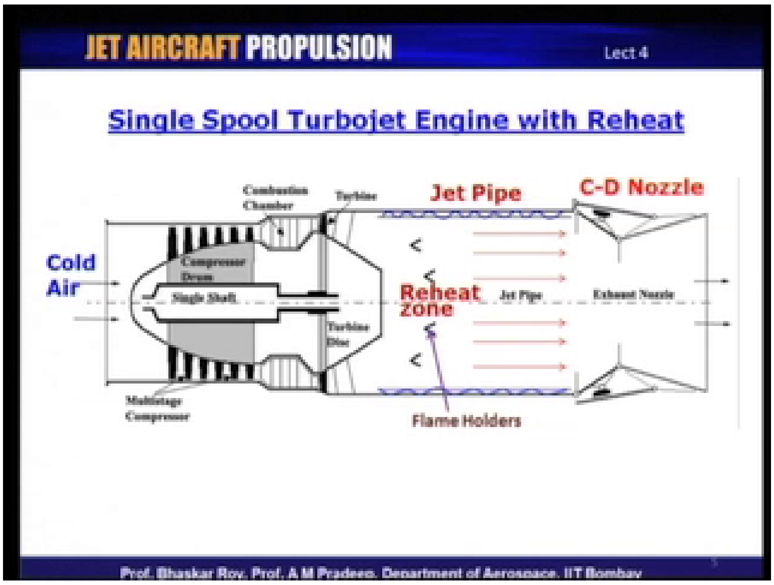

Now, being produced to reheat, so the liners essentially contain inside them the hot gases coming from the turbine, and create a small safety zone for the outer shell of the jet engine or the jet pipe from very high temperature. That is being created inside the reheat zone, and where as I mentioned temperatures could indeed be higher than, what you had earlier, and as a result of which these liners are integral part of the reheat or after burning engines essentially for protection of the jet engine body.

Now, what happens these reheat flow goes into the nozzle. Now, what I have written here is a C-D Nozzle, which is a abbreviation for convergent divergent nozzle. So, what you can see here, we have a convergent part of the nozzle. And then, we have divergent part of the nozzle. Now of course, we will be talking the dynamics gas dynamics of these nozzle systems in much more detail later on in our nozzle chapter, and a little bit of that would be done much before that in your thermodynamics chapter in terms of the aerothermodynamics of the flow through the nozzles.

But at this moment let us, just look at that we have a convergent divergent nozzle following a reheat zone or a after burning zone. Now, normally you would see that most after burning engines or rather I would say all after burning engines would almost necessarily have a C-D Nozzle-a convergent divergent nozzle. Now one of the reasons, you have reheat is to raise the temperature or the energy of the gas to high values. And then, why do you raise the energy to high value, so that you can indeed get a high velocity jet through the nozzle.

Now, when you try to do that, when you try to create a high velocity jet through this nozzle through this nozzle system, which is let us say a C-D Nozzle, the high velocity jet means that the flow through this nozzle would convert high potential energy at the station in jet pipe to high kinetic energy. So, there is a huge potential energy drop through this nozzle. So, potential energy both in terms of pressure, and temperature or drop through this nozzle, and this nozzle system now converting high potential energy to high kinetic energy.

Now, high potential energy has been created partly by creating the high temperature gas by the help of a reheat. Now, where does the high pressure comes from now this simply means that, if we are going to have a reheat engine or an after burning engine it is necessary, that we have a C-D Nozzle, and if the C-D Nozzle is going to convert all the potential energy or a good part of the energy to high velocity jet. The pressure available here also should be very high, that means the compression process that we have right in the beginning of this jet kind of this kind of jet engine should raise the pressure to such high values, that even the turbine has extracted some of it is pressure for doing work. It would still retain a high pressure come through this reheat zone, and this high pressure. And now, high temperature gas can be released through the C-D Nozzle to create a high velocity jet.

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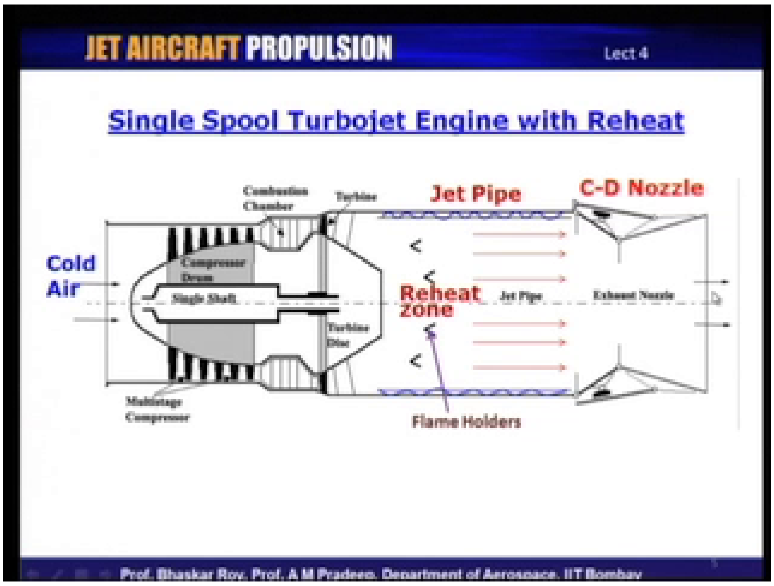

You see, if you do not do that, if you do not do that the pressure over here is likely to go below the atmospheric pressure. And in which case, you are not going to have a jet flow coming out of this nozzle. So, it is necessary that you take care of the pressure; that is available at the exit phase of the nozzle a priory well before in your design of jet engine. Because when you are raising the temperature, it is necessary that it already has a high pressure available with it. Only then, you can deploy a C-D Nozzle to create a high velocity jet only high pressure or only high pressure would not do

Let us, look at logically supposing you have a C-D Nozzle; and you do not have a reheat zone; you just have a high pressure; and release it through the C-D Nozzle, what will happens? Now, that you have pressure the flow will accelerate to a high velocity. But the temperature at the exit phase now will be very low, because temperature is a potential energy much of it has been converted to kinetic energy, and as a result the temperature at the exit phase will be so low; that the nozzle or the flow through the nozzle at towards it is exit will face frozen situating or freezing situation; that means, some of the combustion products coming through the combustion chamber will now get frozen, and get stuck into the combustion chamber nozzles.

So both ways, if you are going to have a C-D Nozzle; it is necessary, that you have a process by which you can create high pressure. And a separate process by which you can create a high temperature; so that the C-D Nozzle can be effectively used to create high velocity jet without creating a problem of pressure a reversal or frozen combustion products in the nozzle phase. These are some of the fundamental issues that a jet engine designer would have to contend with at the time of creating this jet engine. And in case of a reheat engine you see, we need to take care of a number of issues before you can say, you have a reheat engine that can create a high velocity jet.

Now, this C-D Nozzle just a word about it is used typically used to create a jet, which is supersonic; we will be of course, talking about it in great detail later on now, this jet is a supersonic jet, which is which means that typically you are creating velocity, which is very high; of course, you need to create velocity that is very high to create more of thrust. So more velocity you create, more thrust you are likely to create on the other hand higher. This velocity is going to be higher is the exhaust gas energy (( )), which it is going out, which means typically that the waste energy that we have talked about in the last class is also going to be of a higher order.

So, a typical heat a reheat engine or after burning engine would invariably have very high waste energy intrinsically associated with its performance, and which of course, also means, that it is efficiency of operation is going to be somewhat on the lower side. Now, this you achieve essentially by creating more thrust; you are creating more thrust deliberately by essentially accepting or sacrificing certain amount of efficiency of operation efficiency of cost means fuel efficiency.

So, you are sacrificing fuel efficiency of the engine, because you desperately need some thrust for your operation of the engine, and for the operation of the aircraft typically this kind of engine is used in military aircraft, where you need thrust desperately whether you are running away from the enemy or whether you are pursuing the enemy typically in situations, where certain amount of fast acceleration of the aircraft is desperately required in those situations fuel efficiency of is of secondary importance. The more important thing is creating high thrust. So, that the aircraft can accelerate or fly much faster at that particular operating point.

This is a dine necessity so reheat engines are typically deployed in most of the military engines, and most of the typical passenger or transport aircrafts are unlikely to have after burning or reheat engines. Because as you see they are fundamentally of lower fuel efficiency in a passenger or transport aircraft; fuel efficiency is of primary importance, and hence that cannot be sacrificed. So, this kind of engine is typically used in military aircraft.

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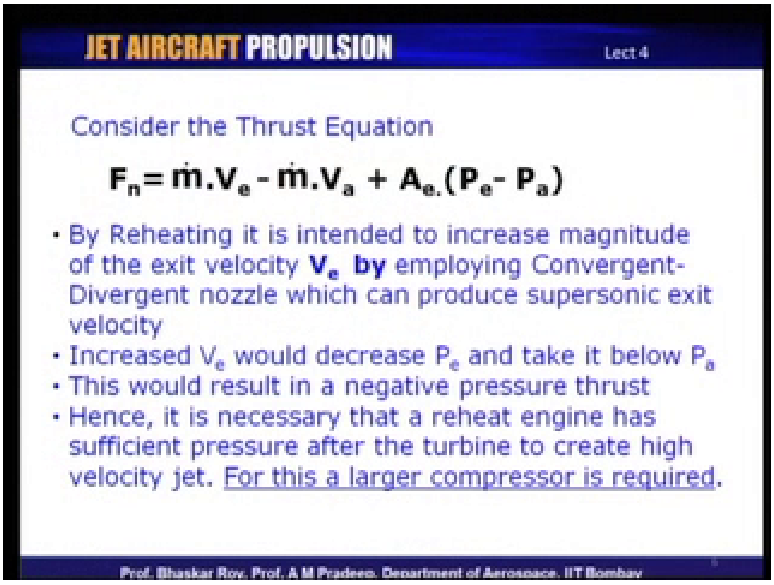

Let us, just summarize some of this point that we have been talking about by reheating the engine, it is intended to increase the exit velocity V e essentially by employing a convergent divergent nozzle. And as I just mentioned it is capable of producing supersonic exit velocity; now increased velocity would decrease P e; and this is what the danger is that it could take it below the atmospheric pressure P a, and which means at the exit phase it would have a negative balance of pressure. The pressure thrust that we have talked about would become actually negative. And this is not definitely a very desired situation. So, it is necessary that you take care by creating more compression a prior before it is released through the convergent divergent nozzle.

And hence, you require a larger compressor; another larger compressor means that in actual compressor situation; it means you probably would need to have more compressors lined up typically most of the modern jet engines have axial compressors. So, larger compressor would essentially mean you have more compressors units to be lined up one after another in a sequential manner to create more compressor; a compression before it goes into the combustion chamber.

Now, to run a larger compressor you probably need a stronger or a larger turbine, because they go together. And hence, this turbine compressor loop or the combination would probably become a little larger than very basic jet engine that we have talked about earlier as a result of this. We have a slightly larger compressor turbine combination in a typical reheat or after burning engine. Only then, you have a high potential energy going into the exhaust nozzle for creating high velocity jet.

So, this is a typical jet engine meant for as I mentioned military aircraft, fighter aircrafts, and these jet engines. Now, as you can see would need to be designed right from the beginning for that kind of purpose, it would have to have a larger compressor, which means it may have to have a little larger turbine. And then of course, it would have to have a reheat, and that jet pipe. So, the entire jet engine would need to be configured, and designed right from the beginning for the purpose of reheat or after burning engine.

So, the basic jet engine without reheat or after burning that we talked about earlier is designed differently. It is a simple basic jet engine. The moment you add a reheat the entire engine would have to be somewhat reconfigured, so that you get full benefit of the C-D Nozzle, which you would like to deploy towards the end to get maximum benefit in terms of thrust production, because that is your primary aim in creating the reheat zone.

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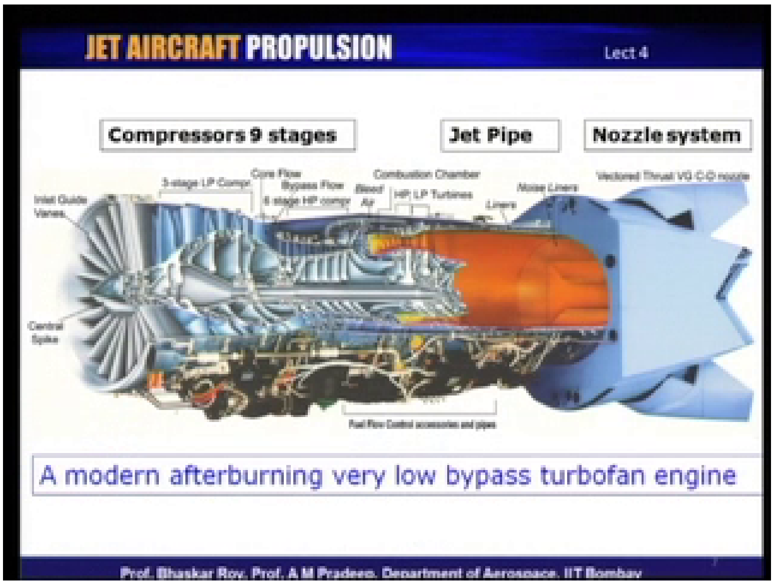

Let us, take a look at quick look at this diagram in which a real jet engine has been captured in a cut out picture. Now, what you can see here is, it has compressors of 9 stages and of course, compression occurs in two steps; first, a row of compressors are done over here; and then there is a very small bypass. Now this is a jet engine, which we call a very low bypass turbofan or one may even call it a row bypass turbojet; one way or the other you are correct. And then this low bypass engine then creates a bypass, which goes through this entire process. And then one can use this bypass which is actually cold air relatively much colder air to feed into the liners, which we talked about earlier, which is used around the entire jet pipe. And now, you can see the bypass here has a very good utility value that it goes into the liners for creating a very cold you know safety zone for the jet pipe.

And then of course, you have the basic core flow coming through the next six stages of compressor goes into the combustion chamber, and goes into the turbines. Now, that we have compressors in two groups or what we will be calling more, and more as two spools. You need to have turbines also in two spools so that you have two loops there one, which we call the h p loop another, which we will call the one p loop. And then of course, after that it goes into this hot zone, and you known shown here as red zone, which is, where you have the reheat or the after burning. And then, you have liners all around it to protect the outer shell of the engine from these very hot gases.

And then, you have a very complicated C-D Nozzle; this particular engine has, what is known as vector thrust variable geometry C-D Nozzle. We will be talking about some of these issues later on in much greater detail. And these are the modern versions of the deployment of the C-D Nozzle in which you can-you not only get a high velocity supersonic jet, but you have control over the direction in which the supersonic jet is released; so, that the thrust generation can be controlled both in magnitude as well as in direction as we have talked about before thrust is a force, which is a vector; and it has a magnitude, and direction. And hence, it is called vector thrust, and this vector thrust variable geometry nozzles allows you to vary the vector of the thrust creation. We will be talking about these things in much greater detail later in the nozzle chapter.

So, this is what a modern slightly low bypass turbofan engine one may call it looks like in which you have a long jet pipe, in which the after burning is done. And then, you have a very complicated modern C-D Nozzle through which high velocity jet is created in a controlled manner, such that you get thrust in a very controlled manner in modern jet aircraft.

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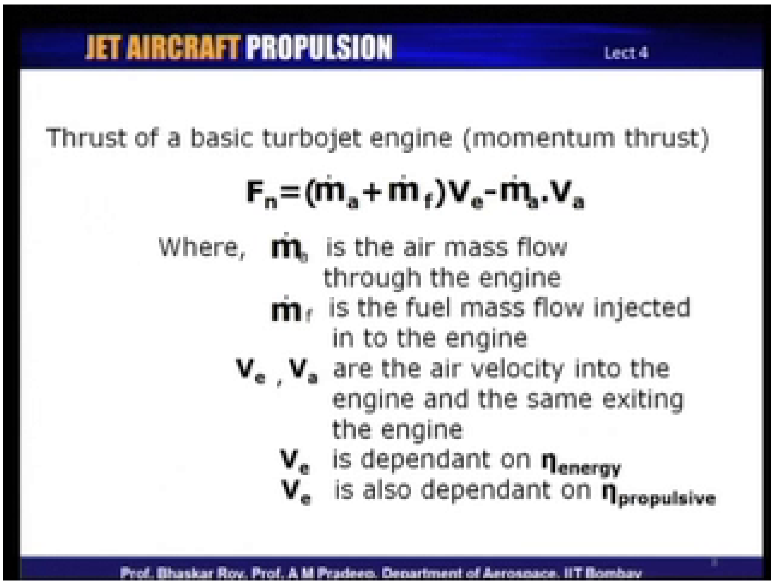

Let us, take a look at now, the parameters that we have talked about in the last class. The basic turbo jet engine for example, creates momentum thrust primarily for the moment. Let us say, we will ignore the pressure thrust assuming at least for the moment that the pressure reached at the exit phase is equal to the atmospheric pressure. And hence, we just at the moment ignore the pressure thrust component, and we have only the momentum thrust.

And then, this momentum thrust now has two components; one which is of course, the exhaust reaction or what we had called the gross thrust. Now, what we see here it has two mass flows the air mass flow, which is come into the engine through the intake system; and the fuel mass flow, which been injected into the engine into the combustion chamber; and two of them together make up the high energy gas that is going out, and that creates the reaction force created by the nozzle let us say.

And then the second term, you have the drag what we would normally call ram drag at the intake itself, which is composed of the mass flow that is coming inside the engine multiplied by of course, the velocity with which it is coming in. Now, as you can see here these components also are dependent on the parameters that we have defined in the last class. The exhaust velocity V e is dependent on the energy conversion efficiency. So, how much V e is created which is created is used for which is used for production of thrust is dependent on the efficiency with which this V e is created inside the engine.

And of course, the V e is also dependent on the propulsive efficiency of the engine so these two efficiencies, we have defined in the last class; and these two efficiencies essentially decide independently, and together what the value velocity of the exit flow is going to be, and then we get the gross thrust and of course, the net thrust. So, V e which is so responsible for creation of the thrust, and we take a lot of trouble to create that V e are dependent on the two efficiencies that we talked about, and which means that we have to create engines, which are of high efficiency; so that you can get high V e, and then you get high thrust.

So, these are the basic parameters, which you have to keep an eye on, when you are designing an engine, when you are putting together various components of compressor, combustion chamber, turbine, nozzle, etcetera, because the V e, which here simply gives you that it gives you thrust. Now, where does the V e come from it, comes from various processes that are going on inside the jet aircraft engine, and inside this jet engine. We have processes by which this V e is finally created, these processes, which are indeed aerothermodynamics processes. We are going to talk about those aerothermodynamics in great detail later on.

But those aerothermodynamics processes have efficiencies; and these efficiencies finally decide, what the value of V e is going to be, so unless you keep an eye on efficiency right at the time of creating these engines your V e is not going to be very good or very high. And hence, your thrust creation is not going to be very high or you might get a good thrust at a very rather low efficiency, which means you would have to pump in more fuel to get a good thrust, which means your SFC is going to be high. So these are the various facets, which the engine creator would have to look into while creating the engine. So, you have pros and cons of various parameters or pushes, and pulls of various parameters. And these efficiency values invariably show up either in the form of V e or in the form of SFC.

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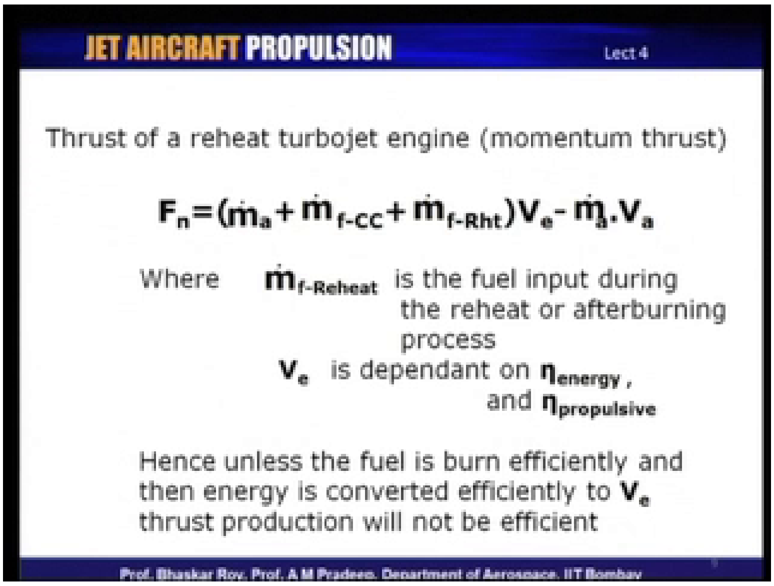

Now let us, take a look at the thrust that is created in a typical reheat engine. The reheat engine creates a thrust that is, now composed of fuel burnt twice once in the combustion chamber. And then, again in the reheat zone, so you have two rounds of fuel now added to the basic air that had come in and that of course, goes into create your gross thrust multiplied by of course, the exhaust velocity V e, which as we have just seen is likely to be (( )).

Now, this V e is again dependent on the efficiency of energy conversion, and the propulsive efficiency that we have talked about... So, unless the fuel, and this is being burnt twice, now once in combustion chamber, and once in the reheat zone unless the fuel is burnt efficiently. And then, the energy is converted efficiently to V e the thrust production will not be efficient. And as I mentioned either it will show up in the form of lower thrust or it will show up in the form of higher SFC; and this is something, which an engine creator or designer would have to bother about right in the beginning while putting together all the components of a jet engine.

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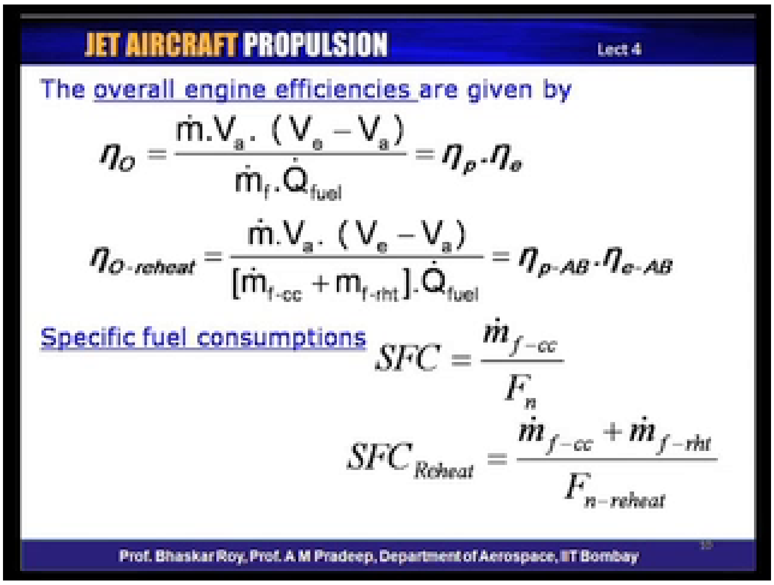

The overall efficiencies that we have talked about, we can take a quick look at them again. And now, we have the overall efficiency, which is of a basic jet engine multiplied by the propulsive, multiplied by the energy efficiency. And this is something, which we had defined before; if you simply you know reconfigure that efficiency for reheat purposes. We shall see here, that we have two kinds of mass flows over here, whole thing multiplied by the fuel that is pumped in, and the fuel is also pumped in twice once in the combustion chamber once in the reheat zone. And then of course, we have two efficiencies here one the propulsive efficiency of the after burning engine. And then, the energy conversion of this after burning engine.

So, the two efficiencies would now be operative in a slightly different manner. You have a big jet pipe over there you have a C-D Nozzle, and they would have to operate very efficiently. And this efficiency would come in into these efficiency parameters that we are talking about, and all of it together will show up as efficiency of thrust production, if the efficiency of the thrust production is not high, and if you desperately need thrust. You have to pump in more fuel to get thrust, which we desperately require. Let us say, in which case it will show up in the SFC definition that is shown over here.

So, this efficiency SFC definition now shows which one we have talked about before that, if you have just a combustion chamber in a basic jet engine SFC is defined in a very simple manner. The moment, you have a reheat engine; you have two rounds of fuel burning; Once in the combustion chamber, and again in the reheat zone, and obviously the SFC is going to go up. Now you are hopefully creating more thrust now through this reheat. So, even though your fuel consumption is going to be almost double your thrust production is going to be pretty high, if not double, and your SFC is going to be on the little high, but hopefully not exactly double.

So, you are creating high thrust most probably at the expense of a high SFC, if you have lower efficiency of either energy efficiency or propulsive efficiency your SFC is going to go up. Hence, you would be constraint to create thrust at the expense of more fuel burnt or your thrust production is going to go down. These are the various pushes and pulls of the operation of a typical jet engine. And this is what an engine creator would have to look into right in the beginning, these are the fundamental parameters that we introduced in the last class.

And as you can see now, a basic jet engine just converted to a simple reheat or a after burning engine introduces a number of a complications or complexities into the operation of the jet engine. And these operations will have to be taken into account right in the process of designing or creating these jet engines. As we go along we shall be talking about more and more complex engines. And hence, the complexity of these parameters would indeed become more and more involved in process of our various versions of jet aircraft engines, that we will be talking about in the course of this lecture series.

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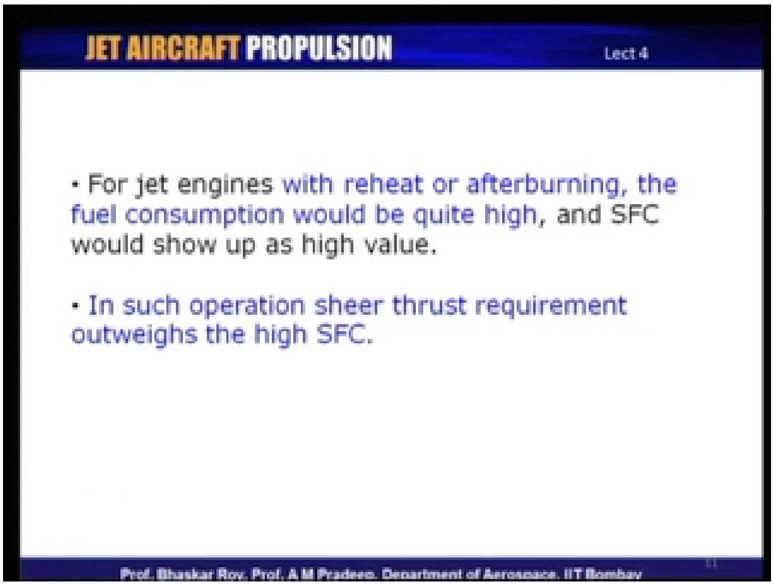

Hence, we can summarize by saying that the jet engines with reheat, and after burning. This is expected that the fuel consumption would be high, and the SFC would show up as high value. In such a situation it is normally expected that the sheared thrust requirement at that particular moment of operation outweighs the high SFC. You are sacrificing the fuel consumption for immediate requirement of thrust production. Obviously, we would probably not like to have this kind of operation happening throughout the entire jet engine operation, throughout the flight, because your fuel consumption is going to be very high in such a case. And then you would need to carry that kind of fuel with you in your aircraft. So, you would need to carry that fuel in your aircraft body this is not a very acceptable situation for the aircraft designer; he would definitely object to it

Hence, quite often most of the engines that have reheat capability do not operate with reheat all the time; they operate with reheat under certain operating conditions, where you desperately require high thrust at many other operating conditions of the flight. They operate simply without operate the reheat; that means with one combustion chamber, and allow the C-D Nozzle to create thrust whatever that is required for flying the aircraft under normal flight conditions in which it is expected that your thrust requirement is not desperately high. You do not require very high thrust for normal flying around for normal go it around or for normal climb or cruise or you do not require very high thrust a normal good thrust is often sufficient.

And hence, a reheat engine does not mean that, you have reheat operation on all the time during the flight it is used only during certain flight conditions in you really badly require high thrust. So, the SFC requirement, SFC constraint means that most of the modern reheat engines operate with reheat, only under certain operating conditions of the flight, and not under all operating conditions of the flight. Because as I mentioned otherwise, you would need to carry a lot of fuel in your aircraft body in which case, the aircraft would have to be very large, and that is not accepted for aircraft design purposes.

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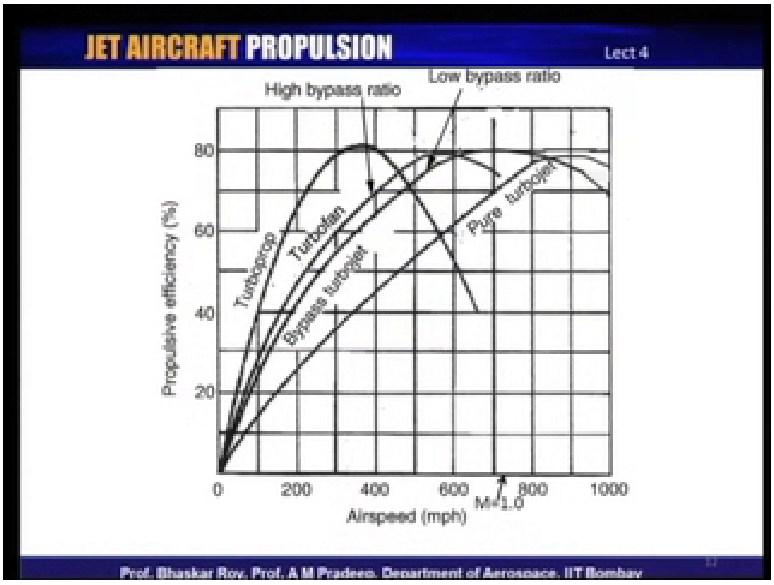

Let us, take a look at some of the performance features of these kinds of engines, which summarize the way in which these engines actually show up finally; as you can see here in terms of propulsive efficiency. The efficiency of thrust creation finally as you can as we have talked about before as you can see here. The propulsive efficiency is high for the turboprop in the low flight zones. This graph is shown in terms of miles per hours obviously, you know. Ye have used American data bank to create; this hence the miles per hour the mark number one is approximately shown over here.

So, the turboprop engine reaches a peak of propulsive efficiency. And then it goes down very fast. We have talked about a little before we have talked about these constraints more and more that turboprop do not have very high efficiency; and it go down very fast, but some are over there which have these turbofans. Now, the high bypass turbofans, which take over from the turboprop take it to reasonably good propulsive efficiencies. And then it comes pretty lowest mark. One they also go down and efficiency and close to efficiencies become slowly uncompetitive compared to let say, the low bypass ratio turbojet or what we call them turbofan engines.

Now, these ones what happens is they carry on the good propulsive efficiency beyond the mark one flight speed, and beyond mark one. They continue to have good efficiency into supersonic speeds, and maintain that reasonable good efficiency, but start going down a little later as they approach mark two flight speed, and that is when the pure turbojet start coming up in their propulsive efficiency. And some are near mark two the pure turbojet start becoming more and more competitive as opposed to the various versions of the turbofan engine; that we have talked about so at very supersonic mark numbers mark two; and beyond you would be looking at a basic heat turbojet engine as your propulsive device below that between mark one, and mark two. You would be probably looking at very low bypass turbojet or turbofan, whatever you call it jet engine as your propulsive device below mark one. You would be looking at turbofan engines specially between 0.6 or 0.65 or near about 0.8 0.85. You would be looking at various versions of turbofan engines.

And we will be talking about those turbofan engines in more and more detail later on below mark 0.6 (( )) speed. You would probably be better off, if you are deploying a turboprop engine. Because they have the highest propulsive efficiency, which of course, shows up in terms of fuel efficiency. So, these are roughly the mark number zones in which various kinds of jet engines are deployed in modern aircraft engines at the very lowest level. You would still have likely to have turboprop engines in between the mark 0.8, 0.85 of flight speeds; and that is why most of the passenger aircraft are flying to say around mark 0.85; and that is why we have the turbofan engine the various versions of turbofan engines with that. We will be talking about more and more in the coming lectures.

But beyond mark one typically you would be looking for engines; you would be used for military applications. You would be looking at the engines which are the bypass. And then to some benefit of SFC, but beyond mark two you would be constrained to use pure jet engines or turbojet engines for your thrust creation. So, these are the rough break up over, which you have your jet engine applications in the modern aircrafts.

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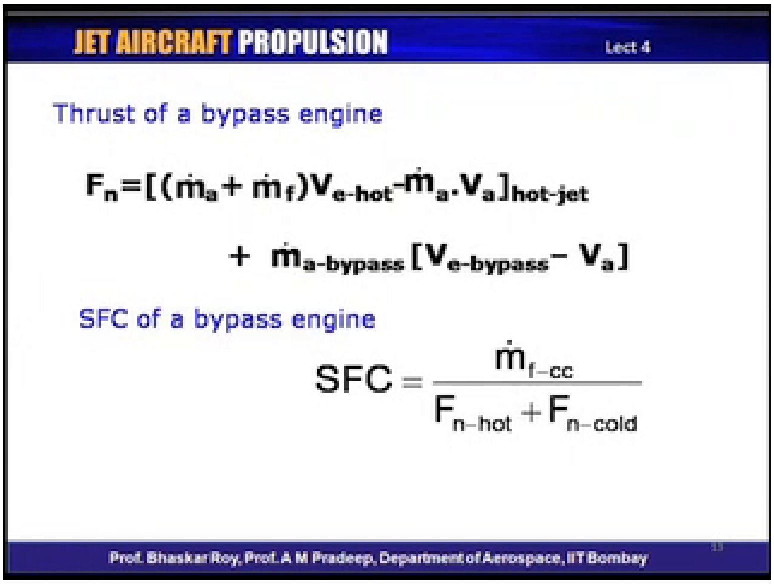

So, the thrust of the bypass engine can be written in terms of various components of the jet engine that we had looked at gross thrust created in terms of the V e multiplied by the fuel burnt. And the air that is coming and this is of course, in terms of your hot jet. And then of course, you have the cold jet which often is used in bypass engines, where you may have a cold bypass jet, and cold bypass thrust. And this creates, what is often known as cold thrust. And you get a certain amount of cold thrust that is associated with the thrust creation and hence your SFC of course, shows up in terms of total fuel that is burnt; and the thrust that is created from the hot jet, and the thrust that is created by the so called cold jet. Now, this is a kind of bypass engine typically you would like to see, if you have a jet engine that has a does not have a reheat, but it is just a bypass engine without any reheat.

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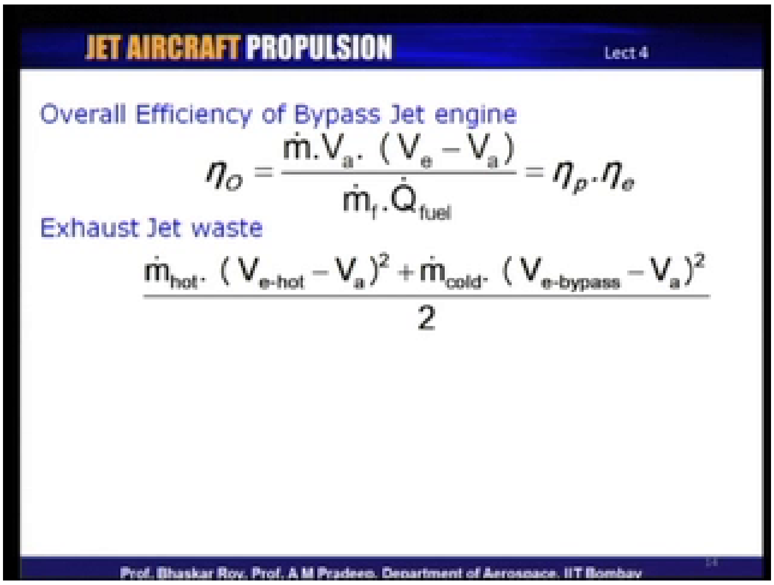

Now, overall efficiency of such a bypass engine without reheat can be again written down in terms of the hot exhaust waste energy as you can see here. You have two versions; one is the cold another is the hot this quickly tell us, you that the cold one would actually have a waste energy, which will be much less. Because it is exits bypass energy of cold would be higher lower V e. And hence, it is going to have a lower waste energy, and it will show up in your overall efficiency of thrust production.

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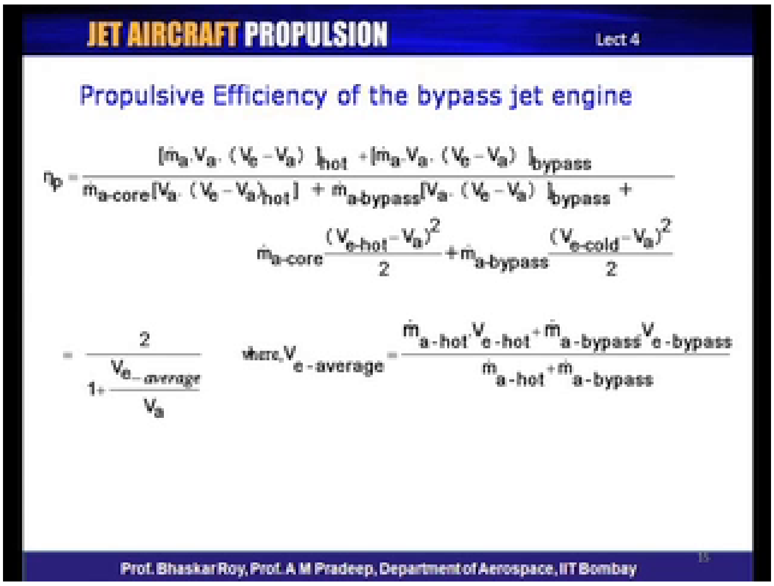

If we put it all together if we put it all together the overall propulsive efficiency of such a bypass engine can be written down in terms of the hot jet; that is hot thrust; that is created. The cold thrust that is created by the bypass. And then of course, these two components put together plus the waste energy. That is going out which again has two components that the hot waste energy, and the cold waste energy.

So, the numerator is your thrust production or the energy associated with the thrust production; and the denominator is the energy associated with the thrust production plus the waste energy that is been created. And this shows up in the form of the propulsive efficiency definition, which we had used before now, we have a V e that is an average V e average of the hot, and the cold.

And it stands to reason that since the cold exhaust velocity is much lower; this average is going to be lower. And hence, your propulsive efficiency of such a bypass engine is going to be higher; and this is exactly, what a bypass engine essentially aims to achieve. And this shows up in the form of SFC, and that is why one tends to have a bypass engine even, if it is a low bypass engine as it is used. We have seen between mark one, and mark two, just a little bit of bypass. And this is why it is done, if you have even, if you have a just a little bit of bypass it shows up in a little bit way in your propulsive efficiency, and it shows up in your SFC; and this is the small benefit that you get, if you do, if you actually have lower SFC you need to carry less fuel in your aircraft body.

So, this is the small benefit that you can get even from a low bypass jet engine; and it shows up in this equation that we have written down for bypass engine.

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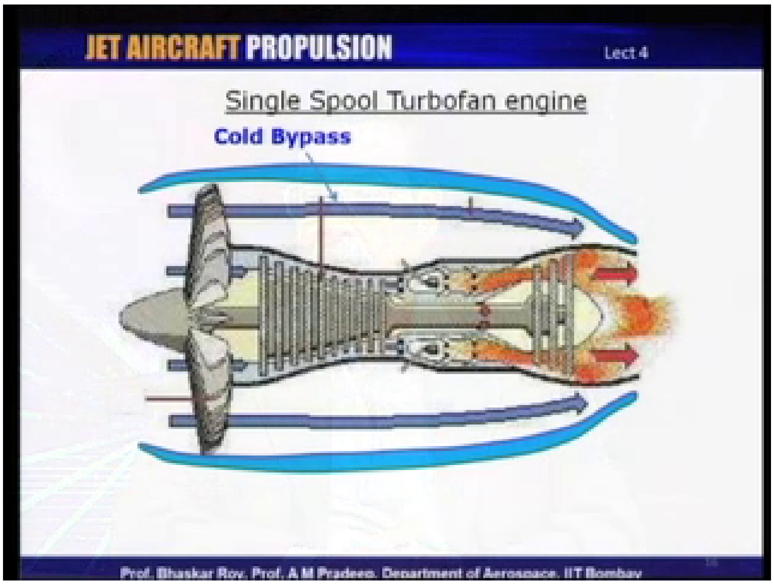

We can have a quick look at a very simple single spool turbofan engine in which it is a single shaft. You just have a turbine through this shaft it runs a compressor; and it runs a big fan; big fan produces the cold bypass; it comes through the bypass duct, and produces a cold jet, and the inner flow comes through the combustion chamber turbine. And then produces a hot jet, and then there is a hot, and cold jet together produce the thrust. And as we have just seen this cold jet would have a lower velocity; the hot jet would have a higher velocity; and two of them together would produce the thrust, and the average velocity of it would be lower. And as a result of which your propulsive efficiency going to be higher in the benefit across in the form of SFC there is another benefit the benefit is, if your exhaust velocity is of a lower value.

And you have a cold jet essentially in configuring your hot jet. The noise created by this jet is going to be much lower. Now, this is an important aspect in modern jet aircraft engine, because most of the jet engines are very high noise creating devices; if it is used in passenger or cargo aircraft the noise is a very important issue because many of the airboat today do not allow engines that create so much noise. So most of the modern engines are being created to reduce the noise, and this is another very important aspect of bypass even, if you have a very small bypass; it reduces the noise substantially it gives you may be a in terms of SFC, but it may give you a fairly substantially benefit in terms of noise reduction. And this is another facet of a bypass engine even, if it is a simple single spool turbofan engine as we see in this picture. So, the bypass engine added to the basic version, and we have seen added to the basic version. The reheat gives you more thrust. The bypass gives you more efficient thrust production, and a lower SFC, and the byproduct it lower noise. So, we have discussed various kinds of basic jet engines.

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In the next class, we will look at multi-spool turbojet engines, and various versions of turbofan engines they are mechanical entities. And how they various components of these engines are put together to make up a whole engine. And this is what we discuss in the next class.