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Introduction to Aerospace Propulsion

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Module No. # 01
Lecture No. # 15

Exergy, availability and second law efficiency

Hello and welcome to lecture 15. This is lecture number 15 of this lecture series on introduction to aerospace propulsion. As I have been mentioning in the last several lectures, we have discussed about several basic concepts of thermodynamics.

We have also defined all the thermodynamic laws and associated importance or significance of these laws of thermodynamics. In today's lecture, we are going to discuss about a rather recent concept. That is a very interesting concept and also a very important concept. That is basically known as exergy.

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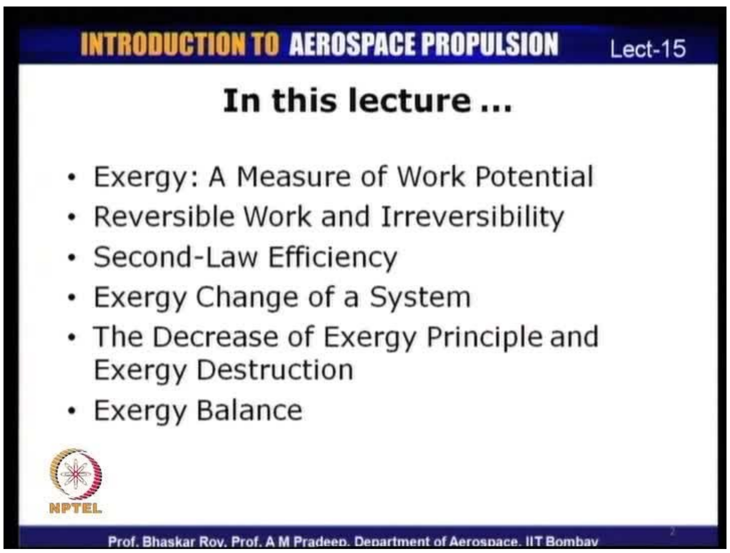

In today's lecture, what we are going to talk about is exergy, which is basically a measure of work potential. We shall then define what is meant by reversible work and irreversibility. We have already seen what are sources of irreversibilities, but how can we quantify irreversibility?

We shall then define what is known as the second law efficiency. Then, we shall define exergy change of a system, then the decrease of exergy principle and exergy destruction. And towards the end of the lecture, we will be taking about exergy balance. Now, exergy as a concept, is a very relatively new concept as compared to other concepts like enthalpy, internal energy and energy in general. These are concepts which have been existing for a rather long period of time.

Exergy is probably in the latest of the terminologies associated with thermodynamics. Exergy is basically a property which measures the amount of useful work that can be extracted from a certain system.

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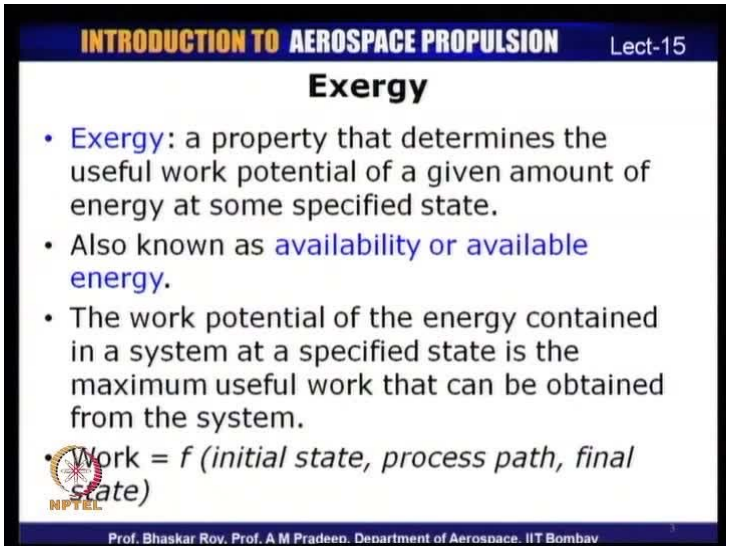

Exergy indicates the work potential of a system and also correspondingly, how much is the useful work for a given amount of energy, at a specified state of the system?

Exergy was earlier also known as availability or available energy. Some of the text books will still contain terms - these terms - that is availability and available energy. Exergy availability or available energy, all of these basically mean the same.

Work potential of an energy contained in a system at a specified state is basically the maximum work that can be obtained from a system, that is, if a system has a certain amount of energy, then - how much is the - what is the potential of that particular system to convert that work into useful work?

As we have seen, work is a function of the initial state, the process path and the final state; because, work is a path function, it is not a point function. Work is not a property of a system, whereas exergy is a property of a system and surroundings, as we shall see little later.

It is important for us to understand. Given a certain amount of energy for a system, how much of that work can actually be utilized into useful work? Exergy is a property that helps us in defining this property.

As we have seen, for any given process, the work output can be maximized, if between these two states the process can be carried out in a reversible manner. If the process can be carried out reversibly, then the work output of that particular system is maximized. That is a very important property, because - we as engineers, designers or scientists - we would obviously like to maximize the work output, work potential of a particular system.

Exergy is a property which will help us in identifying the potential of that particular process or a system. If you look at a certain system, if you would like to maximize a work potential, it means that you have to extract as much work as possible from that particular system, which means that the system should be in a dead state at the end of the process, which means that after the process is completed, the system will not have any more potential to do any more work.

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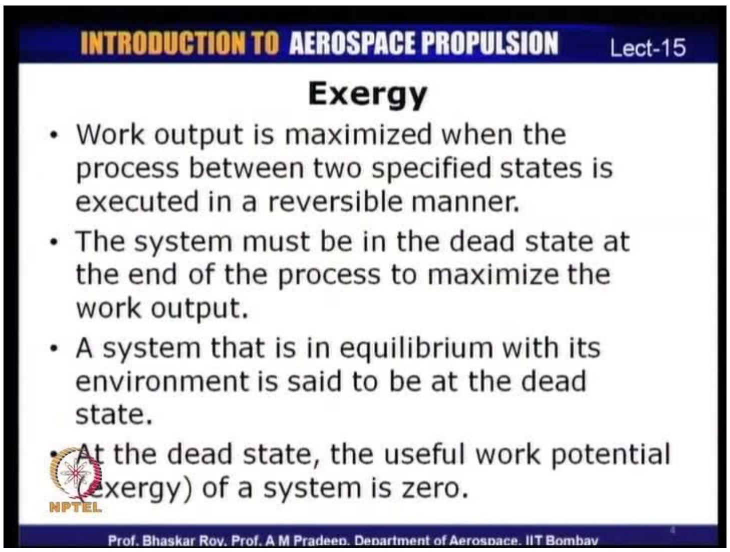

If a system is in complete thermodynamic equilibrium with its surroundings, then that system is said to be in a dead state. The work potential obviously associated with that of a system which is in a dead state is 0.

Work potential can basically be maximized, when the process between the two states is executed reversibly. And the system obviously should be in a dead state at the end of the process, so that we can maximize the work output. And at the dead state, the useful work potential which is the exergy of a system will be 0. Because, there is no more work potential than the system can do.

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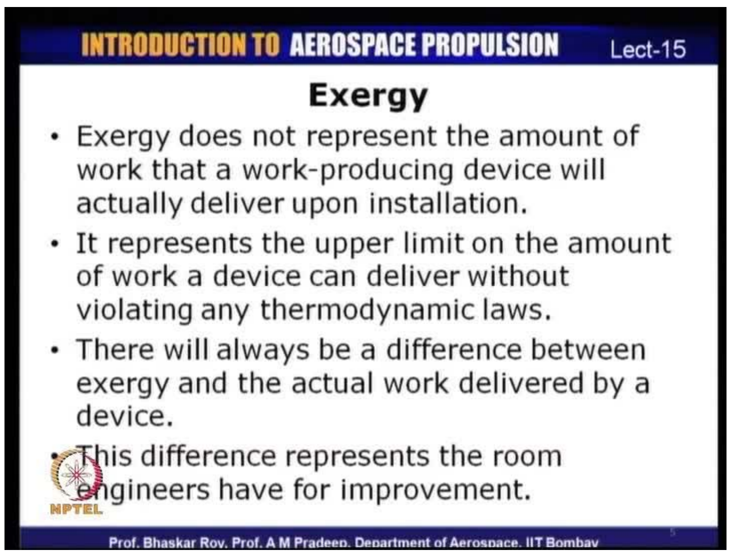

The system exergy as such, does not represent the amount of work that a work-producing devices will actually deliver upon instillation.

No, it does not really represent how much work you can actually get. It basically gives us an upper limit on the amount of work that a device can deliver without violating any laws of thermodynamics.

As we have seen, there are always differences between the work potential and the work delivered. And exergy, there is always going to be a certain difference between exergy and the work output of a certain process. And it is this certain small difference, that engineers always look for, for improvement, that is, you would like to minimize the gap between exergy and the actual work delivered by the system.

Exergy is a certain property which tells us, that this is the maximum work that you can actually extract from this process without violating any of the laws of thermodynamics. As engineers we can always say, that given this process, I can extend the efficiency of this system by minimizing the gap between the exergy and the actual work output of this particular system.

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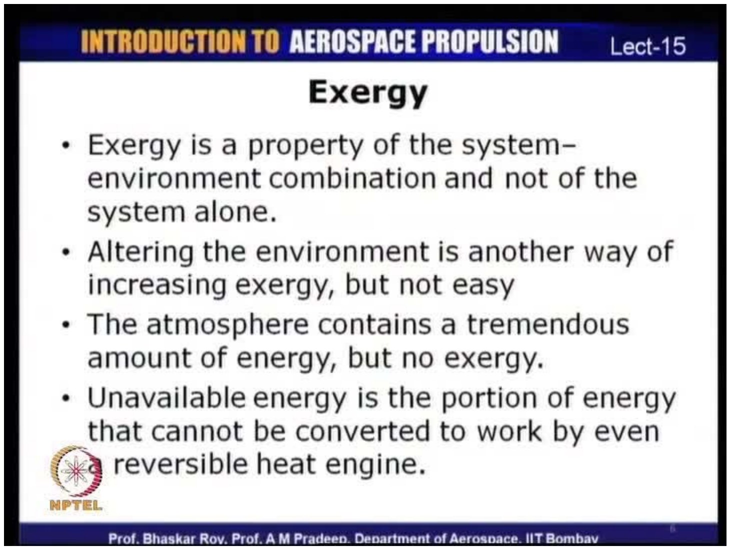

Now, exergy - is as I mentioned - is already a property, but it is not simply a property of the system. Exergy is a property of the system and the environment combination. It is not a property of the system alone. Exergy is a property which links the system and the surroundings. Exergy is a property of the system environment combination, which means that you can either improve the efficiency of the system itself or the other way around is that you can alter the environment to increase exergy, but obviously, that is not an easy task to change the environment to maximize efficiency. Changing environment is one option of improving exergy or the other option is to improve the efficiency of the system.

Increasing the efficiency of the system is an easier method rather than changing the environment itself. As we know, the environment or atmosphere has tremendous amount of energy, because we often consider the atmosphere to be a source and at the same time it can also be a sink; but atmosphere as such, does not have any exergy, because there is no work potential; because all systems come to equilibrium with the surroundings or with the atmosphere, which means that the system or surroundings, the atmosphere, if you consider the whole atmosphere as a source or a sink, they have tremendous amount of energy, but they have no exergy, because there is no work potential for extracting work from the surroundings, because it is with this surroundings that a system will come to equilibrium with, at the end of the process, that is what a certain important aspect of the environment itself. And the unavailable energy is certain part of work or energy, which cannot be converted to useful work output, even by using a reversible process.

We have seen that even in a reversible engine, your efficiencies can really not be 100 percent, because that is not a restriction or limitation of the irreversibilities. It is a limitation of the second law of thermodynamics itself, that you need to have a certain amount of heat which is rejected to the surroundings.

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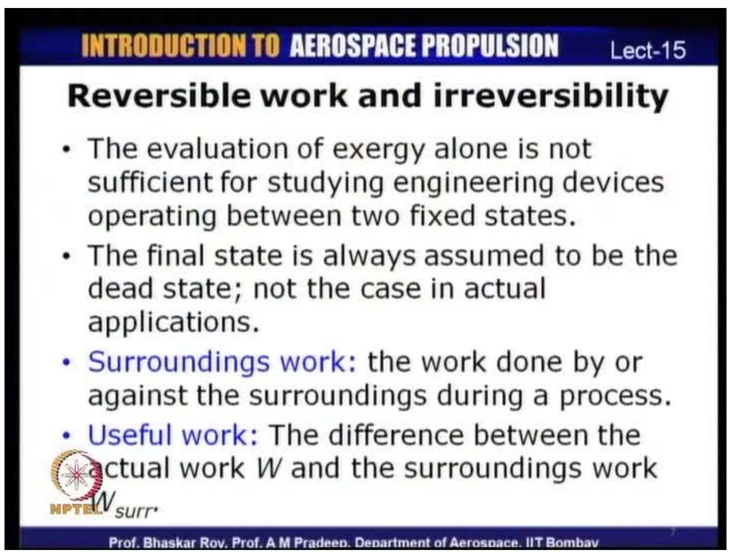

Unavailable energy is one part of energy which cannot be converted to useful work output, even by a reversible heat engine. Even using a reversible heat engine - it should not - it will not be possible for us to convert the amount of energy work output to maximum.

It is not enough, that we understand exergy as a property alone in studying engineering devices which are operating between two fixed states. We normally assumed the final state to be in a dead state. If we have to define exergy or calculate exergy, the final state has to be the dead state, which is not really the case in actual applications, that the final state is not in dead state. So, it is not possible or an exergy alone cannot really help us much in analyzing engineering systems; we need to define a few more terms.

One of them is known as the surroundings work. Surroundings work is the amount of work that the surroundings does on the system, that is, if a system is undergoing an expansion process, then the system has to overcome the surroundings work to be able to do certain useful work output.

And the difference between the actual work and the surroundings work is known as the useful work, because the amount of work that you actually get is the difference between the work that is done by the system and the difference done by the system as well as the work done on the system, that is by the surroundings work.

Surroundings work is basically defining the work done by a process, work which the system has to do against the surroundings during a process, or the work done by the surroundings on the system; and useful work is the difference between the actual work done by the system and the surroundings work.

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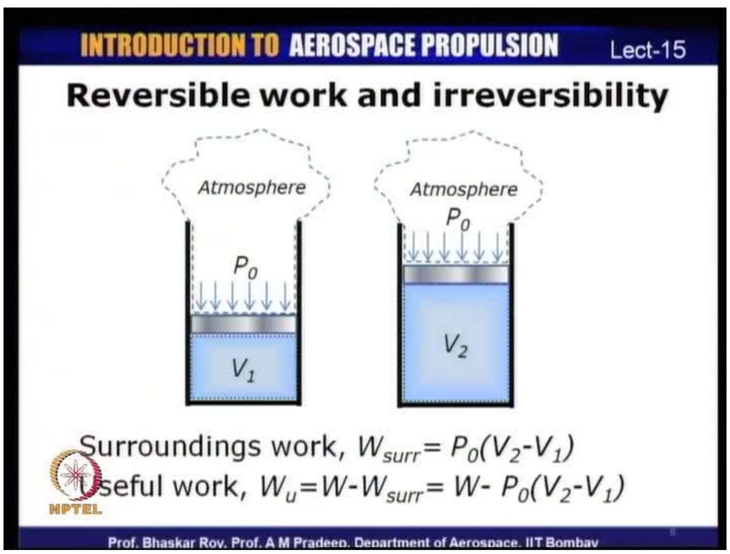

Let me illustrate this point a little further using one example of a piston and cylinder arrangement. In this example that we have here, basically we have a piston cylinder arrangement, which means that there is a certain pressure which is acting on the piston by the surroundings. This is the atmosphere which is shown here by the dotted line. Let us say that this is the atmosphere which has an influence on the piston.

Let us say the atmospheric pressure is p naught. Surroundings work is basically equal to the difference between or the atmospheric pressure p naught multiplied by the difference in the volumes. If the system was undergoing an expansion process, this system has to do a work against the atmospheric pressure. Therefore, work done by the surroundings will be equal to atmospheric pressure p naught multiplied by v2 minus v1. What is useful work here? Useful work will basically be w useful, as actual work output w, minus the surroundings work, which is equal to w minus p naught into v2 minus v1. This is basically how you should be calculating the actual work output or useful work output, but in almost all the practical applications, we know that the surroundings work will basically be a very small quantity; because - atmospheric pressure - if you compare atmospheric pressure and the product p naught into v2 minus v1, that usually will be much small compared to the actual work output, but it depends upon the process. In certain process, you may have surroundings work which can actually be quite comparable to that of the actual work.

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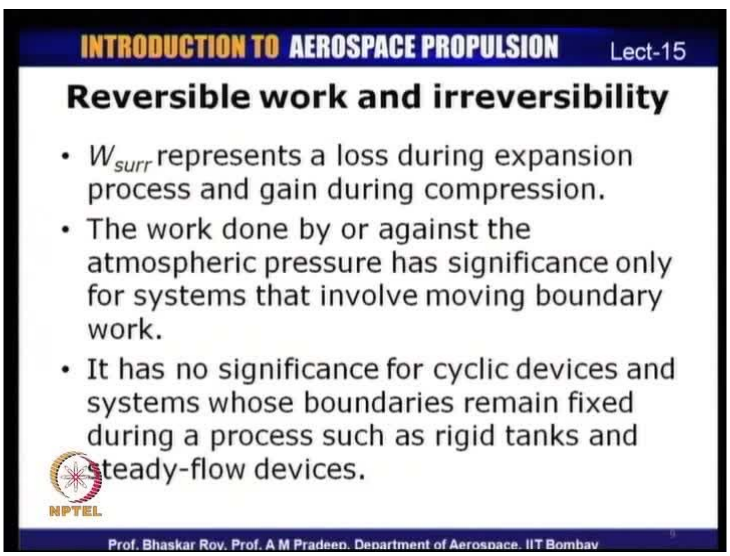

Work surroundings, basically represents a certain loss during an expansion process, because as we have seen in this example which is an expansion process, the system is doing against the surroundings work to be able to do a certain useful work output. Useful work output here was w minus the surroundings work. Now, if you were to consider a compression process, that is, a piston is actually moving into the cylinder - compression process - the surroundings work can actually act as a gain; that is, surroundings work will add up to the actual work done on the process. In that case, the useful work will be equal to w, which is actual work plus the surroundings work.

Now, surroundings work, or work done by the surroundings, or work done on the surroundings will have significance only in those processes, which have a certain moving boundary or in those processes, if there is a certain flow through the process.

It does not have any significance for cyclic devices and systems whose boundaries will remain fixed during a process like rigid tank or turbines and compressors and so on, which are steady flow devices. There is no change in the moving boundary. The boundary walls are fixed; obviously, there is no work done by the surroundings or against the surroundings. And so, that is of significance only if the work done is partially because of this moving boundary.

Surroundings work has a significance only in those processes, where there is a boundary work involved. In other cyclic devices or cyclic processes, surroundings work does not really make much sense, because there is hardly any work done by the surroundings on the systems.

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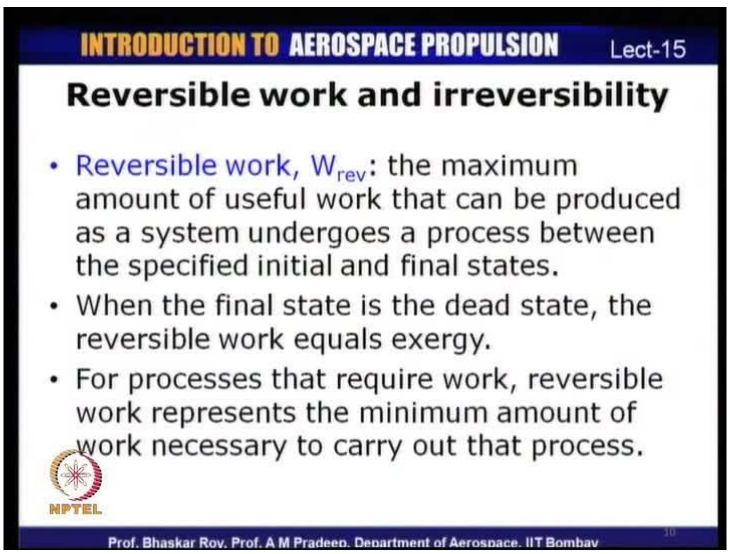

We have now discussed about the surroundings work, the useful work and therefore useful work being equal to actual work minus the surrounding work and so on. Now, let us look at what the maximum work that you can get from a certain system is. I have already discussed that the work done by system can be maximized, if the process is carried out reversibly.

Reversible work is the maximum amount of useful work that can be produced as a system undergoes a process between initial and final state, that is, as a system undergoes process reversibly form initial to final state, the output of the system can be maximized. Now, if the final state of the system is the dead state, then the reversible work will be equal to exergy. As we have seen, exergy is the work potential of the system as long as the m sate is a dead state.

If the system has undergone a reversible process and it has reached its final state and if the final state happens to be the dead state, then the reversible work equals exergy. And if there are processes which require work, reversible work represents the minimum work required to carry out that process.

For processes which require work like compression processes, etcetera, these require work input. For those processes, reversible work represents the minimum work which is required to carry out this particular process.

The difference between the useful work and the reversible work represents or is equal to the irreversibility. As we have seen, that in actual processes, useful work is always less than the reversible work, because of the presence of irreversibilites. What is it that this irreversibility causes? It basically causes a difference between the useful work output and the reversible work output.

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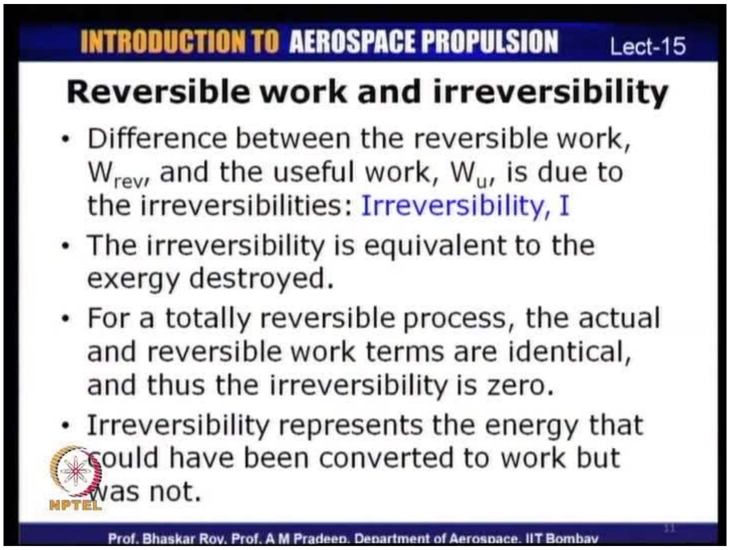

Difference between w reversible and the useful work is known as irreversibility. And irreversibility is equivalent to the exergy destroyed. If irreversibility was equal to 0, it means that reversible work is the same as the useful work. Therefore, you have maximum exergy present. As irreversibility increases, you are decreasing your exergy.

Irreversibility is equivalent to the exergy destroyed. For a totally reversible process, the actual and reversible work terms would be identical and the reversibility obviously will be equal to 0.

Irreversibility basically represents a certain amount of energy, that could have been converted to work output, but could not. So - irreversibility is a certain - you can actually quantify irreversibility, if you can calculate the reversible work and the useful work. Irreversibility represents the amount of work which could have been converted to useful work output, but was not converted, because of other effects like frictional losses, heat transfer through finite temperature differences and so on.

These are sources of irreversibilities. The presence of these irreversibilities leads to the fact, that your actual work output is less than the reversible work output. Let me explain this irreversibility using this example:

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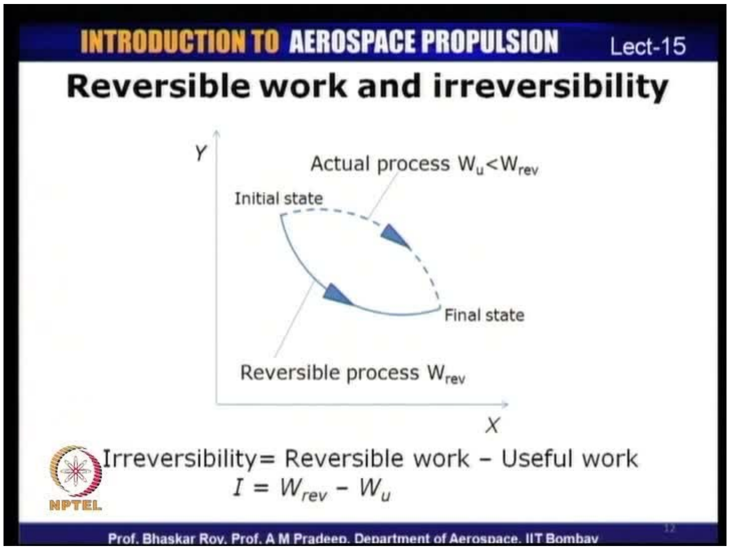

Here, we have a process which is taking place between its initial state and final state. Let us say, the process has been indicated in a process diagram, in coordinates x and y, which could be any other coordinate. This system was initially, at its state here, that is, initial state and this is - let us say - the final state.

This is how the process could take place, if it was a reversible process. It is shown by a solid line, which indicates a reversible process. Let us say, this is the actual process indicated by the dotted line. Actual process, the W, useful work output is less than the reversible work output, because of irreversibility.

The useful work here for the actual process is less than the reversible work. As per our definition for irreversibility, irreversibility is equal to the difference between reversible work and the useful work. Irreversibility I is equal to W reversible, that is the reversible work during the reversible process minus the useful work.

What we can see is that if these two processes, the closer these two processes are, the lesser is the irreversibility, that means as the actual process approach the reversible process, the useful work output approaches the reversible work output, which means that the irreversibility becomes closer to 0.

Irreversibility being 0 means, that the exergy of the system is at its maximum level. And as the irreversibility increases, it means that – your - the exergy associated with that system is decreasing, which is why I said, that irreversibility is an indication of exergy destroyed or reduction in exergy.

Exergy is one of the properties of a system plus surroundings combined, but we will normally refer to exergy in terms of useful work and reversible work. The amount of work when useful work and reversible work is equal to each other is basically the exergy. For a process which is carried out reversibly, the work output basically represents the exergy of the process itself.

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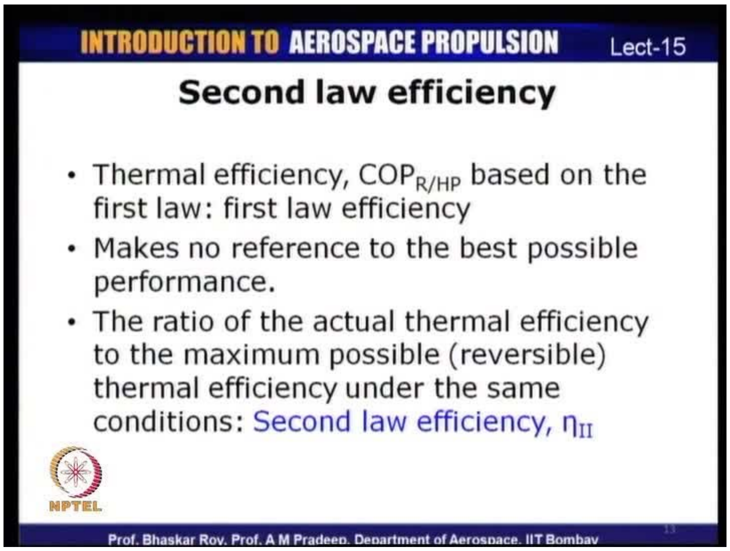

Now, what we shall discuss next is a consequence of this discussion we had on exergy, work potential and so on. It is basically known as the second law efficiency. Now, we have already defined thermal efficiencies, COP of refrigerator, heat pump, etcetera. These are efficiency definitions which are based on the first law of thermodynamics. As per first law, we can define, that there is a certain heat input to the system and there is a heat rejected by the system. Difference between these two and the ratio of the work output basically will gives us an indication of the efficiency of the system.

Efficiency, thermal efficiency or COP - these are terms which are based on the first law of thermodynamics. These are also commonly referred to as the first law efficiency, but there is one short coming or short fall of this definition of efficiency. This efficiency definition does not make any reference to the best possible efficiency or best possible performance. The ratio of the actual thermal efficiency to the maximum possible efficiency, which is what we would get if the process was reversible under the same conditions, is known as the second law efficiency.

This ratio, that is, the ratio of the actual thermal efficiency - which is calculated from the first - which is based on the first law of thermodynamics known as the first law efficiency, ratio of that efficiency to the efficiency of the reversible cycle under the same processor or under the same condition, is known as the second law efficiency. What is the significance of the second law efficiency? We shall illustrate that little later.

Second law efficiency basically gives us an idea of what is the maximum amount of efficiency that you can get, which is from the reversible cycle and what is the efficiency that you are now getting during the actual process, that you are considering at the moment?

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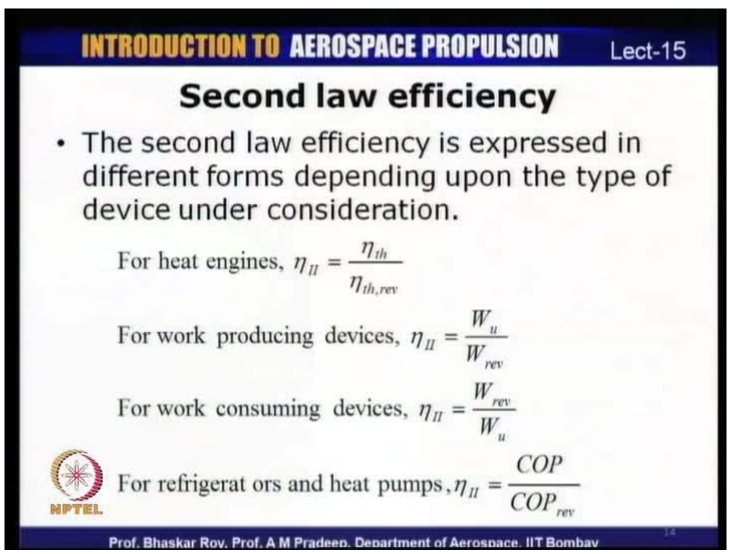

Second law efficiency is expressed in different ways. For heat engines, we normally express the second law efficiency as the ratio of the thermal efficiency, that is the actual thermal efficiency, to the ratio of the thermal efficiency for the reversible process. For work producing devices or for those devices which generate work output like turbines, etcetera, the second law efficiency is equal to the ratio of the useful work to the reversible work. For work consuming devices, second law efficiency is the ratio of the reversible work to the useful work. You can see clearly, that for work producing device and work consuming device, the efficiency definition is similar, but just that the ratios are reversed.

For refrigerators and heat pump, the second law efficiency is defined in terms of the coefficient of performance. It is equal to COP actual divided by COP reversible. This is how you would define the second law efficiency for different systems depending up on what system we are considering.

For heat engines, for example: it is ratio of the actual efficiency divided by the efficiency for the reversible cycle and so on. For refrigerators and heat pumps, the efficiency is basically, ratio of the actual COP divided by the reversible COP.

Now, you can actually generalize this term of second law efficiency in terms of the exergy. Exergy is something we have discussed. Exergy basically represents the work potential of a system, if the system was to be at it is dead state, at the end of the process.

Second law efficiency is basically a ratio of the exergy recovered to the exergy supplied. What does this mean? It basically means, that if you have a system, whatever be the system - its heat engine or work producing device, consuming device and so on - the amount of exergy that you are actually been able to extract from this process divided by the actual exergy which has been supplied, is basically representing the second law efficiency.

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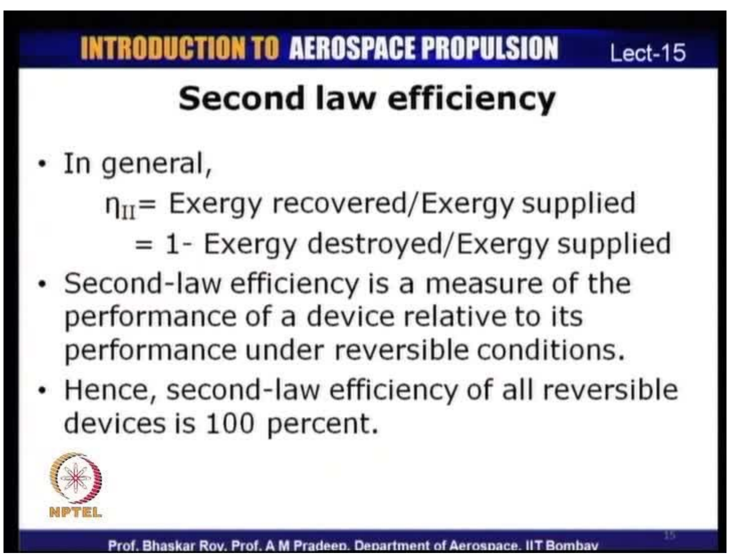

This can be expressed as, a second law efficiency is equal to exergy recovered divided by the exergy supplied, which is the same as 1 minus exergy destroyed divided by exergy supplied.

Second law efficiency is a measure of the performance of the device relative to the performance under reversible conditions, that is, if - your cycle - all real cycles are irreversible. So, second law efficiency basically is a measure of the performance of this device as compared to the performance of the device, if the processes were irreversible, which means that obviously, the second law efficiency for all reversible engines is 100 percent, but is the thermal efficiency of a reversible cycle 100 percent? No, it is not, because thermal efficiency of so called first law efficiency of any engine, whether it is reversible or irreversible, is not 100 percent, but second law efficiency can be 100 percent, if the cycle or the heat engine or the process is reversible.

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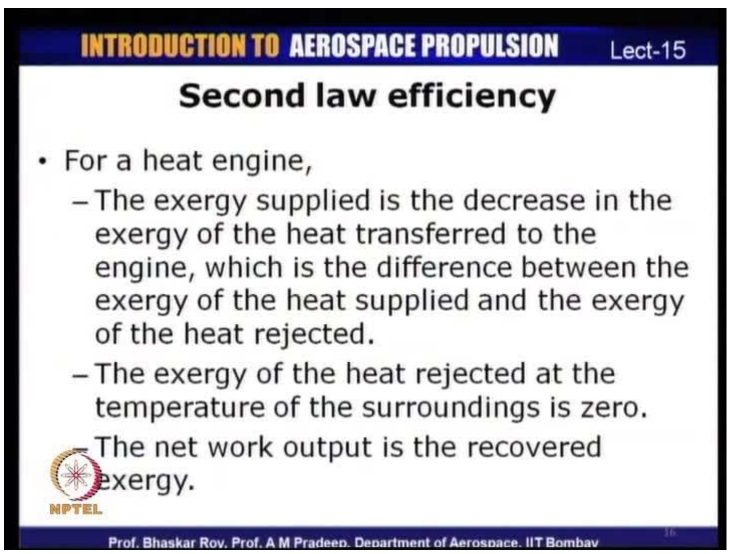

Second law efficiency for reversible processes will be equal to 100 percent. And for a heat engine basically, we have seen that exergy is defined in terms of a exergy utilized and exergy supplied. For a heat engine, the exergy supplied is basically the decrease in the exergy of the heat transferred to the engine, which is basically the difference between the exergy of the heat supplied and the heat rejected.

Exergy of the heat rejected at the temperature of the surroundings obviously, will be equal to 0, because if you are rejecting heat at the temperature of the surroundings, then the exergy is 0. What is the recovered exergy? Recovered exergy is the network output.

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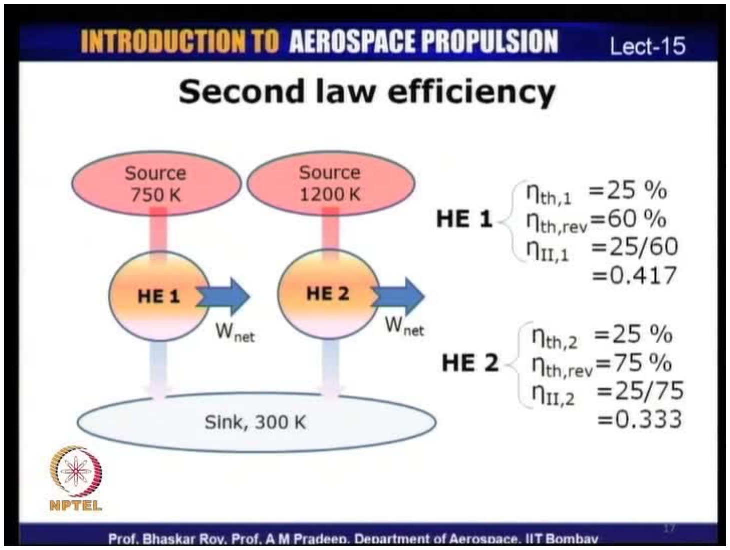

This is how you can calculate the second law efficiency for a heat engine. We will illustrate this point with an example here. Here we have two heat engines: heat engine 1 and heat engine 2, which are operating between a source and a sink. Heat engine 1 is operating between a source of 750 kelvin and a sink of 300 kelvin. And there is a network output from heat engine 1. Heat engine 2, on the other hand, operates between a source of 1200 kelvin, generating a net work output and rejecting heat to the same sink at 300 kelvin.

Now, let us say - the efficiency – the first law efficiency of heat engine, both the heat engines, let us say, the first law efficiency is the same of 25 percent. First law efficiency of heat engine 1, that is, eta thermal 1 is 25 percent, eta thermal 2 is also equal to 25 percent, which as an assumption.

Now, we can also calculate the reversible efficiency for both these engines, because the Carnot efficiency can be calculated for these heat engines as 1 minus tl by th. For the first case, 1 minus tl by th will be equal to 1 minus 300 by 750. So you get an efficiency of 60 percent.

1 minus tl by th for this case is 60 percent, for heat engine 1. 1 minus tl by th for the second engine, the heat thermal efficiency of second heat engine is 75 percent. What does this mean? For a layman, the efficiency of both the engines are same, that it is 25 percent.

What is the difference between heat engine 1 and 2? Well, it does not appear to give any difference between these two heat engines, but if you look at the thermal efficiencies for the reversible processes, they are different.

Let us now calculate the second law efficiency for both these engines. Second law efficiency for heat engine 1 is 25 by 60, that is, eta thermal divided by eta thermal reversible, 25 by 60, that is 0.417. For the second engine, second law efficiency is 25 by 75, that is 0.333.

This basically states, that the second engine is less efficient as compared to the first engine. Why is that? We can also understand that little more. Both these engines have the same thermal efficiency, which means the ratio of network output to the heat input is the same, but the second engine which is operating between a higher temperature source and the same sink will have a higher Carnot efficiency, which means, that the second engine has a greater potential to increase its efficiency and go to the higher efficiency level, than the first engine. First engine has a same thermal efficiency as that of the second engine, but the Carnot efficiency of that is lower, because it is operating between a source which is at a temperature which is lower than that of the second engine. This means that the second engine, though it has a higher potential to transfer to improve its efficiency, it does not, because thermal efficiency is same.

Therefore, the second law efficiency of the second engine is lower than that of the first engine. This is clearly an advantage for an engineer, because this gives us a method by which you can quantify the performance of a heat engine, not just based on the thermal efficiency which is the first law efficiency, but also based on an efficiency as compared to the reversible cycle itself.

Second law efficiency will clearly help us in understanding the performance of an engine as compared to the reversible part of the same engine.

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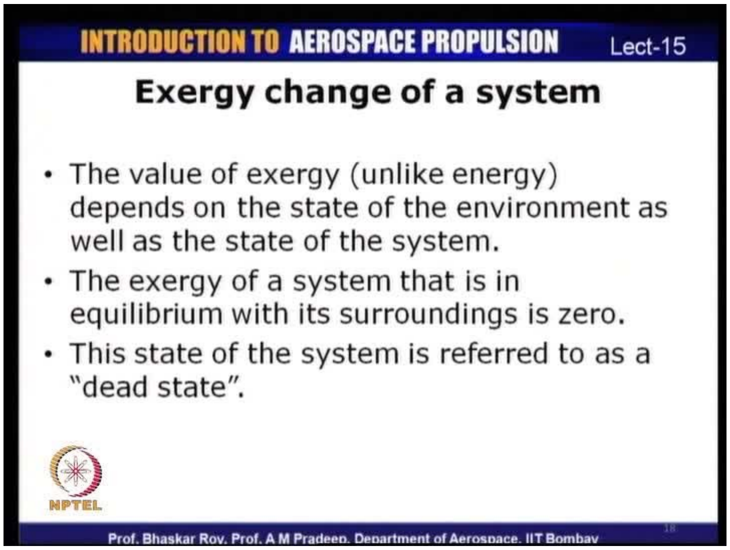

This is how one could analyze the performance of actual engines. Let us say, you are given a choice between two heat engines, which have the so called same first law efficiency, but they are operating between two different temperature sources and sinks.

Though you may be tempted to assume, that both of them have the same thermal efficiency and so they are both the same in terms of performance, but now you know, that if you can now calculate the Carnot efficiencies for those two cycles and therefore you can calculate the second law efficiencies and then decide which of these two heat engines is better.

The value of exergy basically, unlike energy, which depends only on the state of the system, depends on the state of the system as well as the state of the surroundings. And so, exergy of a system that is in equilibrium with this surroundings will be equal to 0, because if it is in equilibrium, there is no scope for any more work potential and the state of this system is basically referred to as the dead state, as we have discussed earlier as well, that this is basically the dead state. Now, what we shall do now, is basically to derive an expression for understanding or calculating exergy of a closed system.

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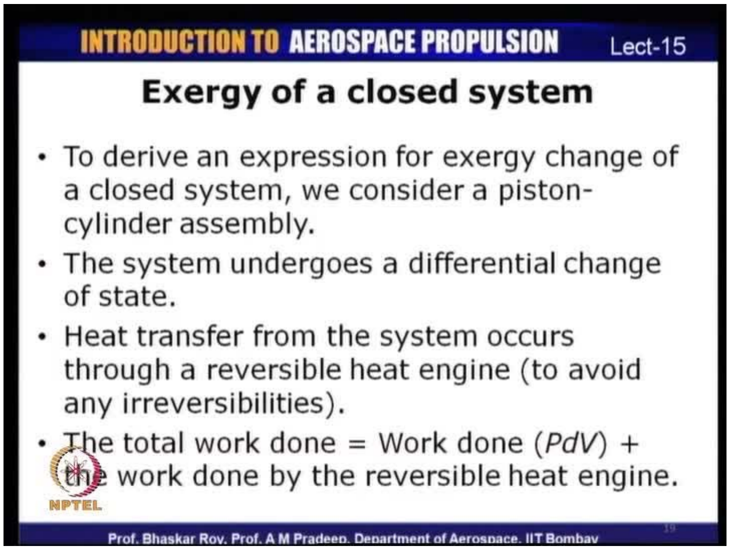

And also we shall derive exergy change for a closed system. Subsequently, we shall derive exergy for open system and exergy change for open systems and so on.

Now, if you have to derive an expression for exergy change of a closed system, we shall consider a piston cylinder assembly, as we have done in the past. Let us say the system undergoes a differential change of state. It is differential change, because we would keep this process as close as possible to reversible process.

Since heat transfer from the system to the surroundings, to a finite temperature difference can lead to irreversibilities, we will transfer that heat through a reversible heat engine.

From the piston cylinder assembly, we are going to transfer heat from the system to the surroundings through a reversible heat engine, so that we can assume that the whole process is reversible. Heat transfer from the system is through a reversible process. There are no irreversibilities. So - there are two - the net work done by this combined system will be equal to the work done by the piston cylinder or assembly, which will be the PdV work or the displacement work, as well as the work output of the heat engine, because it generates a certain amount of work output and so, the net work output will be equal to work done by the piston cylinder, which is PdV work plus the work done by the heat engine itself.

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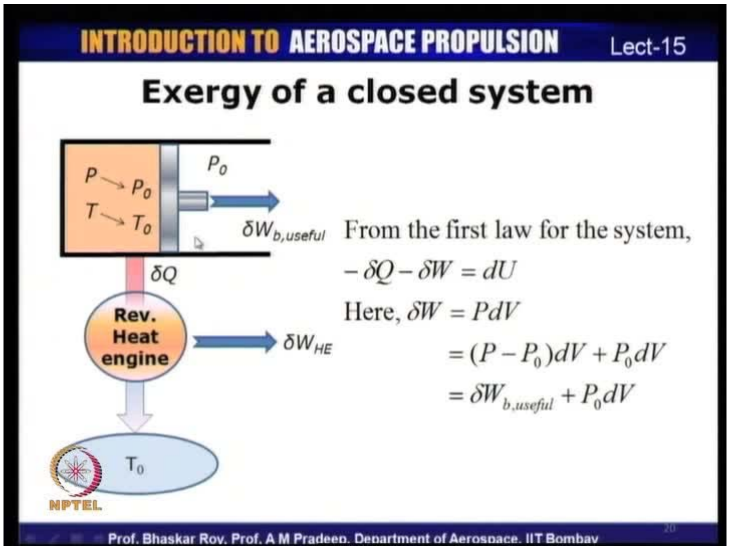

If you look at the system which I was discussing about, this is what it would look like. The system consists of this piston cylinder assembly. Here we have the piston cylinder assembly. Piston initially was at a pressure of P, temperature of T and it is slowly moving towards equilibrium with the surroundings, which is at a pressure P naught and temperature T naught.

It transfers heat at the rate of delta Q to a reversible heat engine, which finally transfers the temperature to surroundings, which is at a temperature of T naught. So system moves from pressure P to P naught, temperature T to T naught. And the system generates a work output, which is equal to delta W b useful. So b here means boundary work and useful work output.

And also the reversible engine is assumed to generate a network output which is equal to delta W HE, which is heat engine. From the first law of thermodynamics, for the system, we already know that Q minus W is delta U. Now, here Q is equal to minus dq, because it is heat transfer from the system.

Heat transfer from the system is negative. So, delta Q is negative. Minus delta Q minus delta W is equal to dU. And for the system, delta W is because of displacement work and delta W is equal to PdV. What is PdV here? It is basically P minus P naught times dV plus P naught dV. P minus P naught dV is the useful work output. We have already discussed that difference between the work done and the work done against the surroundings work, P naught dV is the surroundings work.

P minus P naught dV is the useful work that is done by the system, after overcoming the surroundings work. And there is also P naught dV, which is coming in. Net work output will be equal to delta be useful plus P naught dV, where P naught dV basically represents the surroundings work.

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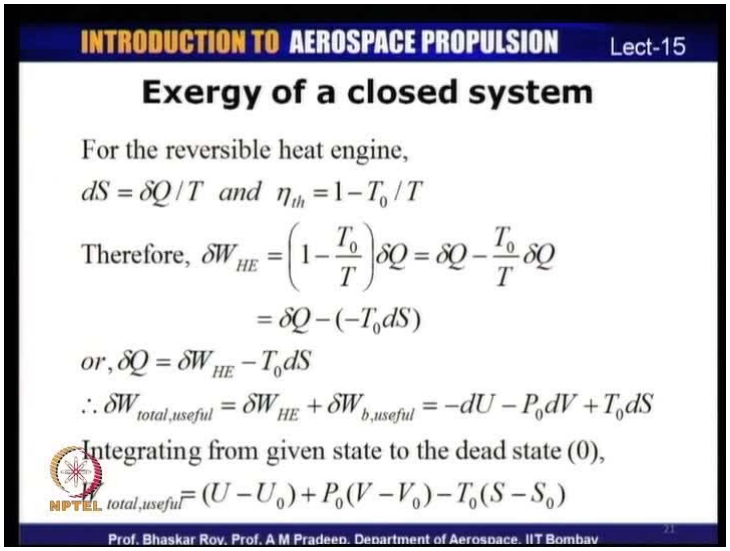

For this system and surroundings combination, we shall now also derive expression for the heat engine part of it.

Now we have seen that the heat engine is the reversible heat engine. For the reversible heat engine, we have seen that the dS, which is the change in entropy, dS should be equal to delta Q by T. And thermal efficiency is 1 minus T naught by T.

Therefore, delta W heat engine is equal to thermal efficiency times delta Q, because thermal efficiency is network output by heat input. Therefore, delta W heat engine is equal to 1 minus T naught by T multiplied by delta Q. Or, which is also equal to delta Q minus T naught by T delta Q, which is in fact equal to delta Q minus of minus T naught times dS, because, dQ by T is equal to dS.

As we have seen already, dS is dQ by T. So dQ divided by T is dS. Answer therefore, delta W heat engine equal to delta Q minus minus TS times T naught times dS or delta Q is equal to delta W heat engine minus T naught dS. If you go to our previous equation which was delta Q minus W is equal to delta U, where we have already calculated delta W for the system.

Delta W total will be equal to delta W heat engine plus the delta W b useful, that is done by the system, which is in fact equal to minus dU minus P naught dV plus T naught times dS. If you integrate this from the given state to the dead state -which is 0 - which is indicated by the subscript 0, the total useful work done is, which is basically the sum of the work done by the heat engine plus that of the piston cylinder assembly, should be equal to U minus U naught plus P naught into V minus V naught minus T naught multiplied by S minus S naught, where all the properties which have a subscript of 0, corresponds to the properties at the dead state.

U naught is the internal energy at the dead state, P naught is pressure at dead state, V naught is volume and so on. All the properties with a subscript 0 is corresponding to the properties at the dead state.

We have calculated the total work done by the system, which consisted of the piston cylinder assembly and the heat engine together. Now, it is possible that - very much possible that - the closed system may also have kinetic energy and potential energy associated with it.

Now, it is a known fact that - kinetic energy and potential energy as - the exergy associated with kinetic energy and potential energy is equal to the magnitude of the kinetic energy and potential energy itself, because these are macroscopic forms of work which can be completely converted into useful work output. Exergy of kinetic energy is the kinetic energy itself. Exergy of potential energy is the potential energy itself.

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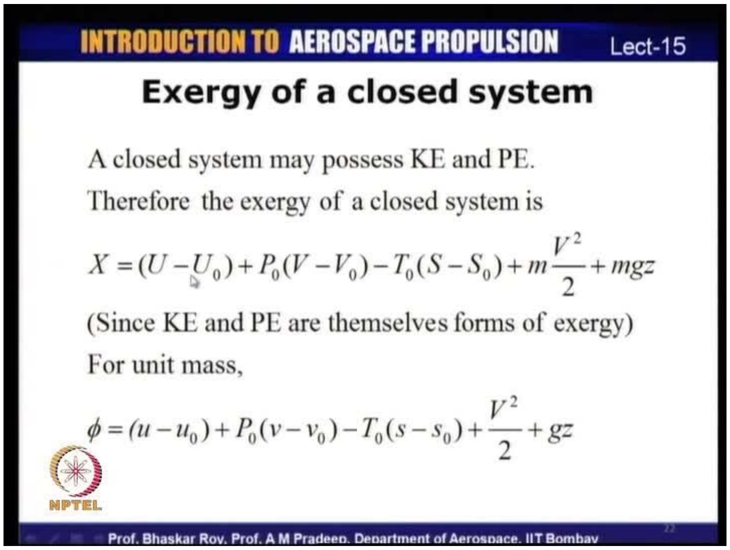

The total exergy of a closed system, which may also have kinetic energy and potential energy can be expressed as x is denoting the exergy of a system, is equal to U minus U naught plus P naught into V minus V naught minus T naught multiplied by S minus S naught plus m V square by 2, which is the exergy associated with kinetic energy plus mgz, which is exergy of the potential energy.

For a unit mass, exergy is expressed as phi. Phi is equal to U minus U naught, small letters, which is specific internal energy plus P times specific volume difference minus T times specific entropy difference plus V square by 2 plus gz. This is one way you can calculate the exergy of a unit mass of a system, if you know the internal energy, the volumes entropy and kinetic and potential energy, if they are present, as compared to the properties at the dead state.

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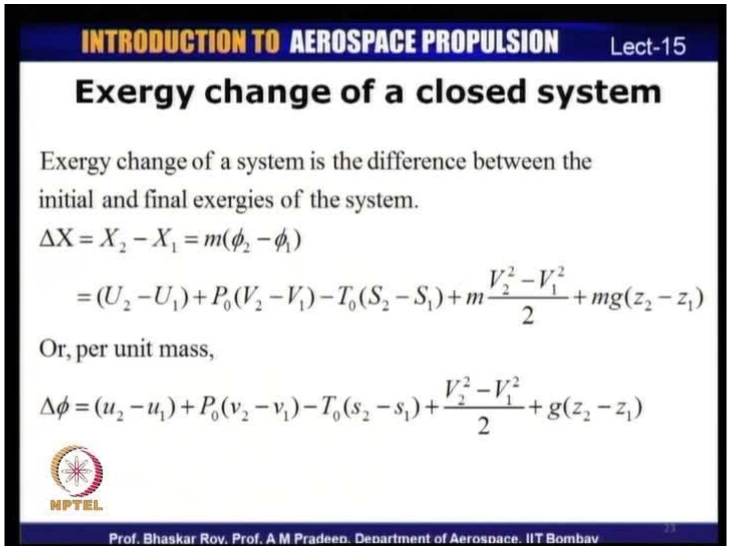

Now, how do you calculate these properties for a change in exergy? Change in exergy of a system is basically the difference between the initial and final exergies of the system. Delta X is equal to X2 minus X1, which is m times phi 2 minus phi 1. That is equal to U 2 minus U1, where U2 is the final internal energy, U1 is the initial internal energy plus P naught multiplied by V2 minus V1 minus T naught into S2 minus S1 plus m V2 square minus V1 square by 2 plus mg z2 minus z1.

This will be the change in exergy between initial and initial state 1 and final state 2. Per unit mass, the same expression is delta phi is equal to U2 minus U1 plus - which is the delta internal energy plus - P times change in specific volume minus T naught multiplied by change in specific entropy plus V2 square minus V1 square by 2 plus g times z2 minus z1.

This basically corresponds to the change in exergy of a closed system. What we have done now is to derive expressions for exergy itself and exergy change for a system which is undergoing change of state from state 1 to state 2, where state 1 is the initial state and state 2 is the final state.

We have seen that exergy depends upon lot of things. It depends upon the internal energy. It depends upon the specific volume. It depends upon the entropy. And if kinetic and potential energies are present, it depends upon those as well. What we shall do next, is to derive similar expressions for a system, which is a flow system or a flow process.

And as we have also done for the energy equation, we are going to derive the exergy equation for a flow process.

Now, as we have seen for energy equations, for a flow process instead of internal energy, you have enthalpy, which is a combination property of u plus pv, which plays a major role in energy change associated with a flow process. If you look at an exergy change of a flow process, exergy change of a flow system will consist of enthalpy, which is h is equal to u plus pv.

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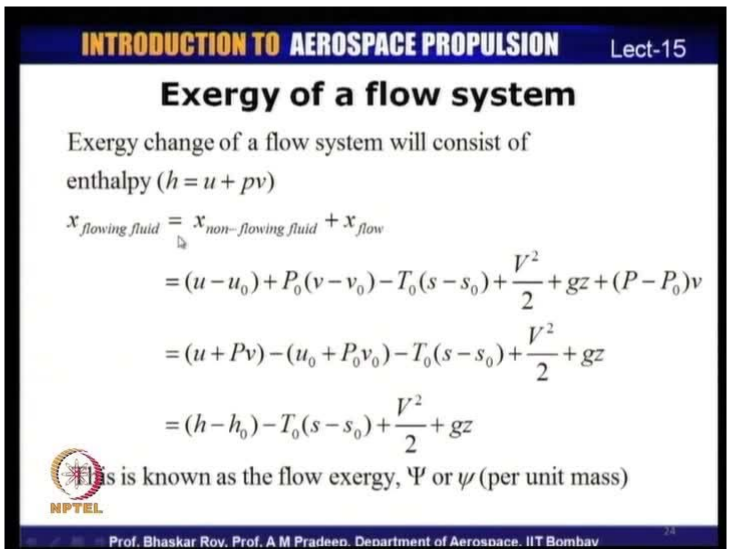

And exergy of a flowing fluid is equal to exergy of non-flowing fluid plus exergy associated with the flow. If you were to use this property, then that will be equal to u minus u naught plus P naught into v minus v naught minus T naught into s minus s naught plus V square by 2 plus gz plus P minus P naught multiplied by v.

This can be rearranged as u plus Pv minus u naught plus P naught v naught minus T naught s minus s naught plus V square by 2 plus gz - which is in fact equal to - where u plus pv is equal to h; u naught plus P naught v naught is h naught.

Exergy of a flowing fluid will be equal to h minus h naught minus T naught into s minus s naught plus V square by 2 plus gz. This is known as the flow exergy. The total flow exergy is denoted by capital psi or exergy per unit mass is represented by small psi.

Exergy change or flow exergy of a system is a function of the enthalpy, the entropy, and the kinetic and potential energies. For non-flowing fluid, we have seen it basically is a function of internal energy, the entropy and the kinetic and potential energies.

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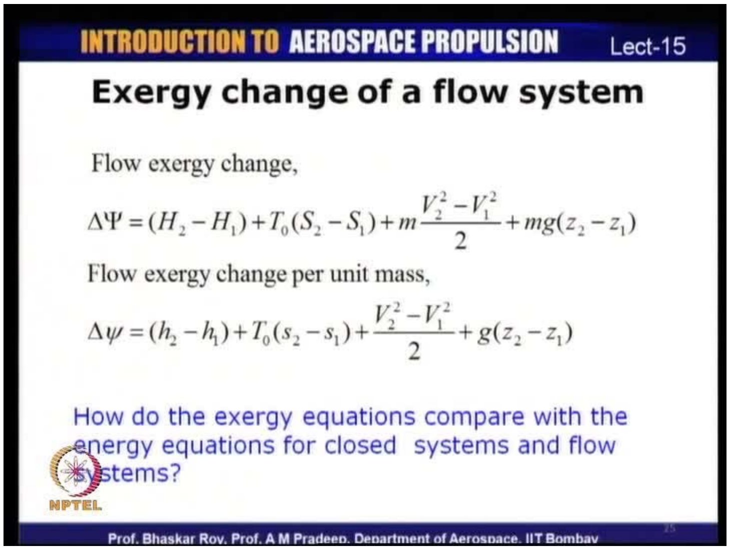

Now, we shall now derive expressions for exergy change of a system, which consists of a flow process. In the same way, we have derived for the closed system. We can actually derive exergy change for a flow system as well.

Now, exergy change of a flow system will be capital delta psi, is equal to H2 minus H1 plus T naught into S2 minus S1 plus m into V2 square minus V1 square by 2 plus mg z2 minus z1. And flow exergy change per unit mass will be delta small psi, is equal to h2 minus h1, where h2 and h1 are specific enthalpies plus T naught into s2 minus s1 plus V2 square minus V1 square by 2 plus g times z2 minus z1.

Now, you can immediately see, that there is a very similarity between the equation for exergy for closed as well as open systems, as well as the energy equations, which we have derived in few lectures earlier on, for closed and open systems. I leave it as an exercise for you to make a comparison between the energy equations for open and closed systems, as well as the exergy equations for open and closed systems.

Make a comparison between these two equations and - you will come up with - you can actually make a comparison between what is it that makes a difference between exergy and energy equations for open and closed systems.

That would be an interesting exercise to compare these two equations, because you will see that many of these terms are identical. These equations differ by one particular term. I leave it to you as an exercise to discover what is the difference between the exergy equation and the energy equation.

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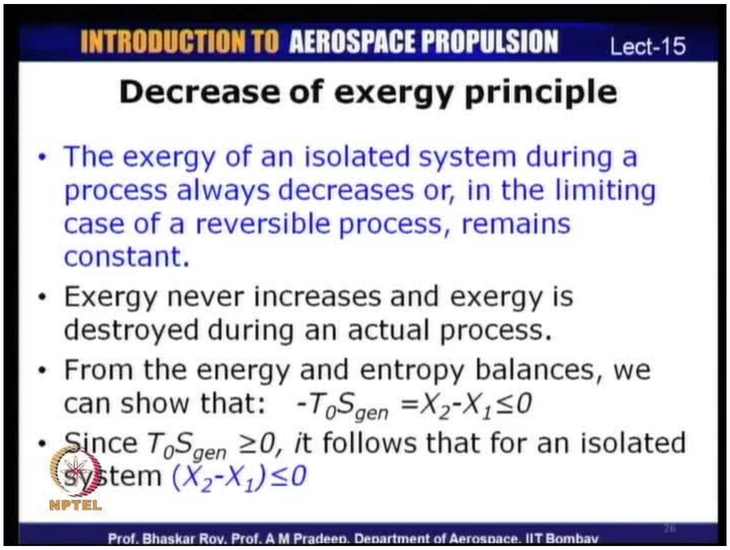

Now, what we shall discuss about next is an interesting aspect, which is known as the decrease of exergy principle. You have already seen increase of entropy principle. We have correspondingly, what is known as a decrease of exergy principle, which states that exergy of an isolated system during a process always decreases or in the limiting case of a reversible process, it remains constant. If you recall, we have defined entropy equation increase of entropy principle in a similar way, which was, entropy of an isolated system during a process always increases or in the limiting case of a reversible process, remains constant

Exergy on the other hand, for exergy, it is exergy of an isolated system during a process always decreases and in the limiting case, it will always remain constant, if it is a reversible process.

As a consequence of this, it means that exergy never decreases. And during all actual processes, exergy will be destroyed during actual processes. If you look at the energy and entropy balances for a system, we can actually show, that minus T naught into S gen is equal to X2 minus X1 less than or equal to 0. This comes from the entropy and X energy balances, which we have done already earlier. If you look at those two equations, then you can actually show that minus T naught S gen is equal to X2 minus X1 less than or equal to 0.

Now, since T naught into S gen is always greater than or equal to 0 and why is it greater than or equal to 0? Basically, because T naught is absolute temperature. It has to be positive; it cannot be negative. And S gen, as per increase of entropy principle, cannot be less than 0; it can only be equal to 0 in the limiting case.

This product, T naught into S gen is always greater than or equal to 0. Therefore, for an isolated system, X2 minus X1 should be less than or equal to 0. This is what basically the decrease of exergy principle states, that exergy of a process or exergy change of a process will always decrease. And for a reversible process, it can - in the limiting case - be a constant equal to 0, which also can be proved from the entropy principle as well. We have already seen the increase of entropy principle. Decrease of exergy principle - is like - is very similar to that of increase of entropy principle, just that it - is a corollary to the, or it - complements the increase of entropy principle.

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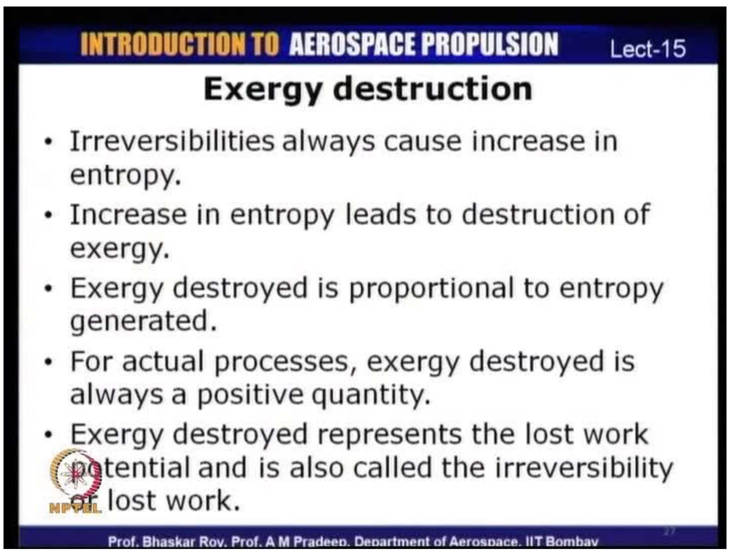

We have already seen, what causes increase in entropy? Irreversibilities cause increase in entropy. And in this lecture, we have also discovered that irreversibilities can lead to destruction of exergy.

Irreversibilities always cause increase in entropy and increase in entropy leads to destruction of exergy. So, exergy destroyed is proportional to entropy generated, which means that whenever you have entropy generation taking place, it will be followed by corresponding destruction of exergy.

For actual processes, exergy destroyed will always be a positive quantity, that is, exergy destruction is going to be always a positive quantity for actual processes. And therefore, exergy destroyed represents the lost work potential. Therefore, it is also called the irreversibility or lost work. You have seen, irreversibility is the difference between the reversible work and the actual work Therefore, higher the reversibility - it means that - higher is the work potential which has been lost.

Exergy destroyed is basically the irreversibility, which means, that higher is the exergy destroyed, higher is the work potential, which has been lost or which cannot be converted to useful work output.

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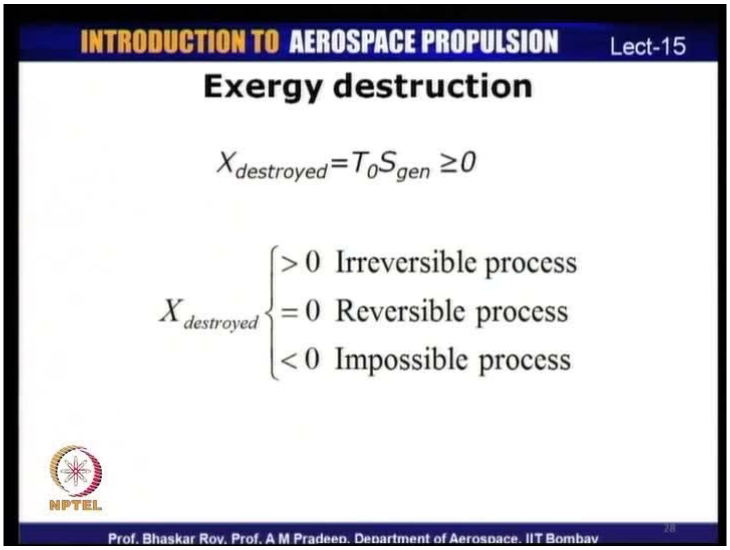

As a consequence of the decrease of exergy principle, what we have is, that exergy destroyed is basically equal to the product of T naught into S gen, which is entropy generation, should be greater than or equal to 0. Exergy destroyed is equal to T naught S gen, which is greater than or equal to 0.

For irreversible processes, exergy destroyed is greater than 0. It will be equal to 0 for reversible processes. And it will be less than 0, which means that it is an impossible process. So exergy destroyed less than 0, is an impossibility.

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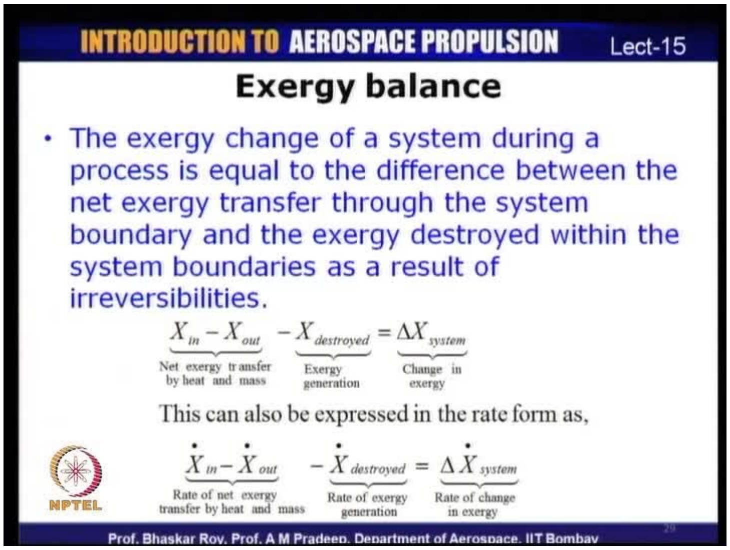

Now, let us understand what is meant by exergy balance. Exergy change of a system during a process is equal to the difference between the net exergy transfer through the system boundary and the exergy destroyed within the system boundaries, as a result of irreversibilities. This is very similar to that of the entropy balance, which we have carried out earlier on, where in we had net change in entropy plus entropy generation is equal to change in entropy of the system.

A similar expression can also be written for exergy balance; that is, exergy in minus exergy out, which is net exergy transferred by heat and mass, minus exergy destroyed which is exergy generation is equal to the net change in exergy of the system, which is basically delta X of the system. And therefore, in the rate form it can also be expressed as X dot in minus X dot out, minus X dot destroyed is equal to the rate of change in exergy. This is basically the exergy balance, which we can carry out for a process which is undergoing a change of state, while we have already done this for the entropy, where we have defined the entropy balance. We have also done it for the energy where we have defined it as the energy balance.

Now we have the exergy balance. All of them - if you look at it from the border perspective, they all mean basically very much the same thing.

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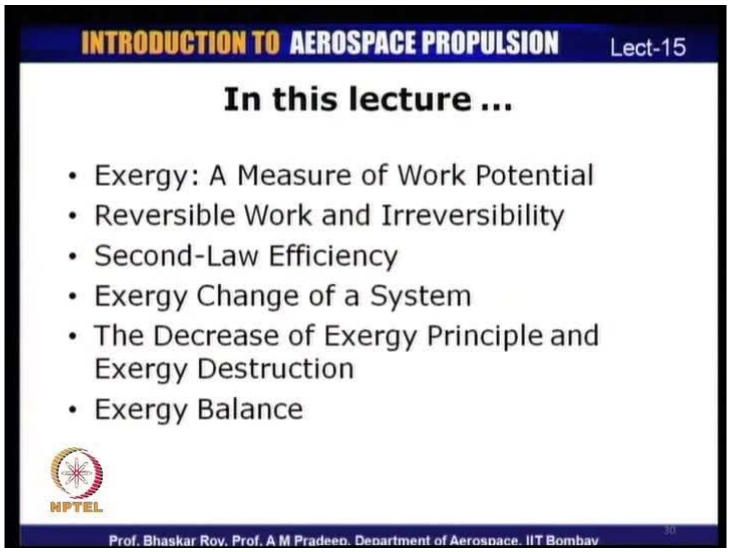

Let us review what we have been discussing in today's lecture. We have been taking about exergy as a measure of the work potential. It is a new term which we have understood and we have defined that as the measure of work potential. We have discussed about what is meant by reversible work and irreversibility associated with a work process. Irreversibility is basically difference between the reversible work and the useful work.

We have defined what is meant by second law efficiency, which is the ratio of the actual efficiency to the efficiency of the reversible process. We have derived expressions for exergy change of a system for closed systems as well as open systems or flow processes. We have then defined the decrease of exergy principle and exergy destruction. And towards the end of the lecture, we were discussing about exergy balance.

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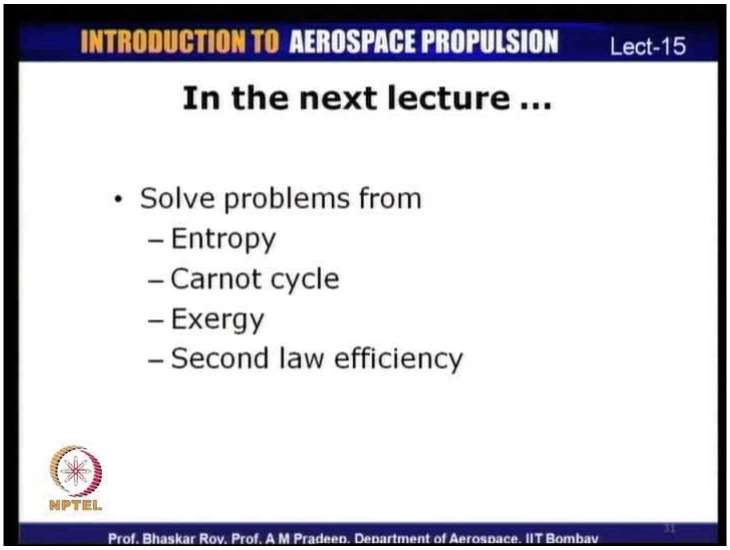

This is what we had discussed in today's lecture, very important term of exergy, but it compliments what we have already discussed about entropy and energy earlier on. In the next lecture what we shall be doing is, we shall solve some problems from entropy, Carnot cycle, exergy and second law efficiency.

We shall have a tutorial section during the next lecture. We shall solve problems which are related to entropy, Carnot cycle, exergy and the second law efficiencies. We shall take this during our next lecture which should be lecture 16.