Solar Energy Technology
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Lecture - 29
Long Term Solar Energy System Performance
Simplified Design Methods (Contd.)

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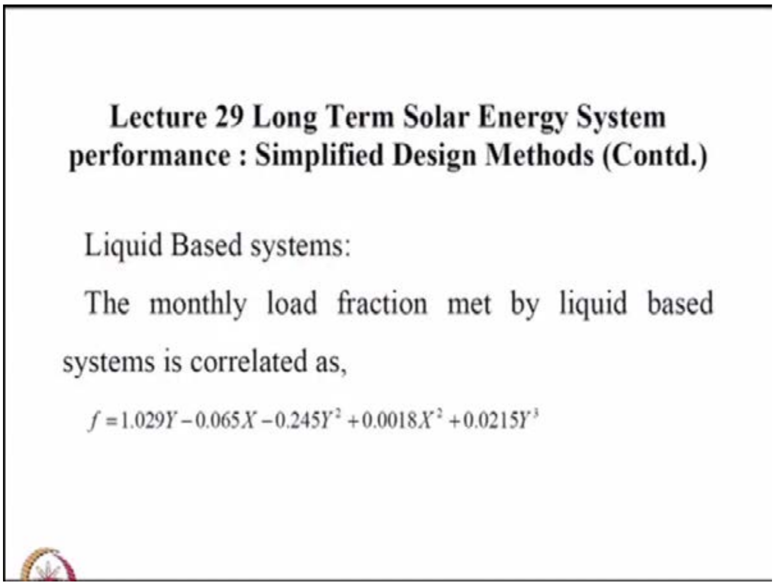

So, we shall continue with the long term solar energy system performance methods, the simplified design methods. Last time, we have discussed the f chart method based upon air as the working fluid, which correlates the solar load fraction in terms of 2 non dimensional parameters, the non dimensional absorbed energy and the non dimensional collector loss. Similarly, if the collector is a liquid based in general it is water, but sometimes anti-freeze solutions are added and even high capacity thermal capacity fluids are also being used and some of the oils. And however, this correlation is valid for liquid base systems. The methodology of the developing the correlation is the same, a large number of stimulations have been conducted, depending upon a different number of locations in a good range of parameters.

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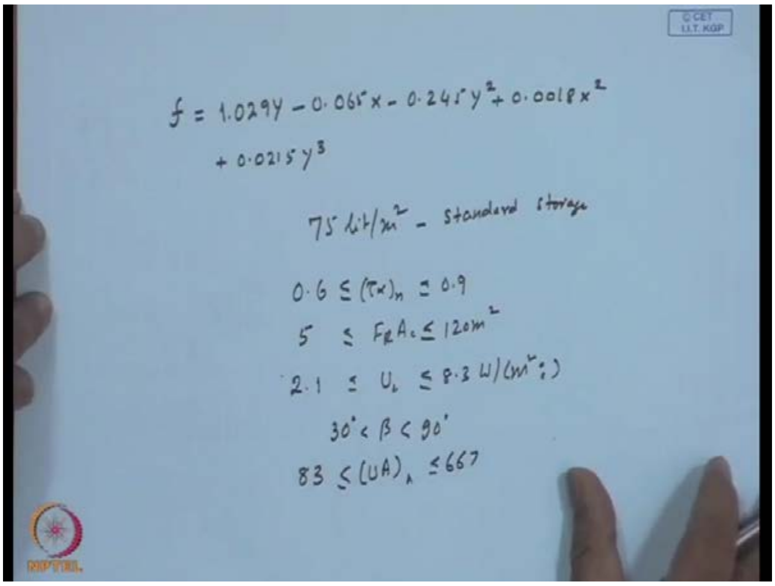

And the monthly solar load fraction for liquid based collectors has been related to Y and X as following. So, you will notice the remarkable similarity of the correlation of the liquid base systems to that of the correlation for the air base systems, which is not surprising. So, they give comparable performance expect, when this X and Y are a bit too large, either because of a non standard storage or non standard flow rate etcetera, etcetera. However, the slight difference comes in the air and liquid based systems mainly, because of the storage and the heat exchanger effect.

In addition, you will find that the liquid based systems have certain volume of water like 75 liters per square meter of the collector area as the standard storage. So, apart from the pressure drop and the pumping power requirements for a given X and Y, it depends that they will give more or less the solar same solar load fraction. But the real question is will the air collector and the water collector have similar F R U L and F R tau alpha correct even cos in general liquid systems have better values of these 2 parameters that characterize a collector F R U L and F R tau alpha.

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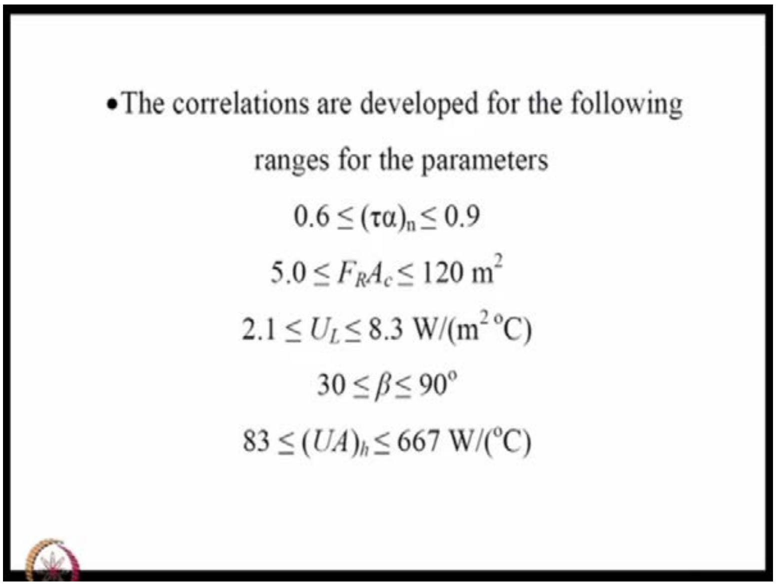

So, ranges of the parameters are the same however, I shall repeat 0.6 less than or equal to normal transmitters of certain product less than 0.9 and this area heat removal factor product is within the limits of phi 220 meter square. And the overall loss coefficient is between 2.1 to 8.3 watts per meter square degree C, and beta is 30 degrees less than beta less than 90 degrees. And the building loss coefficient, which we discussed yesterday in detail is in the limits 83 to 667. So, this when multiplies the degree days will give you this heating load directly.

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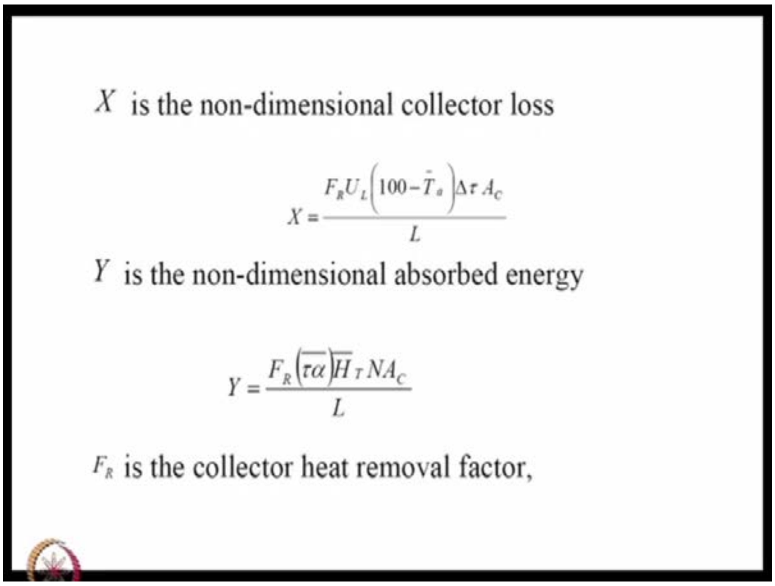

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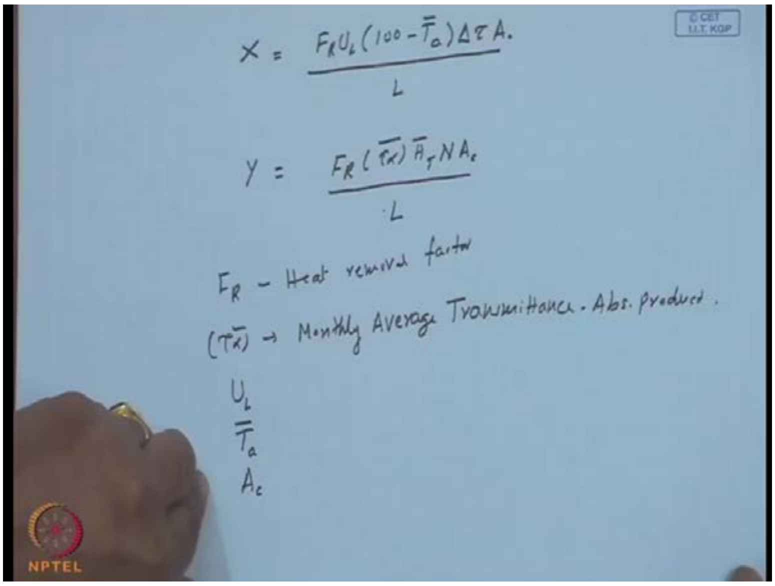

So, we shall recall X and Y are identically defined the non dimensional collector loss is F R U L times 100 minus the monthly average daily temperature T a bar into delta tau, the number of seconds in the month multiplied by the area of the collector by the load. Similarly, is Y the non dimensional absorbed energy is F R multiplied by transformational product, average for the month into tilted radiation monthly average daily multiplied by the number of days in the month and the area of the collector upon the load. Of course, F R is the heat removal factor and tau alpha bar is the monthly average transmittance absorbance product we shall write. Of course, U L is the overall heat loss coefficient, T a bar is the monthly average daily temperature, A C is the collector area and these are all we have written in detail in the last lecture. So, I am not repeating.

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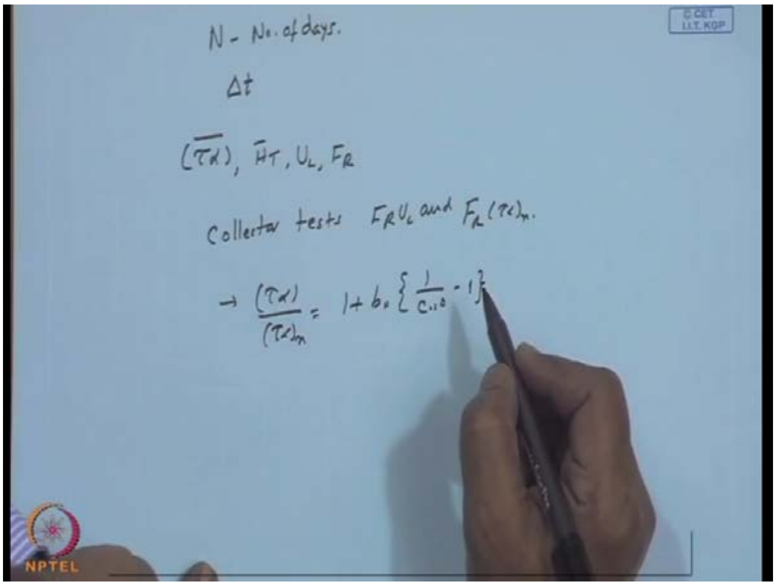

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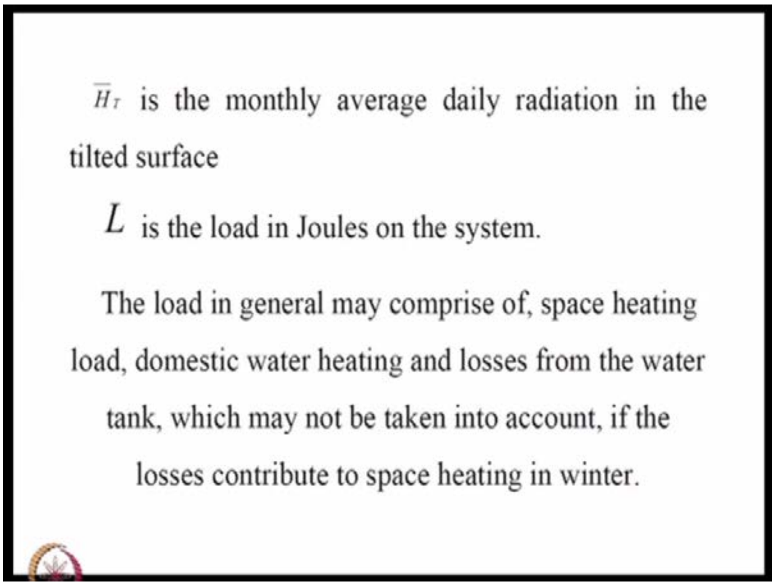

N is the number of base, this is one reason I write them or rewrite them a times is or we are using the same notation consistently. It will be easy for you to remember and check a the consistency of the equations. H T bar is the monthly average daily radiation in the filter surface and L is the load in Joules on the system. Now, we have spent in calculating tau alpha bar, H T bar, U L, F R. Of course, from the collector test, you can get F R U L and nearly F R tau alpha normal from which you can have the relation of H tau alpha by tau alpha N is 1 plus b 0 times 1 by cos theta minus 1. And you have got the effective angles of incidence for the direct radiation in the form of a graphical representation, or the effective angle of incidence for the ground reflected radiation and the sky diffuse radiation, which are constants. They do not change with time they are a function of the slow beta only, that is your theta g and theta d. So, one can estimate your tau alpha bar as for the relations which, we already dealt with in detail.

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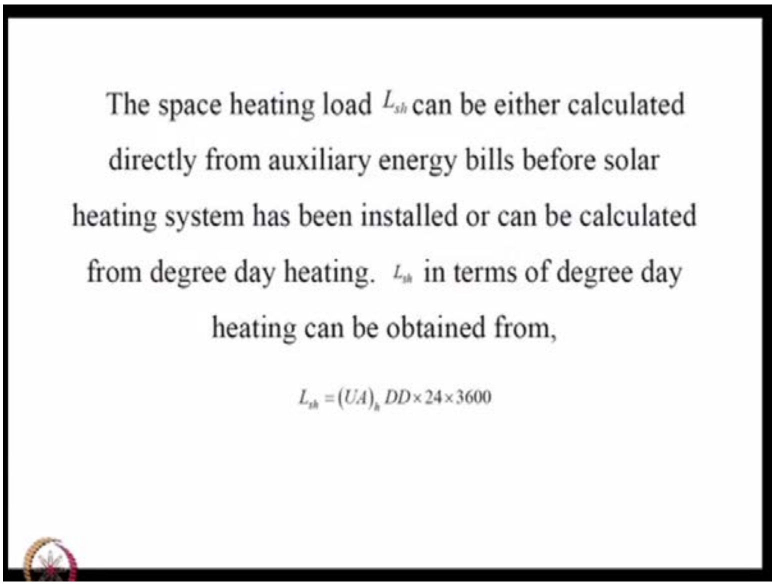

So, like we have done for the liquid based systems either, you use the utility bills to get the space heating.

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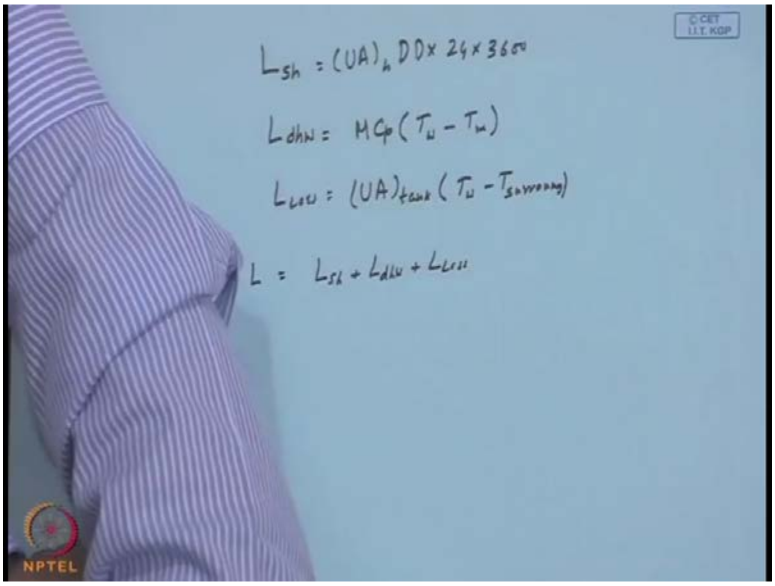

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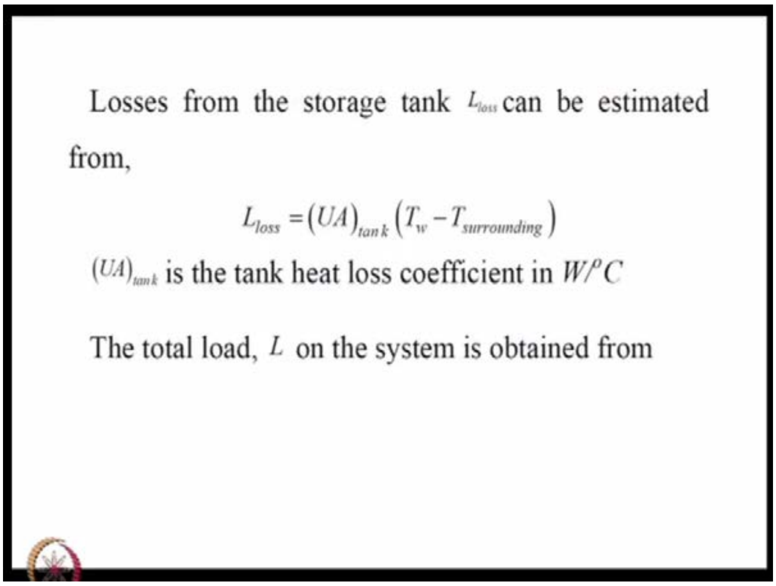

Or calculate L space heating as UA h that is the building heat loss coefficient multiplied by degree days multiplied by 24 into 3600 to make it consistent units. Then hot water requirement space heating, domestic hot water is mass of the water required multiplied by the, this specific heat multiplied by the water main temperature T m. And the temperature at which the hot water delivery is required or desired. And of course, a loss from the tank is based upon the UA of the tank either you can estimate or from the manufacture specifications you can use it and the temperature difference, that is available for the losses will be T w minus the T surrounding, which may be different from the ambient temperature. So, L will be L s h plus L d h w plus L loss.

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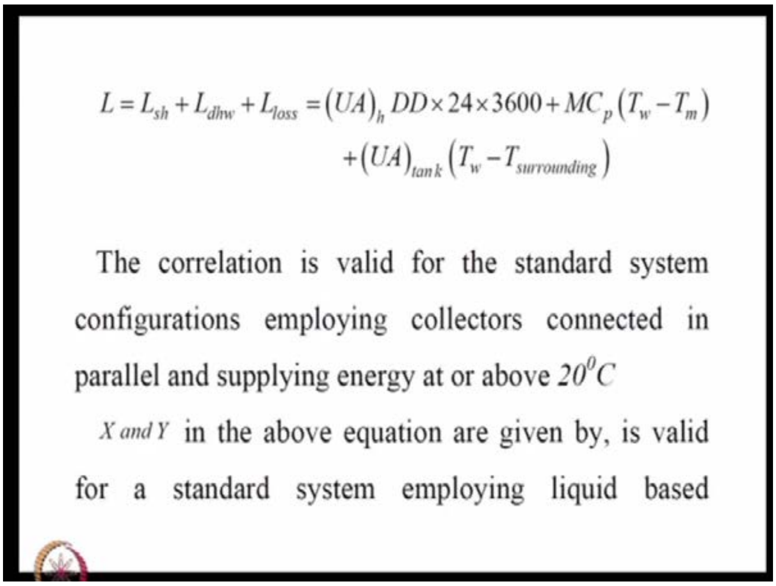

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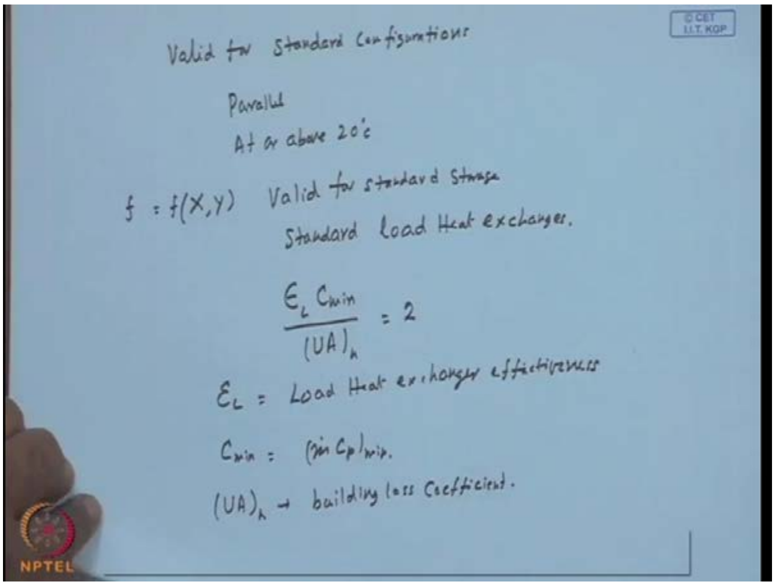

So, that is what we have written in detail each term contained. So, once again the system is valid for standard configurations I am sorry the correlation is valid for standard configurations like the 4 5 pictures, I have shown schematically and all the collectors are in parallel, then energy delivery H or above 20 degree C.

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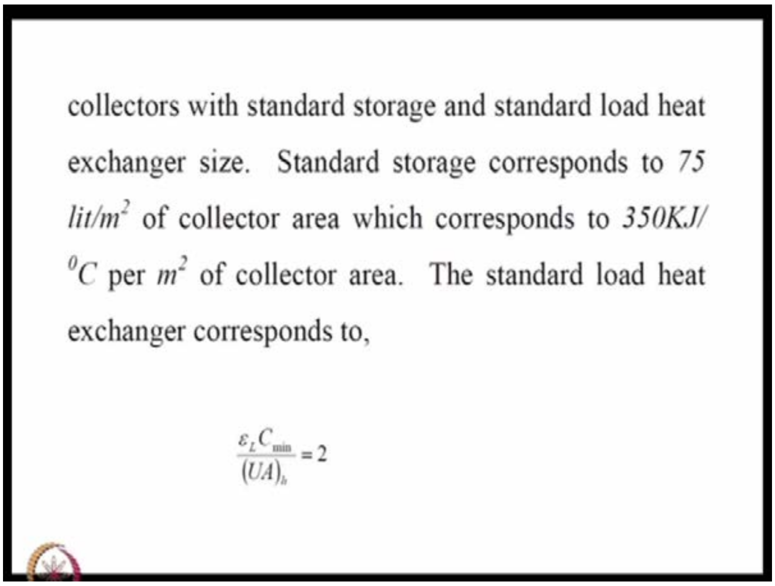

So, the equation of F in terms of X and Y is valid for standard storage, just like the case for the air systems and standard load heat exchanger. This load heat exchanger was absent in the case of a air systems, because when you are using space heating based upon an air system. You directly let the hot air go the quantity being controlled by the temperature set inside the room and your desire.

Whereas, in the case of water heating, there should be a exchange mechanism from the heat of the water to heat the air, which in turn goes to the rooms to keep it at a comfortable level of approximately 20 degree C. So, this is valid standard load heat exchanger for a value of epsilon L C minimum by UA house equal to 2. Of course, epsilon L is the load heat exchanger effectiveness and C minimum is m dot C p minimum of the fluids of the 2 sides of the heat exchanger. And UA h is the building loss coefficient. Obviously, this is non dimensional there is a easy way of looking at these things.

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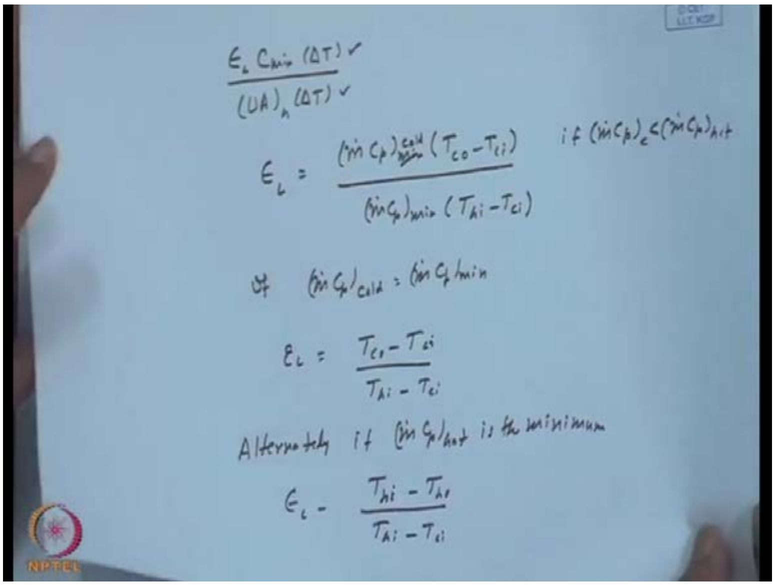

First of all, if I put a epsilon L C minimum and some delta T by UA h times, some delta T, not that the delta T relevant for calculating these specific heat and load is the same as the delta T across the heat exchanger. But dimensionally one can draw some comfort that this is the ratio of the capability of the heat exchanger transfer, a certain amount of heat to the amount of heat that needs to be transferred.

So, if you have a large heat exchanger, it can transfer the desired amount heat with low delta T and if it is a smaller heat exchanger it requires a larger delta T and hence a penalty on the heat exchanger effectiveness. And I shall recall also, heat exchanger effectiveness between the conventional assumptions of your heat transfer analysis in heat exchanger. This can be written as m dot C p minimum times T co minimum T c i. If m dot C p of the cold is less than m dot C p of the hot by. So, I can write this in fact as cold by m dot C p minimum times T hi minus T c i.

So, if m dot C p cold is the minimum then epsilon L is given by T c o minus T c i upon T hi minus T c i. Alternately, if m dot C p hot is the minimum, you have epsilon L is T h i minus T ho by T hi minus T c i. So, the inherent assumption is the heat loss by the hot fluid is the heat gain by the cold fluid. This may not be in general true sometime some books in heat transfer, they defined the heat exchanger effectiveness as desired effect either, it is the cooling of the hot fluid and heating of the cold fluid upon m dot C p minimum times T ha minus T c i. So, this is only to recall and make you little comfortable with this parameter, this is already known to us within already of the heat transfer.

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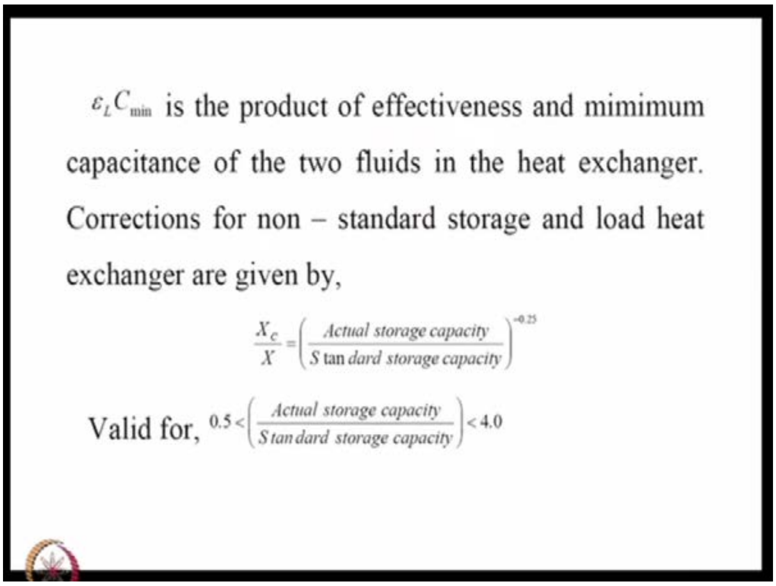

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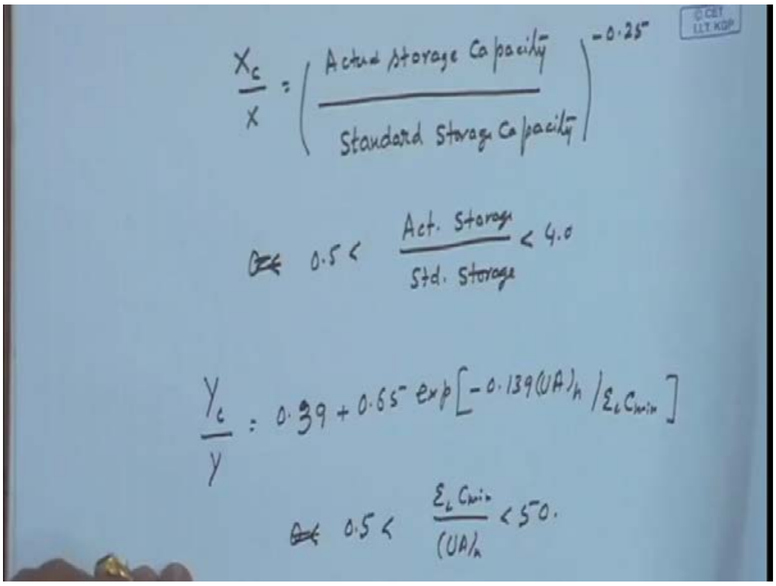

So, if there is standard storage is not there or, the heat exchanger effectiveness is not the standard just like, we have done in the case of the f chart method. The correction have been given X C upon X is actual storage capacity by the standard storage capacity to the power minus 0.25. This is valid in the range of 0.5 less than actual storage by the standard storage less than 4.

Fairly by range, half of the standard storage to 4 times the standard storage. Similarly, if the heat exchanger is non standard, the variable Y is corrected to Y C from the original Y. According to this equation, 0.39 plus 0.65 exponential minus 0.139 UA h by epsilon L C minimum, if epsilon L C minimum by UA h is equal to 2, this will be equal to 1. And this is valid range of 0.5 less than epsilon L C minimum by UA h less than, it is a pretty a while range for the epsilon L C minimum by UA h product 1 4 that of the standard heat exchanger to that of 50 times that of the standard heat exchanger.

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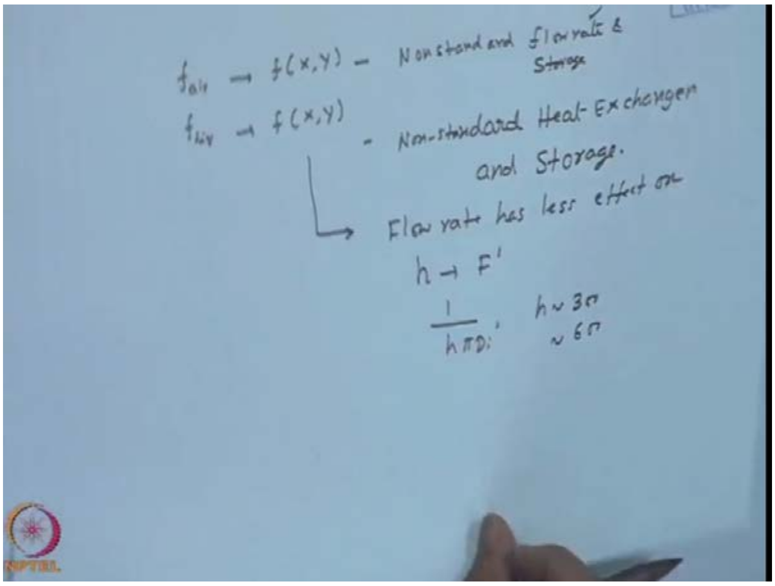

Now, if you combine f air for an air based system and f liquid for a liquid based system have been correlated in terms of 2 non dimensional variables X and Y this, this X may be different, but it is only a functional notation and if this is corrected for non standard flow rate and storage. This is corrected for non standard heat exchanger and storage. So, you may be little surprised, why the flow rate does not come into the picture in the case of liquid and the heat exchanger does not come into the case of a space heating. That way, we had already explained if it space heating L as it is used and in the case of a liquid system, the flow rate typically, flow rate has less effect on heat transfer coefficient and hence, ultimately on f dashed the collector efficient factor.

So, the flow rate let us say 2 liters to 4 liters are unless the range from laminar to turbulent flow changers, my heat transfer coefficient are pretty much in the same range and more importantly, if you recall the expression for f dashed, the resistance is something like 1 by h and h, if it is of the of the orthodox 300 even, if it becomes 600, 1 by H pi Di will be still small. Consequently the flow rate of the liquid system does not make much difference in f dashed. Whereas, for air system flow rate is an important thing and the correlation is standard for 10 liters per second, per meter square all the collector area, for other flow rates, we need to have the correction. So, that is the philosophy in providing a correction for the flow rate for air based systems, and such a correction has not become necessary for the liquid based systems. Since, the convection resistance in the case of liquid based collectors is quite small.

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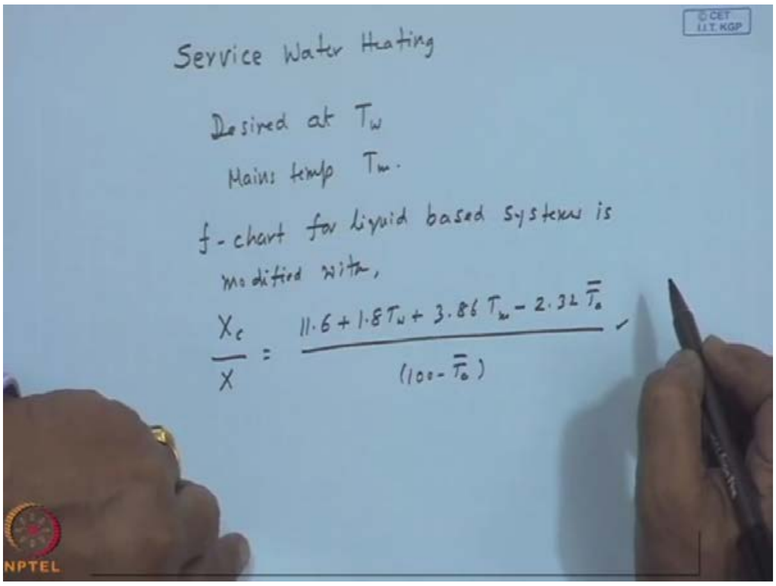

So, the general need is also the third one its before we go to the next method, service water heating without saying that minimum temperature is so much. If you want desired at T w, mains temperature is T m then simply, f chart for liquid base systems is, is modified with X C being given in terms of the X as 11.6 as a constant plus 1.8 times T w plus 3.86 T means minus 2.32 monthly average ambient temperature T a bar upon 100 minus T a bar. So, you simply change the value of X to X C as given by this equation and use the f chart for the liquid base correlation and you will have the solar load fraction made by service water heating system.

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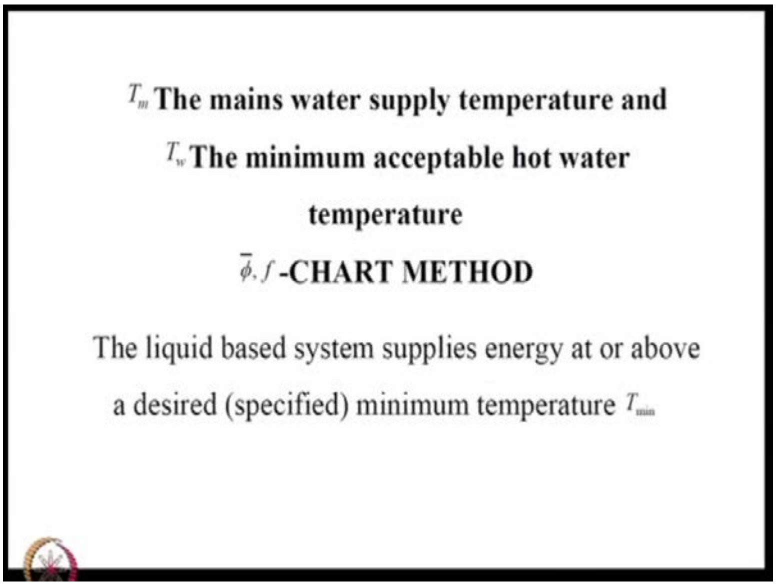

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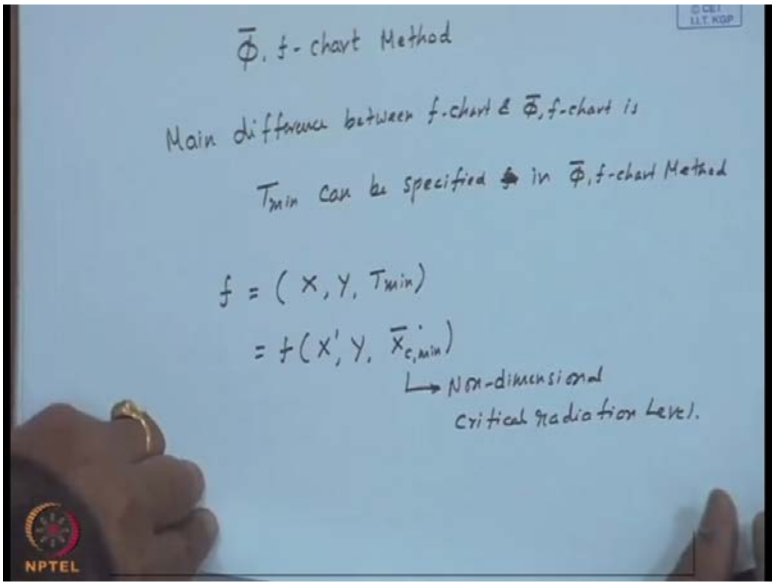

So, T m is the mains temperature and T w is the minimum acceptable hot water temperature. So, this is a slightly modified approach to that of the f chart and then came the design methods, which is quite popular little more general than the f chart method, which is called the phi bar f chart method. Main difference is between f chart and phi bar, f chart is T minimum can be specified in phi bar f chart method. In other words if you want energy delivery at R above a certain temperature T minimum, you can use phi bar f chart method. Interestingly, for some applications where f chart method is applicable, you can use phi bar f chart method, but not there other way around.

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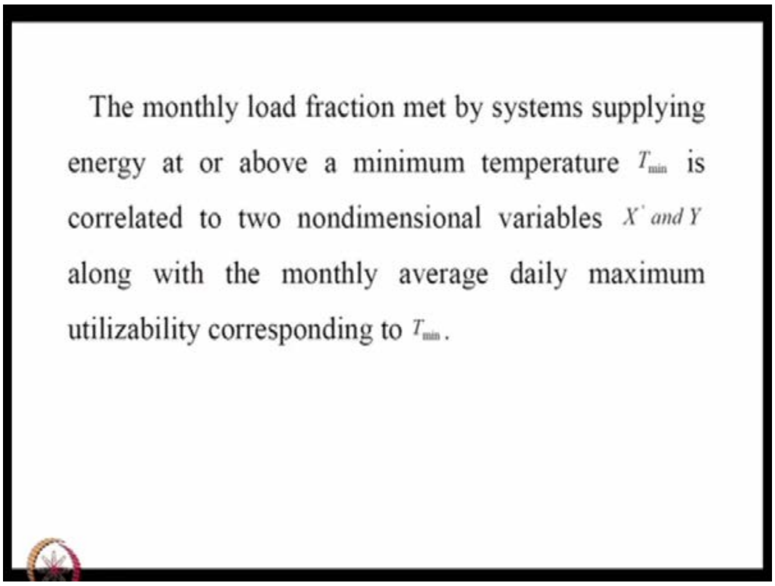

So now, monthly load fraction is somehow should be similar to my X Y and somehow I have to relate to T minimum. So, this is slightly modified and it is related to some X dashed a modified X and the same as Y and this will give rest to, what is called an X C bar minimum which is I will say, a non dimensional critical level. If you remember very preliminary idea of the critical level was given.

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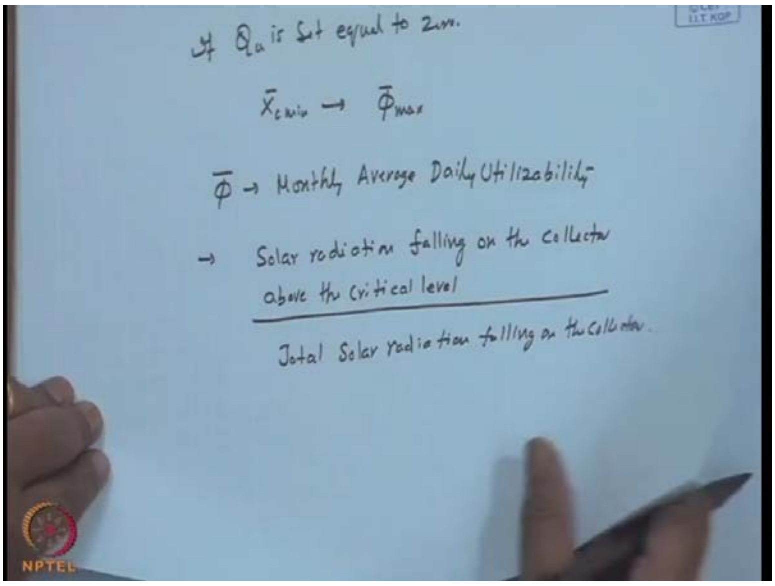

That if Q u is set equal to 0, the radiation falling on the collector for Q u be 0 will be the so called critical radiation level. In other words under your solar radiation, above this critical level of I C, you will not have any useful energy deliver at the temperature desired. So, this X C bar minimum will correspond to will spend considerable time on some monthly and phi bar in general is the monthly average daily utilizability. We have also in a cursory manner, introduce the concept of utilizability, this is nothing but solar radiation falling on collector, above the critical level to the total solar radiation, falling on the collector. The general definition is how much of solar radiation is above the critical compare to the total solar radiation falling on the collector.

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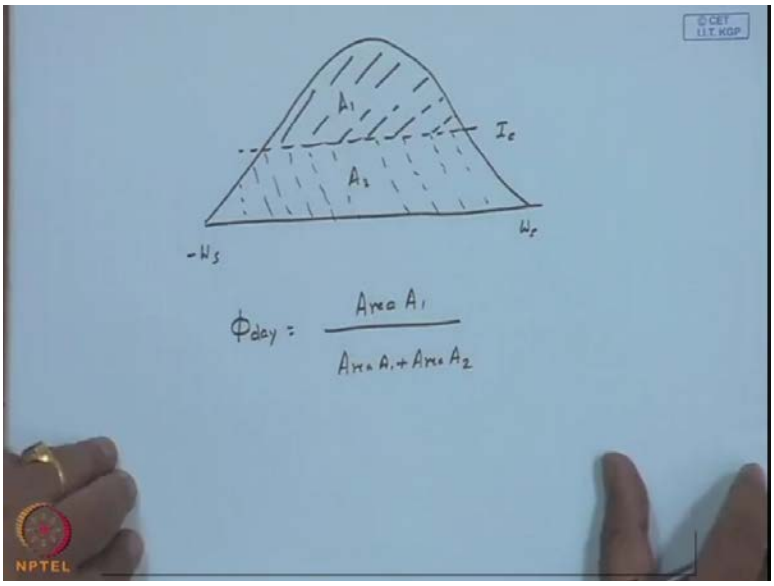

A pictorially, if this is some sort of it does not have to be smooth it can be cloudy etcetera, etcetera. This is minis omega S to plus omega S. This is solar radiation distribution, it does not have to be symmetric, if the collector is not facing south and this is my I C. That is a critical level, which you are talking about, then if this is area A 1 and this is area A 2 way under the line. If it is a single day, utilizability for the day, will be area A 1 by area A 1 plus area A 2. That is the solar radiation available above the critical level to the total solar radiation available. So, this concept can be applied for a month.

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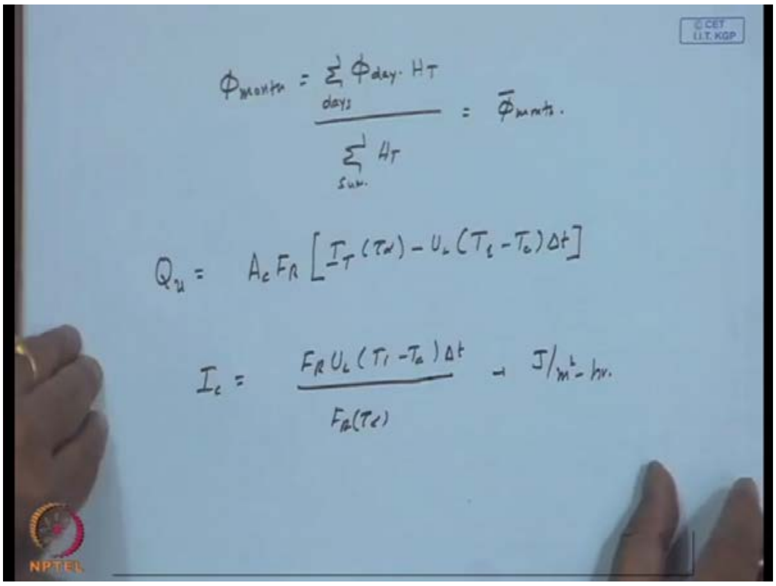

If you want phi month, I can say that phi day multiplied by H T sum over the days by H T sum. This is a little more easy way of conceiving the definition of utilizability, what I am trying to do is I am taking up the solar radiation every day above the critical level, upon the total solar radiation falling on the collector in the month. This is also equal to phi bar numerically it does not make any difference, because it is a ratio of both.

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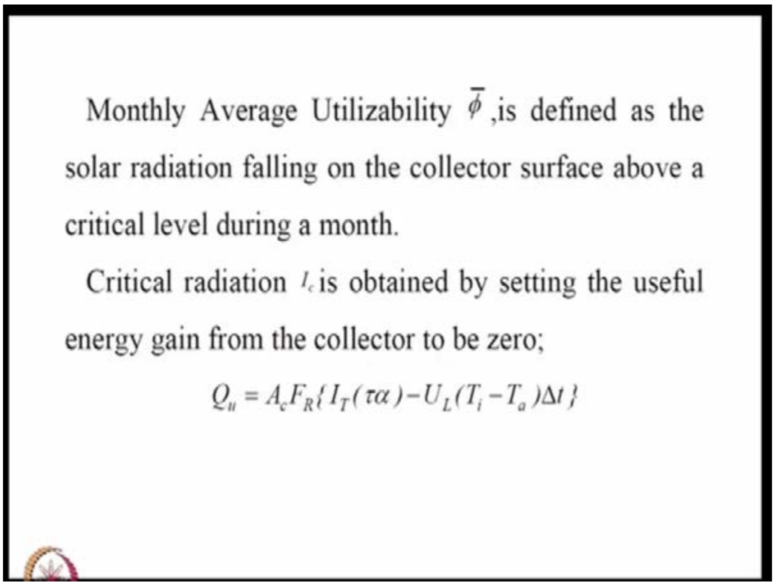

So, let us go to little bit about the, a critical level. So, my useful energy gain equation is Q U, A C, F R times I T tau alpha minus U L into T i minus T a for the sake of completeness and clear clarity, here I shall use the time factor delta T. Otherwise, you may not be able to calculate the critical level over a period of 1 hour integrated compare to the intensity at a instant. So, if you set Q u equal to 0, the critical level at that can be obtain by F R, U L, T i minus T a by F R tau alpha times delta T. So, if it is for a period of 1 hour, I will get it as joules per meter square hyphen hour. So, with reference the previous diagram.

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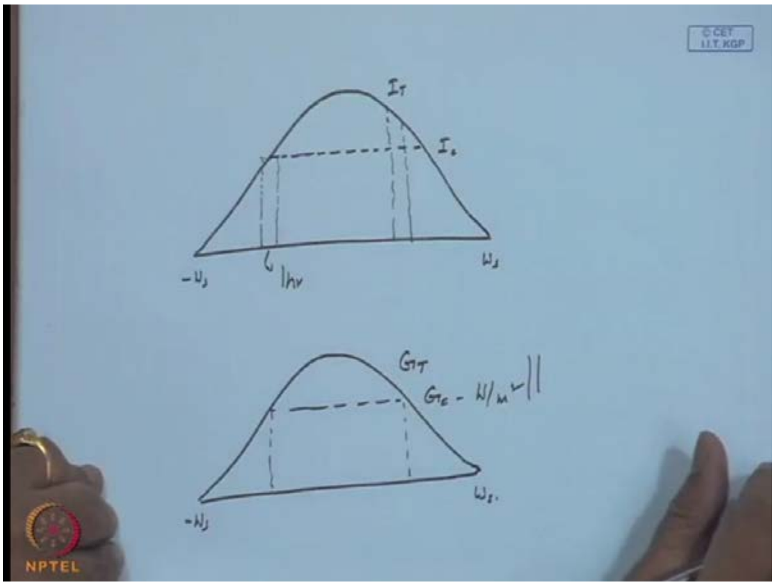

What, we really calculated is may be something like this, this is 1 hour and this is continued and that is what I am saying is I C or else this is I T, I T is each hourly interval or minus omega S, plus omega S. Alternately, you can call it G T intensity on the a tilted plane to G C, the intensity of the critical level, then this will be in watts per meter square which is nothing, but the ordinate over here. We shall not go into this because, practical way of calculating with the, a utilizability will be with the hourly data, because that is the more or less the smallest time scale that is available to us.

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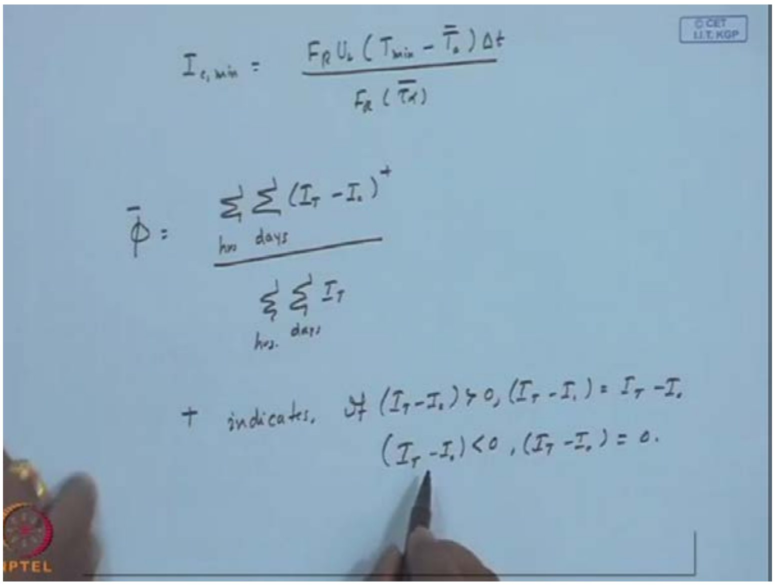

And I C minimum will correspond to F R U L in the minimum temperature at which my energy delivery desired times delta T upon f or tau alpha bar because, I have already extended to T minimum, I have extended to monthly average. Analogously, taking the average temperature divided with the average transmittance of certain products over the month.

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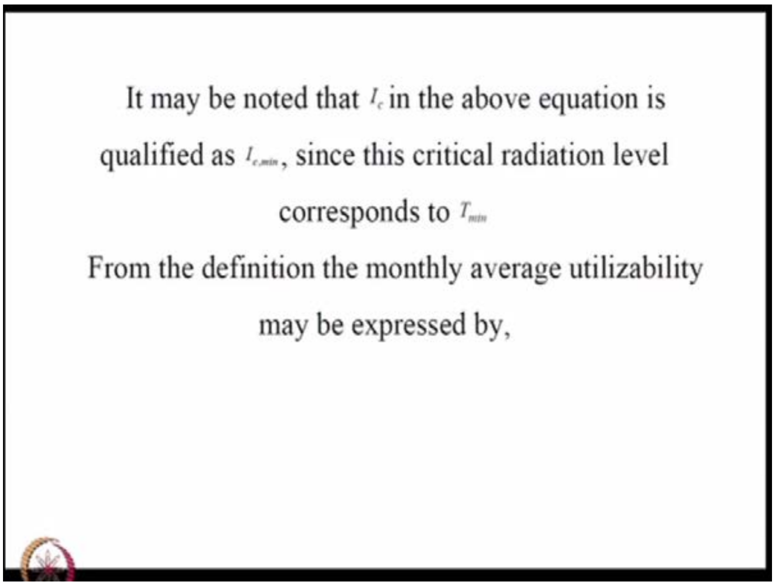

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$$\bar{\phi} = \frac{\sum_{hrs}\sum_{days}(I_T - I_c)^+}{\sum_{hrs}\sum_{days} I_T} = \frac{\sum_{hrs}\sum_{days}(I_T - I_c)^+}{\sum_{days} H_T}$$

$$= \frac{\sum_{hrs}\sum_{days}(I_T - I_c)^+}{N\bar{H}_T}$$

So, from the definition how do I write down now, my phi bar should be equal to summation over days over hours I T minus I C super script plus by sigma I T over days, over hours. That means this indicates if I T minus I C is greater than 0, I T minus I C equal to I T minus I C and if I T minus I C is negative, I T minus I C set as 0, which means again with reference to the figure.

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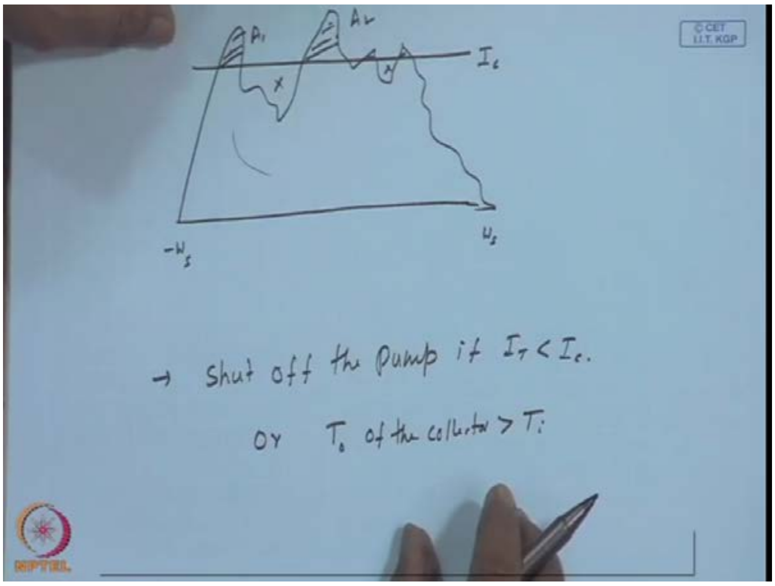

You have imagine, a wavy cloudy day, where the solar radiation are being increasing or decreasing. If this is my I C, here is the contribution; here is a contribution; here is a small contribution, here this is negative; this is negative, that it will not subtract from this positive things, it is straitened as 0. In other words practically speaking, if I give them A 1, A 2 and the total area beyond that so only, A 1 plus A 2 by the area below the critical level, we have to take of this solar radiation. So, practically it means shut off the pump if, I T is less than I C or T o of the collector should be greater than T i.

This is where, the practical difficulties there was mentioning a will come in when you system on a system scale experiment, or even on a component scale experiment. The control may not be able to shut it off exactly, when T o is greater that T i. How much greater? It have a, It will have a bandwidth of 5 degrees or 2 degrees or 3 degrees and consequently my shutting off or starting will not be exactly according to the mathematical control.

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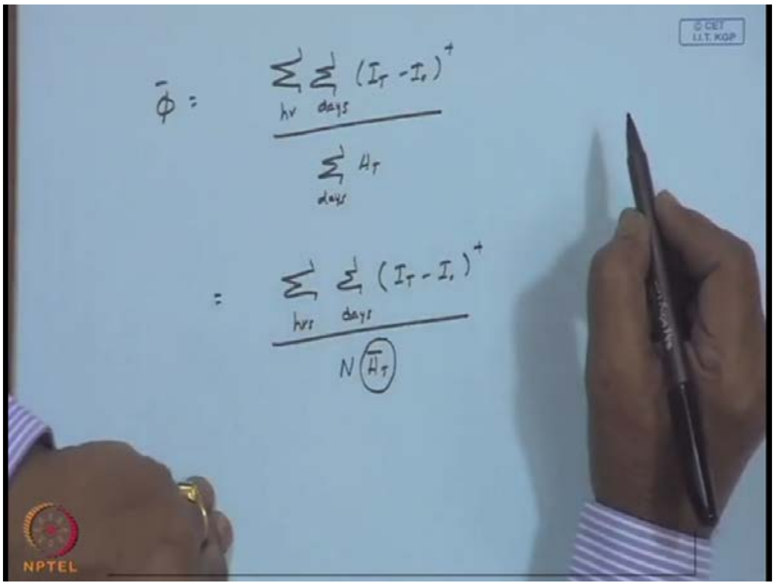

So, the same phi bar can be rewritten over the days, and the hours I T minus I C plus by sigma H T of the days, which is also, one of the reasons why I am writing though, it is a very simple algebra is. Now, you will understand, why we were worried about a calculating a H T bar tau alpha bar etcetera, etcetera in the beginning.

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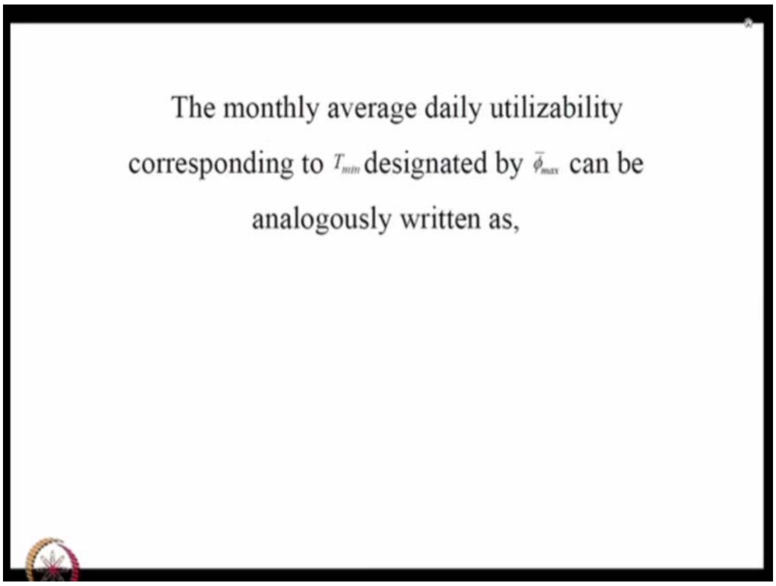

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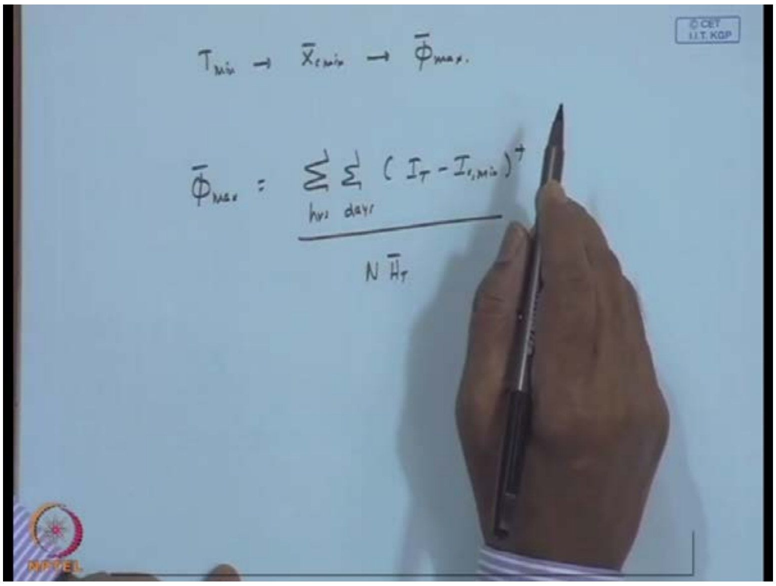

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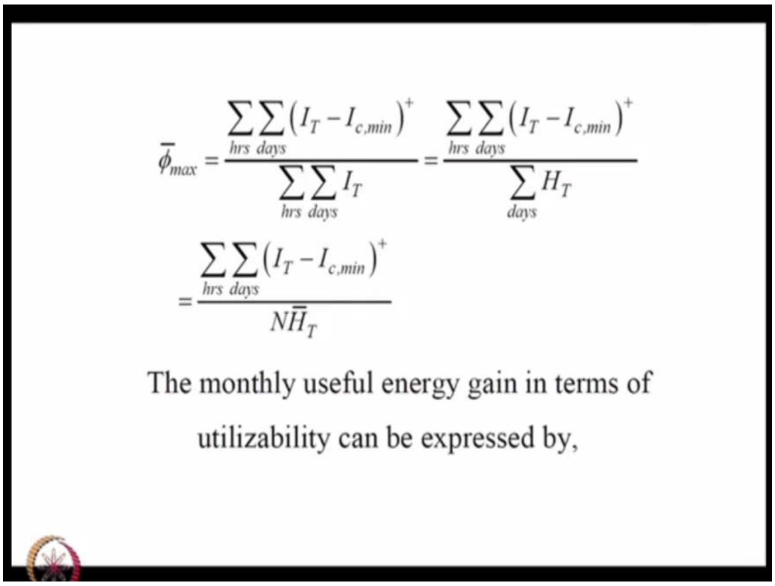

So, if T minimum corresponds to X C bar minimum that corresponds to phi bar maximum that means, this is the solar radiation that will be available to you, above the critical level, corresponding to the temperature at which energy delivery at T minimum decided. So, you can rewrite this equation, I will write down just the last one, phi bar max should be equal to summation over hours, over days I T minus I C min plus by N times H T bar. So, the emphasis on the minimum temperature at which energy delivery though it is a same correlation, you can automatically calculate whether, you call it X C or X C bar minimum or I C or I C bar minimum. If you use the correct non dimensional critical level X C bar, you will also automatically get the correct answer. But we specific we say T min corresponds to X C bar min which yields phi bar max.

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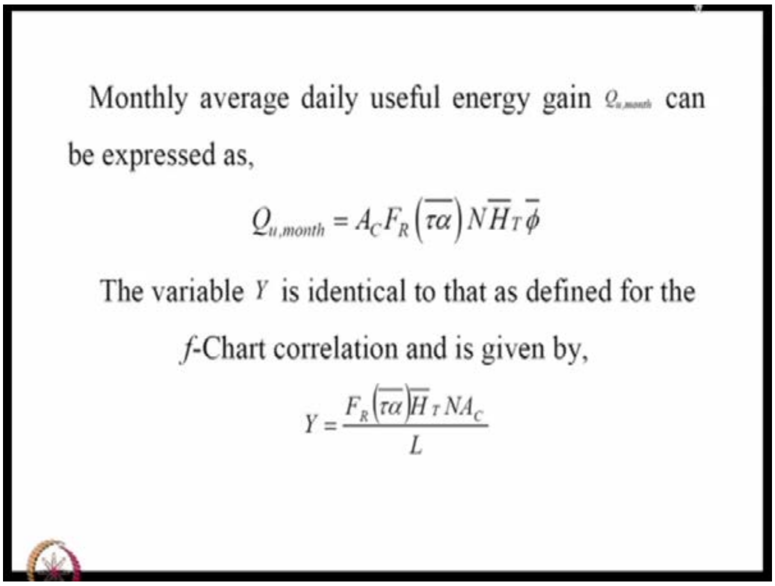

Now, apart from the phi bar f chart method.

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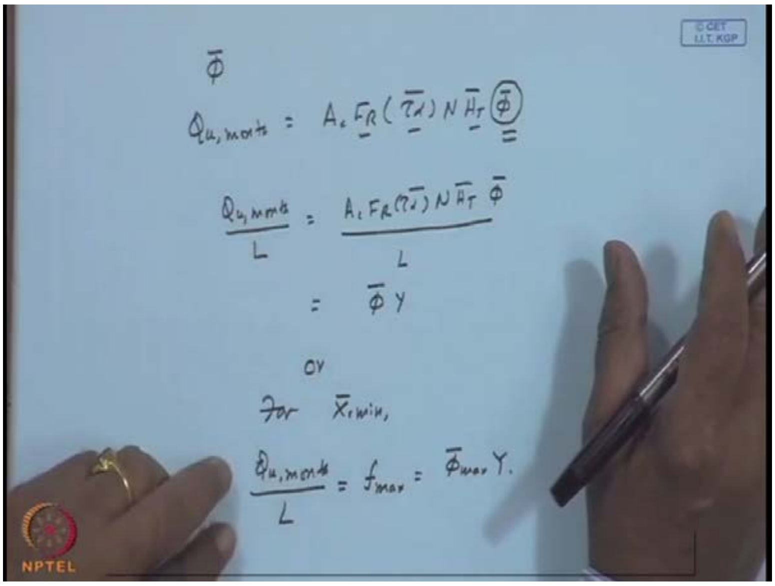

If you have a this phi bar so Q u in a month, I can calculate it as area F R times tau alpha bar N HT bar phi bar. We are not talking anything about the load fraction, we are also not also saying whether, this much of energy will be sufficient or not sufficient. Whether, something will be wasted or something will be stored, but the output from the collector one can expect it to be the product of this quantities and phi bar is to be found out, if we find out HT, I know tau alpha bar, I know F R is a collector parameter.

So, method so, calculate everything is known except, the monthly average daily utilizability. So, we shall reserve the calculation procedure for the monthly average daily utilizability having understood, that it is a ratio of the solar radiation available above the critical to the total solar radiation falling on the collector. We will go ahead

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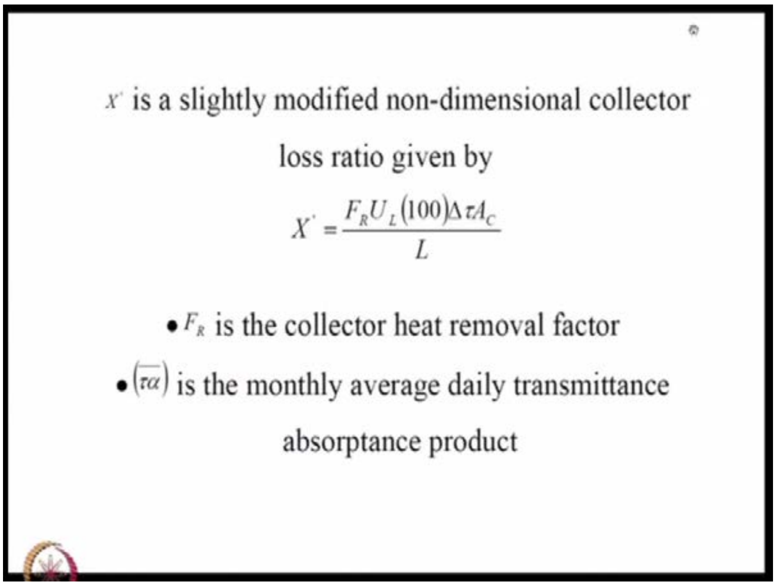

And see the correlation for the monthly solar load fraction in terms of the utilizability. Now, if, if you recall the definition of the non dimensional absorbed energy F R tau alpha bar and HT bar by L is nothing but my Y. So, if phi bar max is the corresponding utilizability for the X C bar minimum. In a way this Q u month, if I normalized with the load, I will have a product phi bar max Y which in one sense is the absolute maximum solar load fraction, where the system can supply without other calculations.

If all the energy delivered by the solar collector is going to meet the load, there are no loses on the pipelines, there are no losses in the heat exchanger, or in the tank then this will be the solar load fraction, that will be met. So, in one sense simple knowledge of utilizability can give an estimate of what is a possible solar load; solar load fraction maximum. This is an almost an ideal way of a number that one gets, so again, slightly I will write this before, we proceed further with the definition or the simple correlation.

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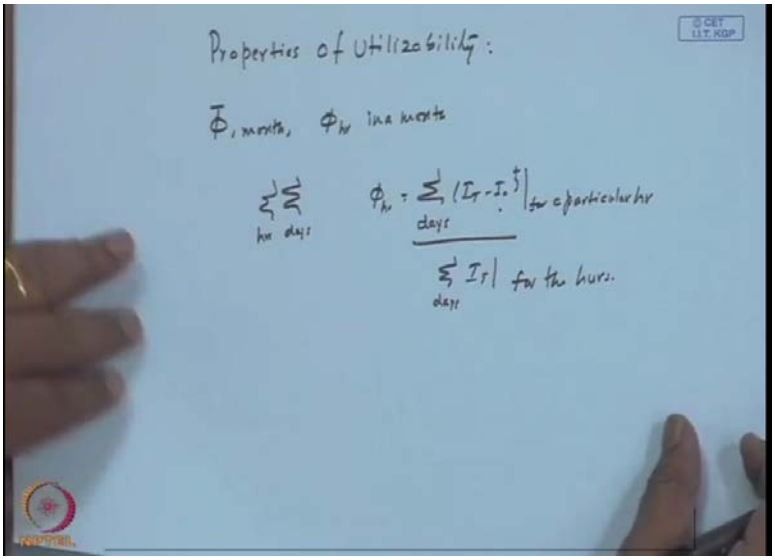

What are the properties of this utilizability, I can define this phi bar of the month, I can define a phi bar for the hour in a month. Of course, as I explained for the day also, this is in terms of summation over the days and hours. This will be summation over days I T minus I C plus for a particular hour. So, in other words, if you consider the hours 7 to 8, I will pick up the solar radiation of 7 to 8 for all the 30 or 31 days in the month. And how many of them are above the critical level that will be summed up the negative contributions will be ignored that divided by of course, sigma I T overall the days for the hour.

So, it is not the utilizability for several hours in the day, but it is the utilizability of all the days in the month for a given hour. So, if I know each hours utilizability and you sum it up and you will get the monthly average daily utilizability also, this has got a bearing with my clearness index distributions, which we discussed long time back. And again I will come back to that because, if the monthly average clearness index daily basis or hourly basis is a 0.7, 0.6. Whatever, there will be days with a clearness index less than that number and there will be days with clearness index higher than that number. So, some of the days will be contributing to the energy in other words I T will be more than I C during certain hours, or I T will be more than I C during a part of the day and that knowledge will help us in calculating utilizability.

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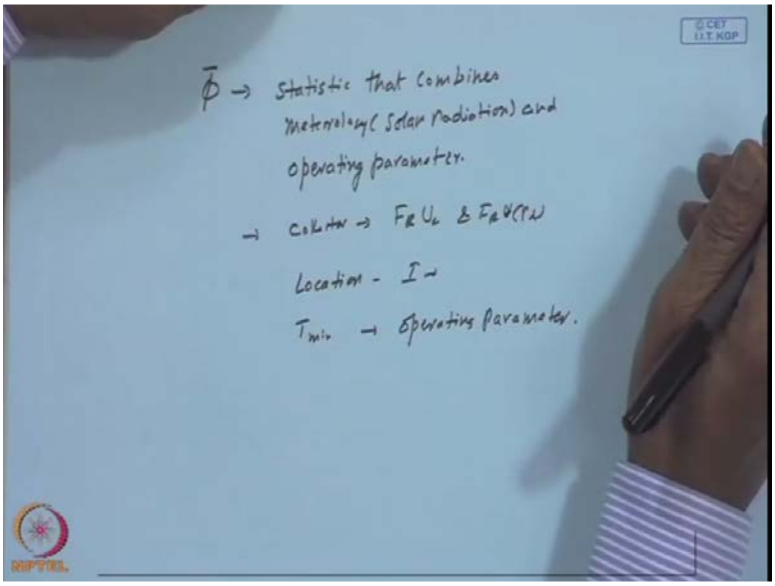

The, I should be mentioning that this is a statistic that combines, metallurgy rather solar radiation and operating parameters. So, this takes care of your collector through F R U L and F R tau alpha location because, my I T is location dependent and T minimum is an operating parameter. So, if some method of calculating this monthly average utilizability is known to us or, even the hourly utilizability is known to us. So, that one can obtain the monthly average daily by summation over 10 hours or 12 hours whatever and this is depends upon the collector parameters, the location through the radiation and in fact the ambient temperature also and the minimum temperature, which is desired of the system.

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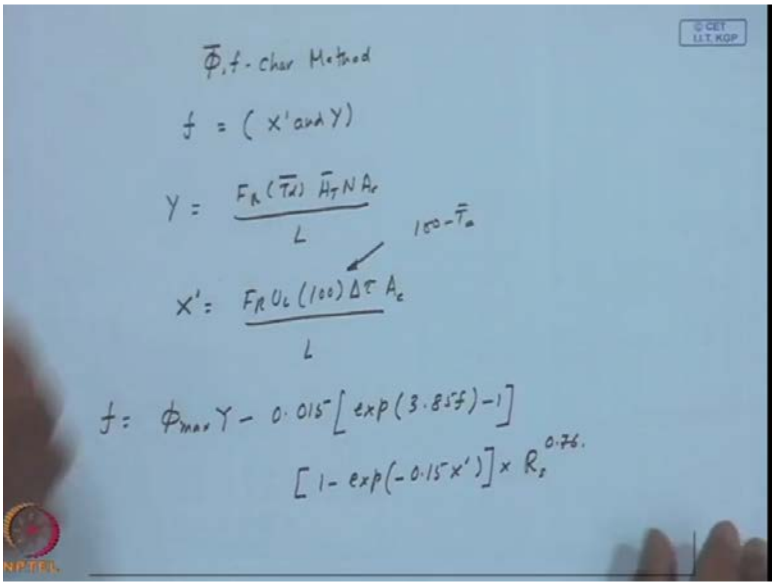

Again, the phi bar f chart method relates the solar load fraction to 2 variables X dashed and A Y, Y is exactly the same as the one that we have written for the f chart method. Where F R is your collector heat removal factor transmittance of certain products solar radiation monthly average daily multiplied by the number of days in the month and the area of the collector upon the load. And the non dimensional collector loss is slightly modified as X dashed equal to F R U L times 100 times delta tau that is number of seconds in the year sorry, month by a C upon L. So, only difference is this comes in place of 100 minus T a bar so, the symbols are explained over here U and H T bar is the L S. All these things are known so coefficient reads f is equal to phi bar max Y minus 0.015 exponential to the power 3.85 f minus 1 times 1 minus exponential minus 0.15 X dashed times R S to the power 0.76. This equation needs bit of exponential as we guessed or as that estimate rightly.

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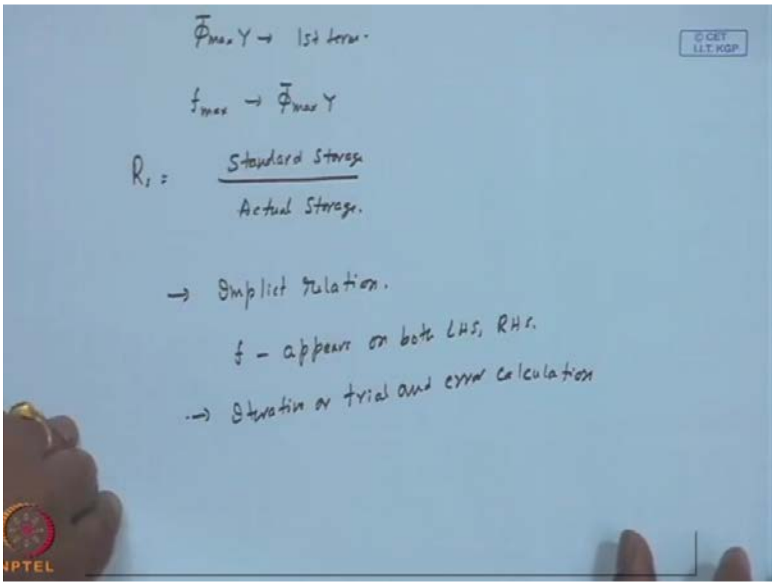

Your phi bar max Y is the foster if all the other non-linearity since second and third terms are assume or to be a small or 0, you will get simply f is which will be the maximum phi bar max Y. And this also contains r s the standard storage by actual storage unlike in the f chart correlation where the storage size is not explicitly present in the correlation and X or Y has to be corrected depending upon the storage standard are different in this case that is included in the correlation itself. The other little uncomfortable aspect is this is a implicit relation that is your f appears on both left hand side and the right hand side it cannot be separated.

So, this needs an iterative or trial and error calculation so compare it to f chart in addition to it taking into account the minimum temperature at which energy delivery is desired. This relation is explicit and we need to calculate yet not known to us the monthly average daily utilizability appears to be a exciting parameter, which compares of the statistics of the solar radiation and the collector parameters.

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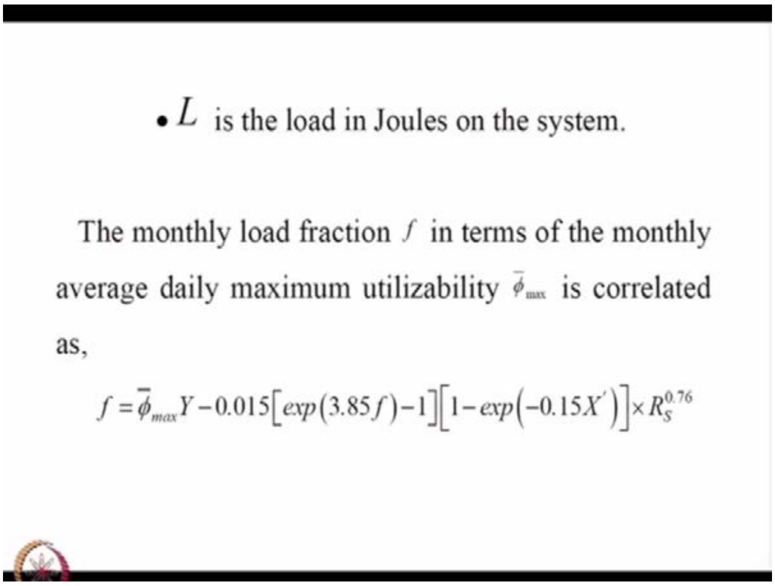

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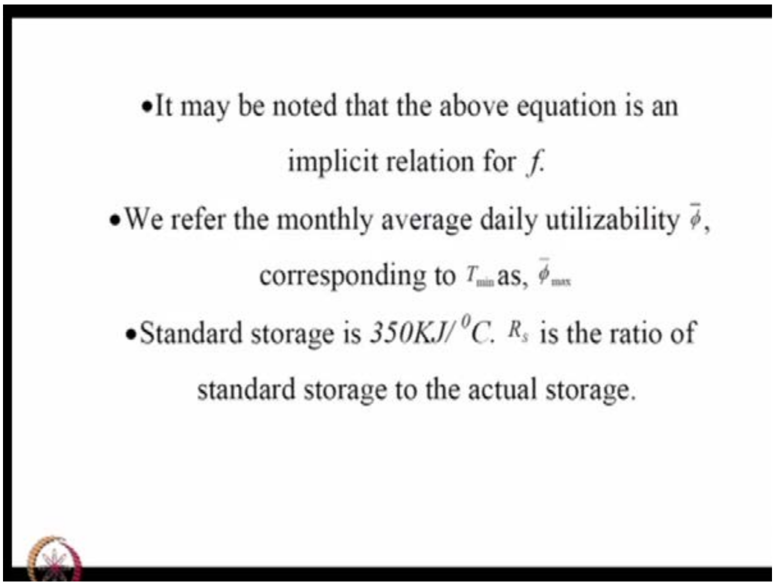

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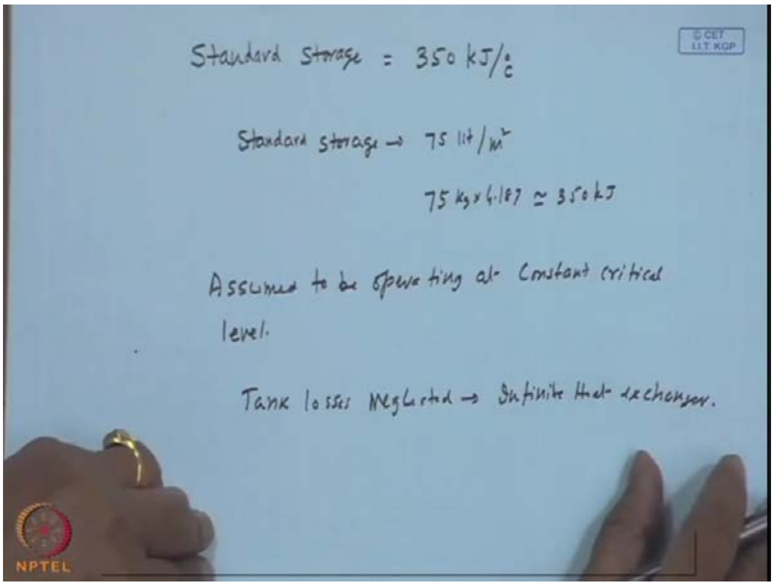

And the operating condition at which the energy delivery is desired so, this is what I have already, written over here and standard storage I should tell you 350 kilo joules per degree C. Now, in the case of liquid base systems or previously in the case of f chart correlation standard storage is considered to be 75 liters of water per meter square of the collector area. This if you multiply by 75 is approximately 75 Kg multiplied by 4.187. The specific heat is approximately equal to 350 kilo joules.

So, the storage sizes are comparable and this is standard systems employing for liquid based collectors connected in parallel. The collectors are assumed to be, this is an important assumed to be; to be operating at constraint critical level. So, you have a situation here the monthly solar load fraction can be calculated for a system delivering energy at or above a desired certain temperature. The additional parameter that needs to be calculated is the monthly average daily utilizability, but the limitations are a storage can be taken care of and, but the critical level is assumed to be constant. Yet methods are to be found out to calculate the utilizability other than the detail calculations through a correlation or, some other simplified method. If your critical radiation level is bearing with time.

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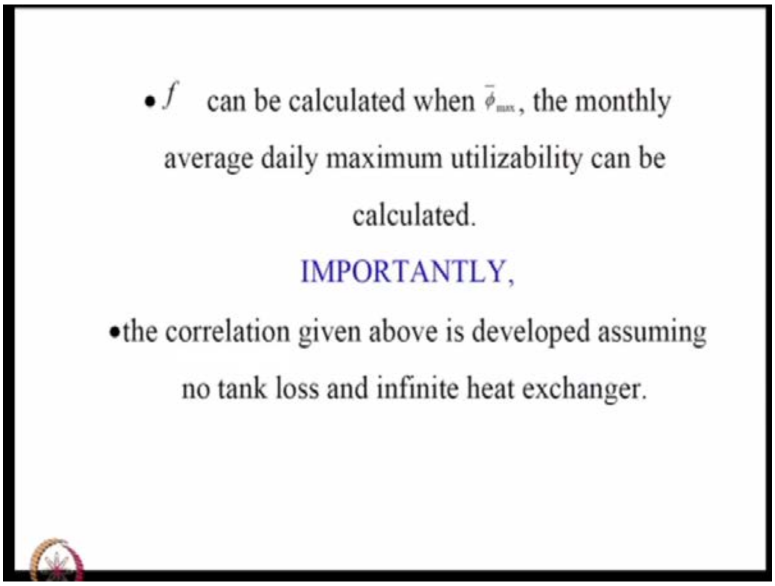

Now, last but not the least, this correlation we do not know anything about the heat exchanger number 1. Number 2 we also have not explicitly considered or implicitly considered in deriving this relation, the losses from the tank. So, you might wonder why the losses from the tank were not there in the f chart nor, I mentioned about the tank losses and the heat exchanger correction. Only correction for this size as a heat exchanger was there because, it was explicitly developed for different values of epsilon C minimum by U A U A h, whereas, in this case as such this stands tank losses neglected and an infinite heat exchanger, in other words there is no delta T required in the heat exchanger. So, this we shall stop now and continue with it in the next class.