Advanced Design of Steel Structures
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Lecture - 63
Fire - resistant design - 2

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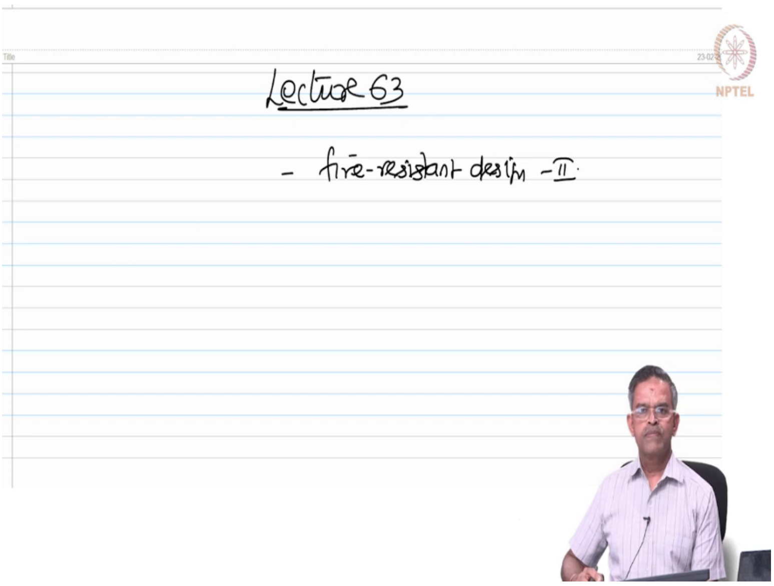

Friends, welcome to lecture 63 of Advanced Steel Design, where we are continuing to discuss the procedures for Fire resistant design as a part of this course. In the last lecture, we discussed about some essential characteristics of fire, what are the tips for good fire-resistant design buildings, and so on. Now, we will focus more on design methods for fire resistance. This is what specific reference to API-RP 2A, American Petroleum Institute Recommended Practice 2A.

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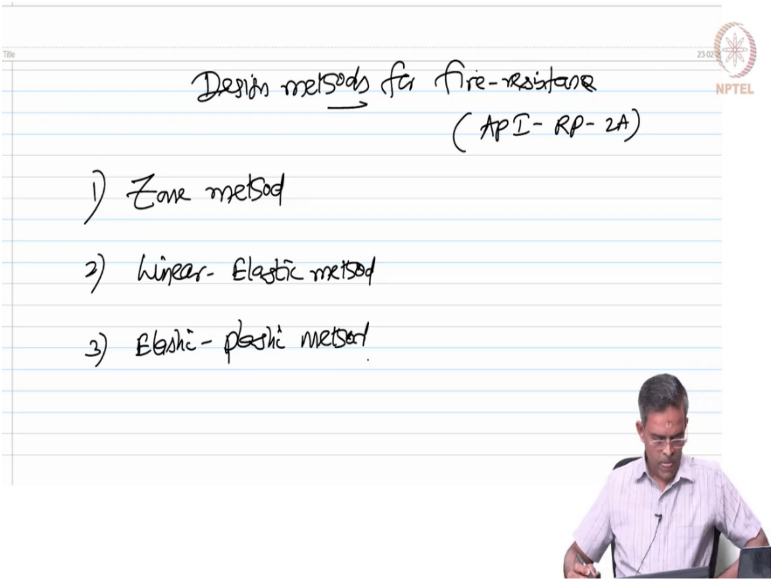

This specific course says there are 3 possible ways by which you can design fire resistance structures. 1 is by what is called as a zone method, 2, linear-elastic method and the 3rd one is elastic-plastic method.

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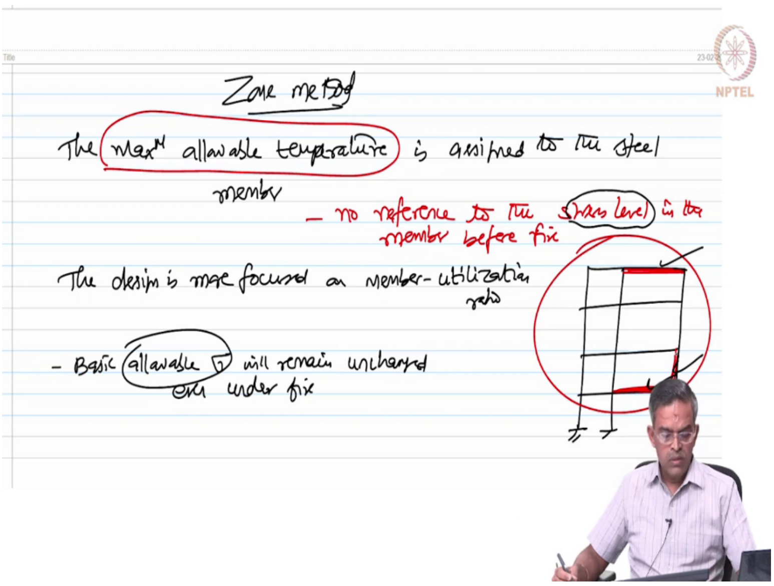

In the zone method, the maximum allowable temperature is assigned to the steel member. This method has no reference to the stress level in the member before fire.

Let us say, in a given building, there are zones where there is a possibility of fire, let us say this member, and let us say in this member, column and this beam. These are the possible locations where a fire could outburst.

So, now these steel members are assigned to a maximum allowable temperature up to which it has to sustain. When you do that, you do not have any cross reference to the stress level in these members before fire. So, the design is more focused on member utilization ratio. The basic allowable stress will remain unchanged even under fire.

That is the reduction in stress level due to high temperature is not accounted in the design as the allowable value. They remain unchanged. So, this method is focusing only on certain areas, on certain members which has got high proximity of fire, probability of fire occurrence is higher. So, that is why this method is called zone method.

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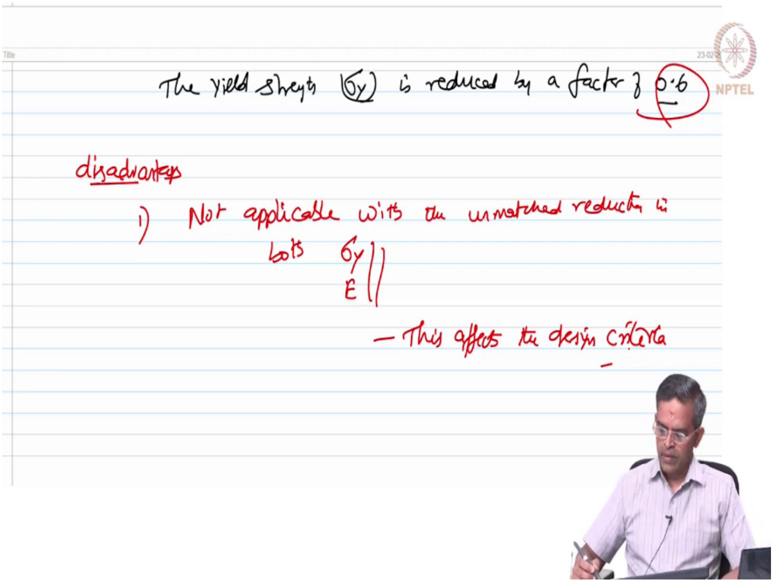

In this method, the yield strength σ_y is reduced by a factor of 0.6. Now, there are disadvantages of this method. 1, it is not applicable with the unmatched reduction in both σ_y and E, because you have a constant number. So, this affects the design criteria.

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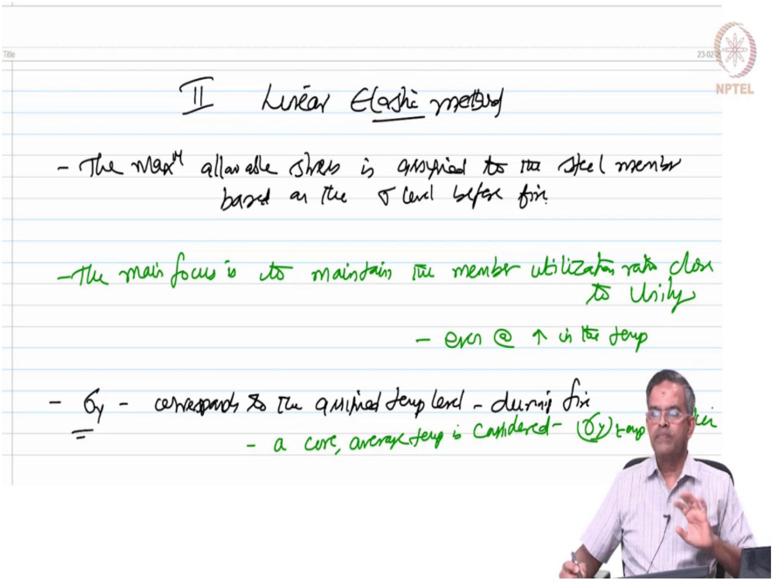

The 2nd method is linear elastic method. In this method, the maximum allowable stress is assigned to the steel member based on the stress level before fire. So, here the main focus is to maintain the member utilization ratio close to unity. So, effective utilization is ensured and this is done even at increase in the temperature.

In this design method, the stress level corresponds to the assigned temperature level. So, you have to pick up the yield value with respect to the corresponding temperature level of steel during fire. So, when you talk about the temperature variation during fire, then you may ask me a question what temperature should I consider for estimating σ_y from the material property? That is a good question.

You can have a maximum temperature; you can have a minimum temperature. So, what we generally consider is, your core average temperature is considered and the equivalent σ_y at that temperature is taken for design.

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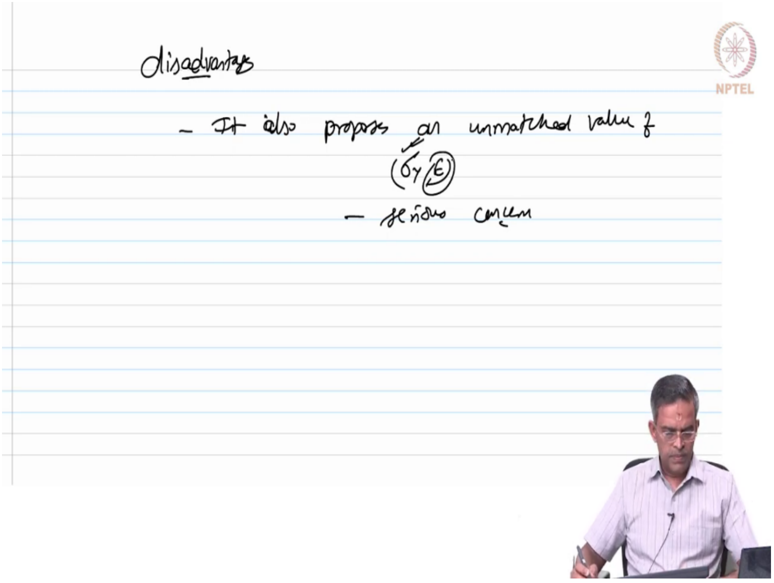

This method has some disadvantages. This method also proposes an unmatched value of σ_y and E, which is a serious concern because the degradation in young's modulus and the yield strength are not same at a specific temperature. It considers an average core temperature value for which σ_y is considered, but E is not accounted with respect to the temperature variation.

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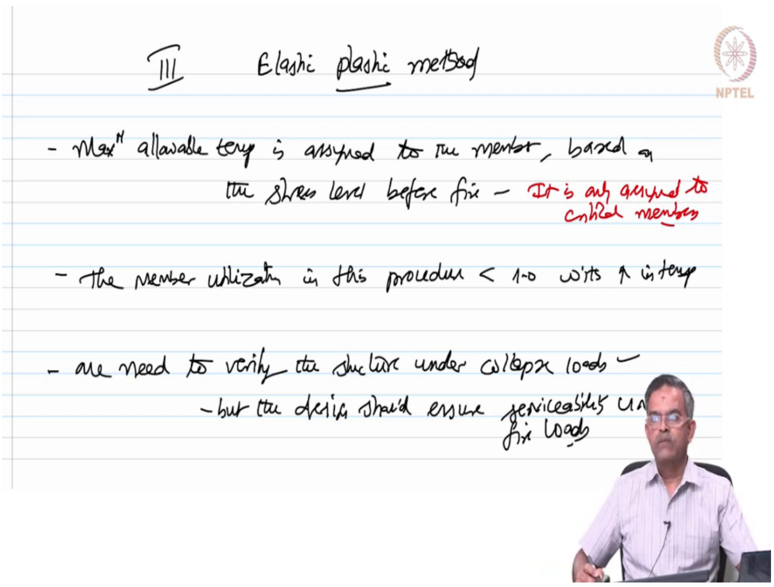

The 3rd method is elastic plastic method, where the maximum allowable temperature is assigned to the member, based on the stress level before fire. Friends, this is not assigned to all the members. It is only assigned to critical members. What do you mean by critical members? The members whose stress level is maximum before fire.

As a result, the member utilization in this design procedure is lesser than 1.0 with the increase in temperature.

So, all members are not subjected to uniform stress range, only those critical members subjected to higher temperature during fire is assigned a specific stress value. So, therefore, one need to verify the structure under collapse. So, you need to verify the structure under collapse loads, but the design should ensure serviceability under fire loads. So, that is the design criteria what this method ensures.

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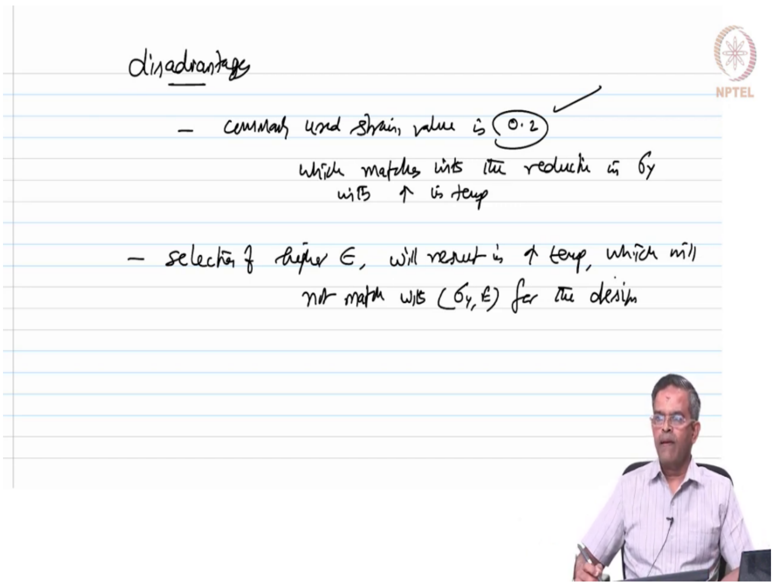

This method also has couple of disadvantages. Commonly used strain value in the design is 0.2 which matches with the reduction in σ_y with increase in temperature. But selection of higher strain, will result in higher temperature. See, you are looking for an average temperature for which the strain value may not be 0.2. In the last lecture, we discussed about the strain variation in steel with respect to temperature.

So, either you pick up the strain value for a specific temperature or for a specific strain pick up the temperature. So, the procedure says you pick up the stress value for a specific temperature for the critical members, but when it assigned the strain value it is 0.2. So, a higher strain value assigned to the members will result in higher temperature, which will not match with the stress and young's modulus for the design. So, that is a concern in this method.

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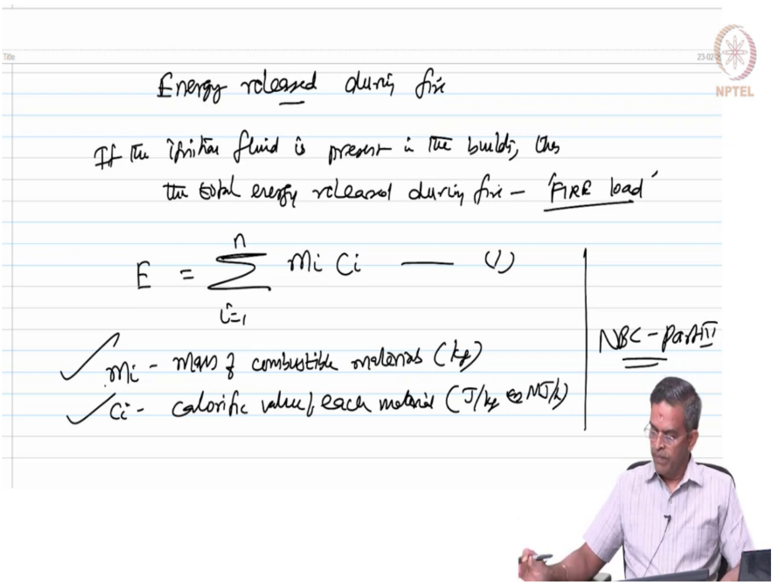

Having said this let us talk about energy released during fire. If the ignition fluid is present in the building, then the total energy released during fire can be given by what is called as fire load. So, fire load is the total energy which is sum of $M_i C_i$, where M i is the mass of combustible materials present in the building in kgs.

$$E = \sum_{i=1}^{n} M_i C_i$$

C_i is the calorific value of each material which is either in joules per kg or of course, megajoules per kg. For common materials being used in buildings, national building core part 4 gives the value of M_i and C_i value of different materials.

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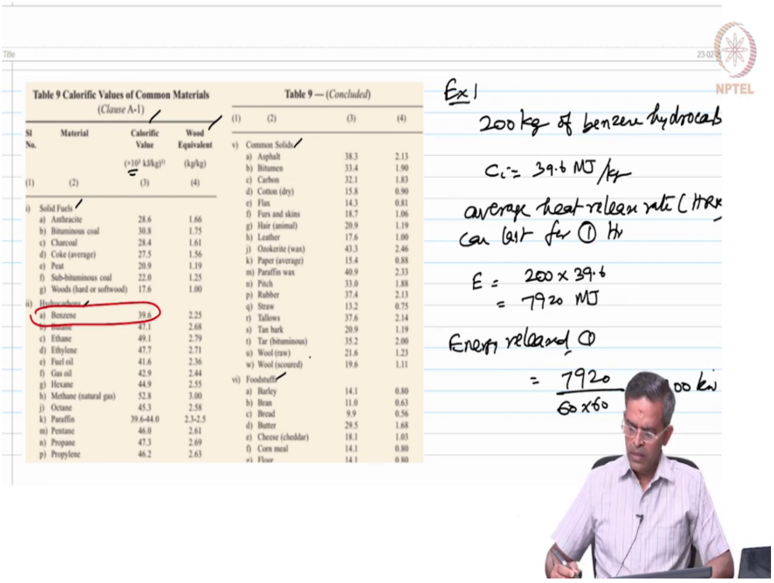

Look at this table which is extracted from the national building core for different material. Let us say solids, hydrocarbons, common solids, even foodstuffs.

A calorie value and the wood equivalence are given in the core. Let us do a small example. Let us say there is a presence of 200 kg of benzene hydrocarbon. If you look at benzene hydrocarbon, the calorific value is 39.6, I can say megajoules per kg; plus 10 power 3 I have taken as megajoules.

Now, the average release rate which is called as HRR can last for 1 hour. So, we can say E is going to be 200 into 39.6 that is 7920 megajoules. So, the energy released Q can be 79; 7920 by 60 into 60, which is 2200 kilowatts.

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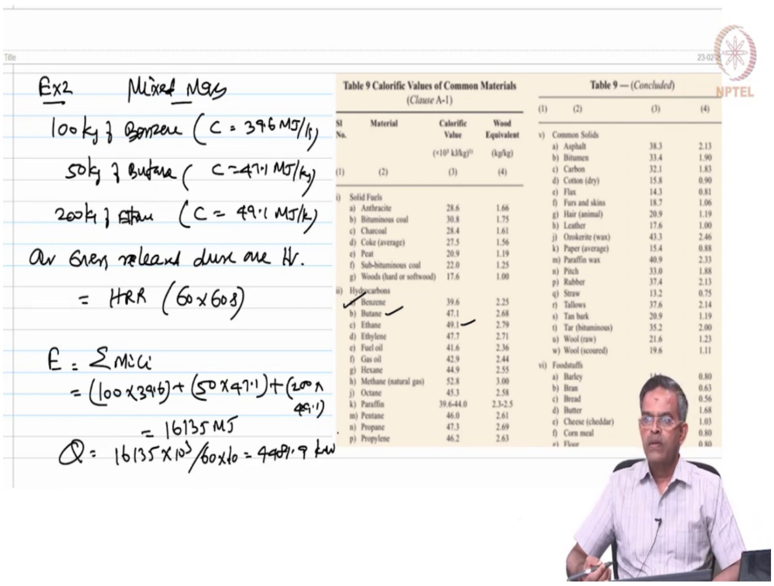

Let us do one more example of a mixed mass. You can see on the screen the NBC table extracted. Let us say the building contains 100 kg of benzene whose C value is 39.6, 50 kg of butane whose C value is 47.1, 200 kg of ethane C value is 49.1.

So, the average energy released during 1 hour is called as HRR, heat release rate that is 60 into 60 seconds is given by sum of $M_i C_i$. In our case going to be,

$$E = \sum_{i=1}^{n} M_i C_i = (100\times39.6) + (50\times47.1) + (200\times49.1) = 16135\ MJ$$

$$Q = \frac{16135\times10^3}{60\times10} = 4481.9 kW$$

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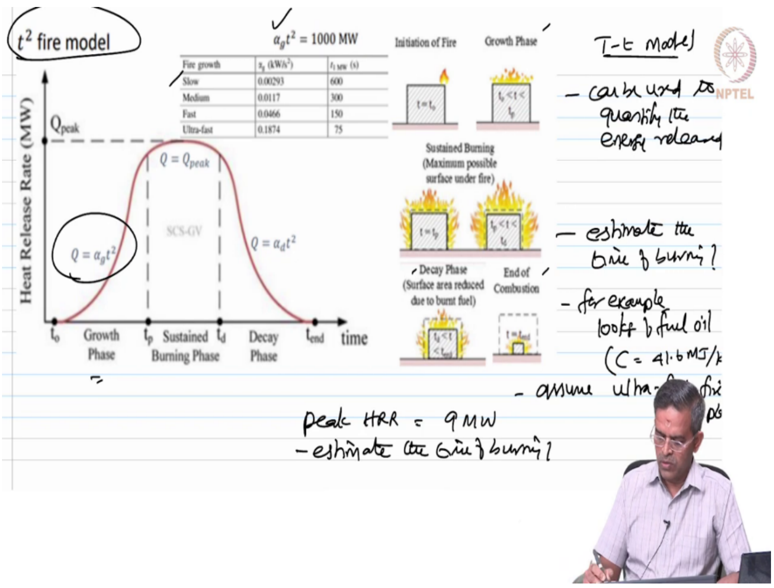

Let us look into the t square fire model which is a very common time temperature curve, which is being used is also called as T-t model or a t square fire model. This can be used to quantify the energy released.

Furthermore friends, you can also see the time temperature or time heat release rate curve where, the α g t square which is the heat release rate depends on a factor which is there for different kind of fire. Let us say, if it is a slow fire growth α g is different compared to ultra-fast fire growth.

Now, if the fire growth rate is known to us, we can estimate the time of burning. We can easily find out how long the fire will be sustained. Furthermore, there are different phases of fire growth initiation, growth phase, decay phase and end of combustion. So, in the growth phase, there is a significant rise in the heat release rate with reaches its peak and then it gets decay as you see here in the figure.

So, now let us say for example, I have 100 kg of fuel oil. The fuel oil has got C as 41.6 megajoule per kg from the table. Let us assume an ultra-fast fire to take place. The peak HRR, that heat release rate is 9 megawatts. We want to estimate the time of burning. Let us do that.

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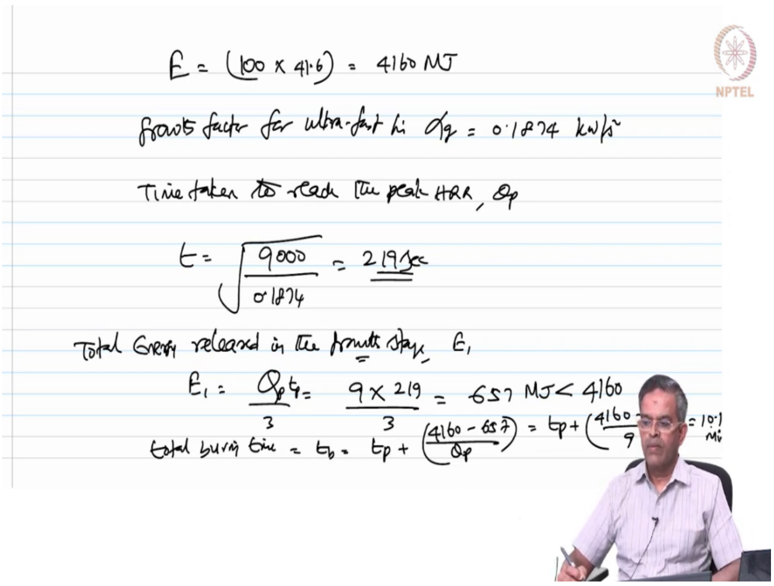

$$E = (100\times41.6) = 4160\ MJ$$

The growth factor for fire or ultra fast fire that is α g from this table, you can see, it is 0.1874, 0.1874 kilowatt per second square. Therefore, the time taken to reach the peak HRR that is Q p is 9000 because we already said the HRR is about 9 megawatts divided by 0.1874 root which will be 219 seconds.

$$\alpha_g = 0.1874\ \frac{kN}{s^2}$$

$$t = \sqrt{\frac{9000}{0.1874}} = 219\ sec$$

Now, the total energy released in the growth stage let us call this E 1 can be computed as

$$E_1 = \frac{Q_p t_p}{3} = \frac{9\times219}{3} = 657\ MJ\ < 4160\ MJ$$

Since, the 657 megajoule in the growth stage is much lesser than the heat release which is the energy present because of the oil or because of the fuel oil. We can say the total burning time will be

$$t_b = t_p + \left(\frac{4160-657}{\theta_p}\right) = 10.1\ min$$

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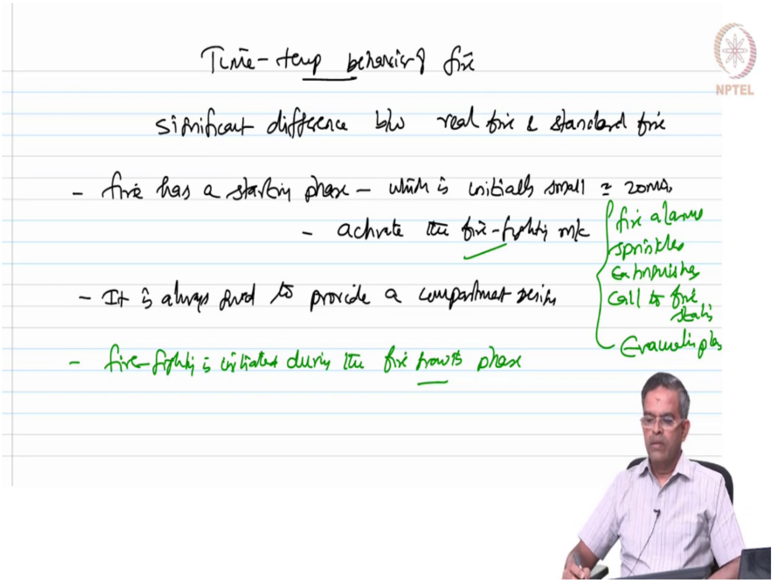

Let us discuss about the time temperature behavior of fire. Friends, there is a significant difference between the real fire and the standard fire. Fire has a starting phase which is initially small about 20 minutes. So, it is during this time, one can activate the firefighting equipment's like fire alarms, sprinklers, extinguishers, call to fire station, evacuation plan etcetera. All can be activated during this time. It is always good to provide a compartment design. So, the fire does not spread to the places where device and equipment's are kept. So, friends, we must understand that firefighting is initiated during the fire growth phase during the fire growth phase.

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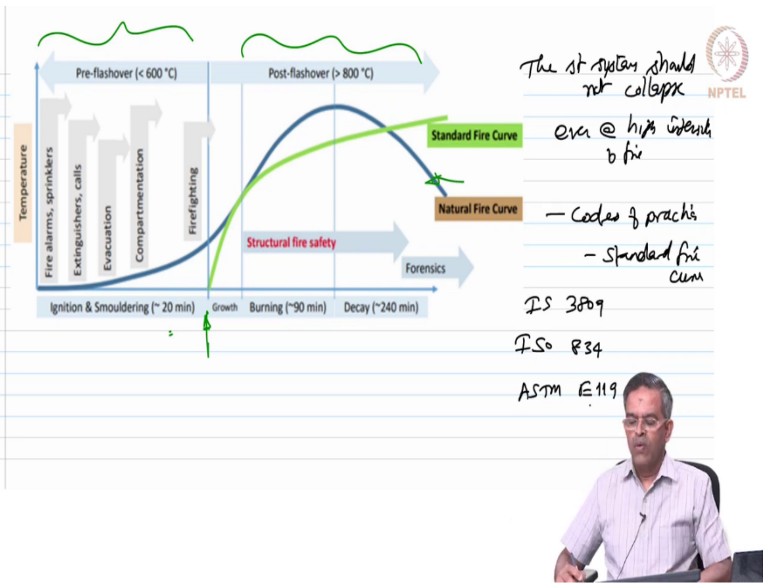

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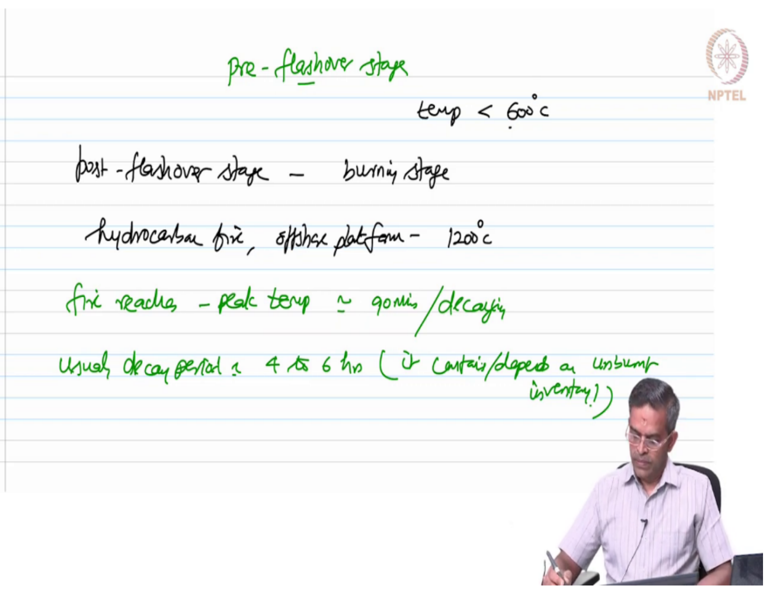

Following by this, let us have something called pre-flash over stage. This is true up to a temperature less than 600 degree Celsius. The post-flash over stage is called as the burning stage. It is interesting friends for you to know that hydrocarbon fires which happen in offshore platforms, can reach the temperature as high as 1200 degree Celsius.

Therefore friends, in such cases fire reaches its peak temperature approximately within 90 minutes and then starts decaying. Usually, the decay period of fire is about 4 to 6 hours. But it contains and depends on the unburned inventory. Let us look at this curve which is the pre-flash over and post-flash over stage. The pre-flash over stage is about approximately 20 minutes on initial ignition and smoldering. Then, the burning takes for 90 minutes, then the decay is about 240 minutes. The natural fire curve is what you see here.

Whereas, the standard fire curve always starts after the pre-flash over stage, after this stage. So, the philosophy for design is that the structural system should not collapse even at high intensity of fire. There are various codes of practices which ensure this fire safety which shows the standard fire curve. For example, IS 3809, ISO834, ASTM E119, helps you by providing the standard fire curve.

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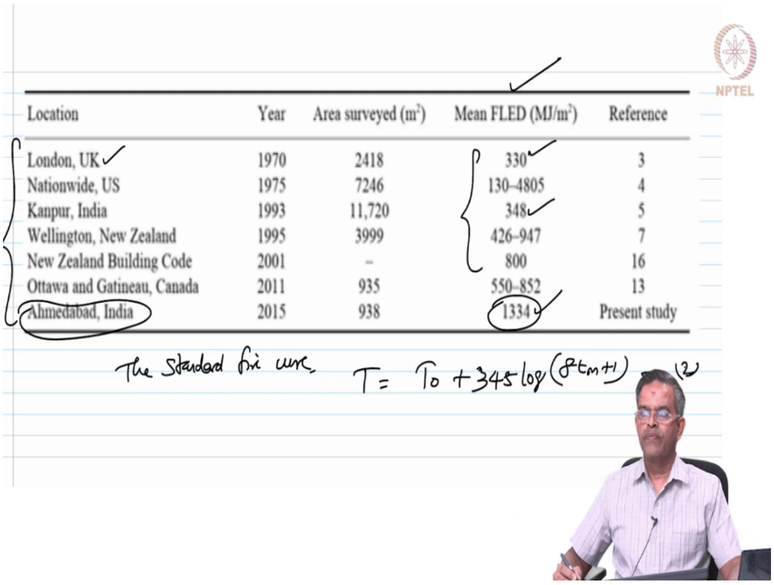

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Furthermore, we can also estimate the fire load energy density which is called as FLED. The fire load energy density depends on different code provisions which are also carried and revised by different countries. For example, in London, the mean FLED energy density is about 330 megajoules per square meter, whereas in India it is about 348. So, it keeps on varying and these effects are reflected in the respective national standards of the countries.

A recent study carried out by IIT, Gandhinagar in 2015 shows that the mean value of fire load energy density is much higher in reality. This was tested in the laboratory and people have reported that the FLED value for design which is referred as different codal provisions are far lesser than the actual value. Now, for the standard fire curve T is given by T 0 plus 345 log of 8 t m plus 1, for standard fire. We call this equation number 2.

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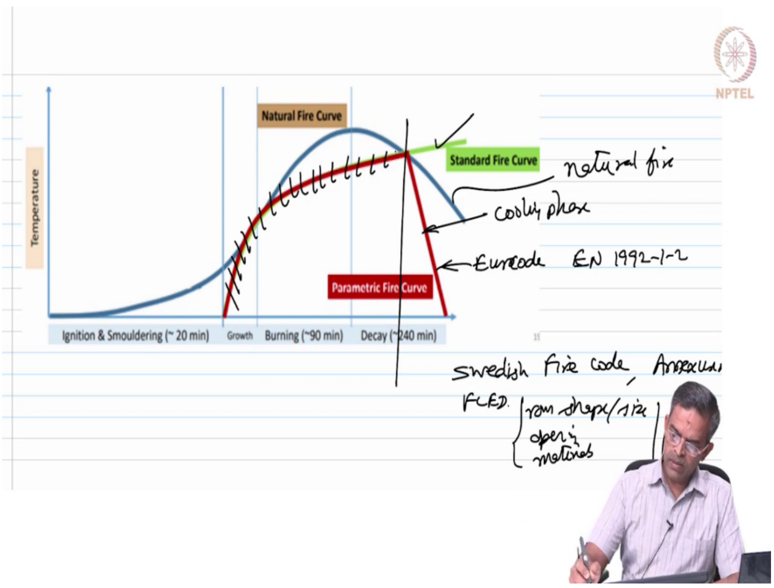

Now, look at this fire curve back again it says that the natural fire curve has got a cooling phase. The standard fire curve closes here, whereas the parametric fire curve, which indicate in Euro code which is EN 1992-1-2 indicates a cooling phase for about short period.

So, now, there is a cooling phase which is shown in the red color here. So, this is for the natural fire which also indicates a cooling phase whereas, in standard fire curve this cooling phase is missing. Whereas, if you look at the Swedish fire code in Annexa A, FLED is revised based on the room shape and size, and openings present in the room, and inventory materials present in the room.

So, there has been a revision in the Swedish fire code to compute the fire load energy density, not at the standard value, but is dependent on realistic parameters as you see here. The standard fire curve only indicates the growth phase, but does not talk about the cooling phase. Whereas, a parametric fire curve used in euro code talks about the cooling phase as well.

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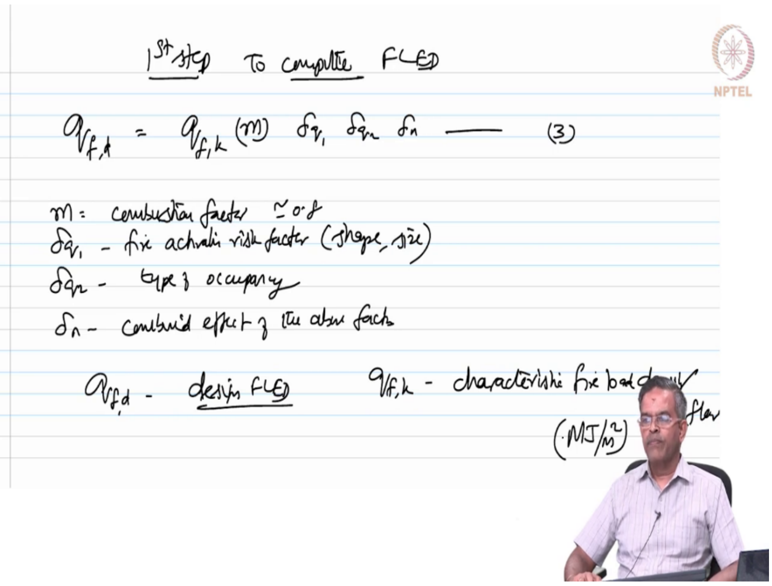

So, therefore, friends in fire resistance design, the 1st step is to compute fire load energy density, which is given by

$$q_{f,d} = q_{f,k}(m)\delta_{q1}\delta_{q2}\delta_{qn}$$

Call this equation number 3 where m is the combustion factor, which is approximately 0.8. δ_{q1} is a fire activation risk which depends on the shape and size.

δ_{q2} depends on the type of occupancy. And del n is a combined effect of the above factors. Now, $q_{f,d}$ is called the design FLED, $q_{f,k}$ is called the characteristic fire load density per area of flow which will be expressed in megajoules per square meter.

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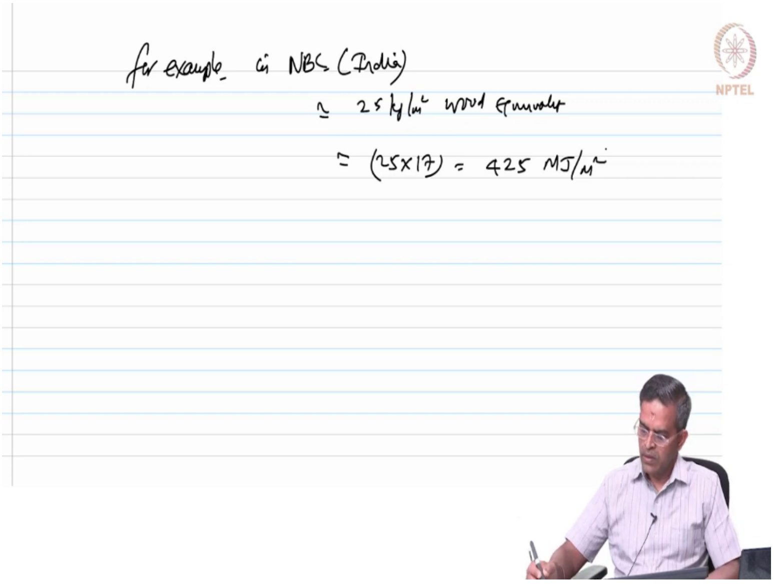

For example, in national building code of Indian practice, it is said as 25 kg per square meter of wood, equivalent of wood. So, we now say, wood equivalent we can say, which is 25 into; the calorific value of wood which is giving me 425 megajoules per square meter.

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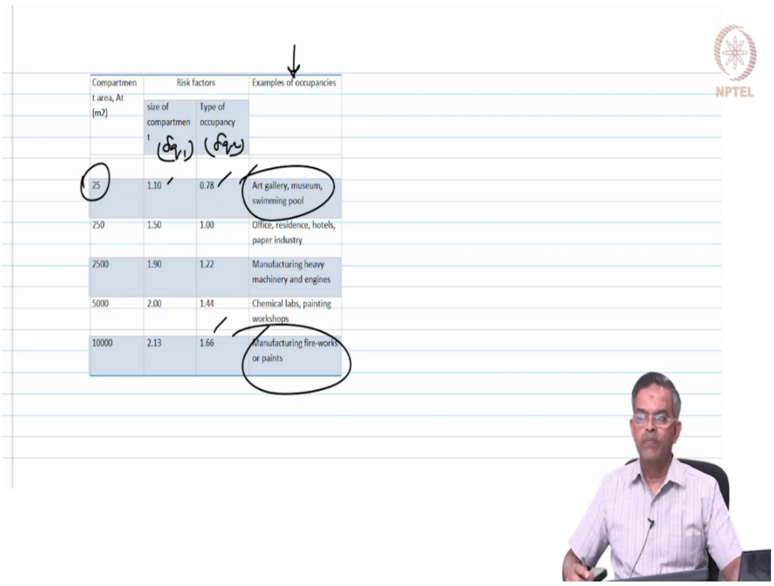

Now, the other factors δ_{q1} and δ_{q2} are given here depending upon the type of occupancy and the size and shape. If the compartment area is about 25 square meters δ_{q1} is about 1.1 and for art gallery museum etcetera is 0.78, whereas manufacturing fireworks is about 1.66. So, the example of occupancy is also listed here which helps me to compute the δ_{q1} and δ_{q2} factors required to compute the FLED of the design value.

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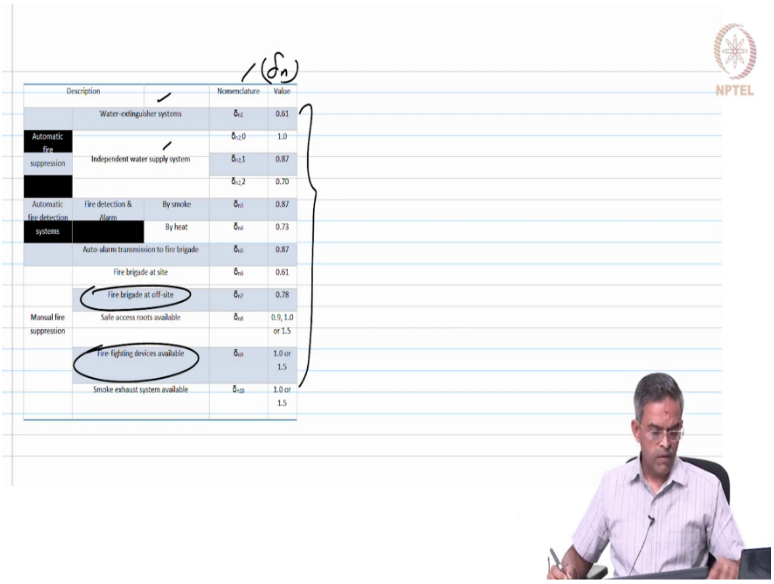

If you have firefighting systems which is useful for suppressing fire with water extinguisher systems, independent water supply system, fire brigade located off site, or firefighting devices available, then the del n value is also varied. So, it is a combined effect which is useful to compute the FLED for the design.

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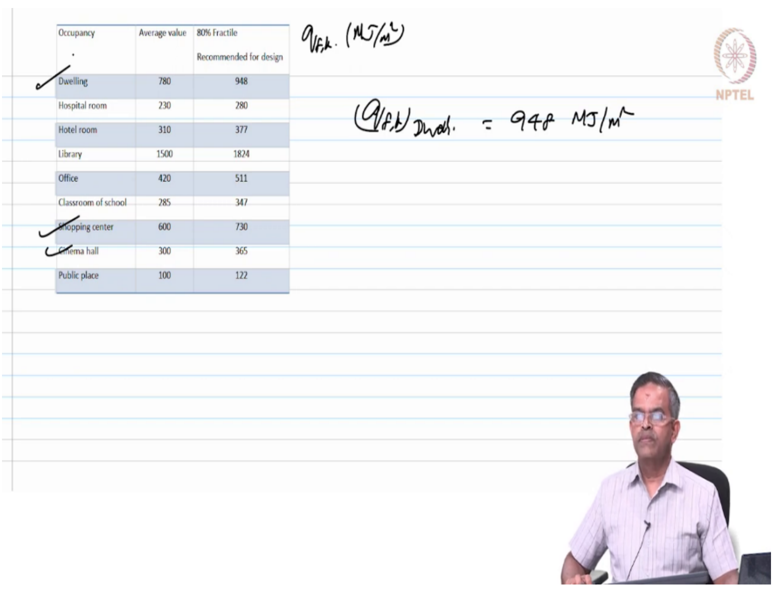

The table what you see on the screen is an average value of $q_{f,k}$ in megajoules per square meter is $q_{f,k}$. So, for example, $q_{f,k}$ for dwelling units is about 948 megajoules per square meter which is equivalent value of wood. So, it is available for different kinds of public spaces as well as private spaces which is used for the design, which is the characteristic value. Now, with the help of this one can compute the FLED.

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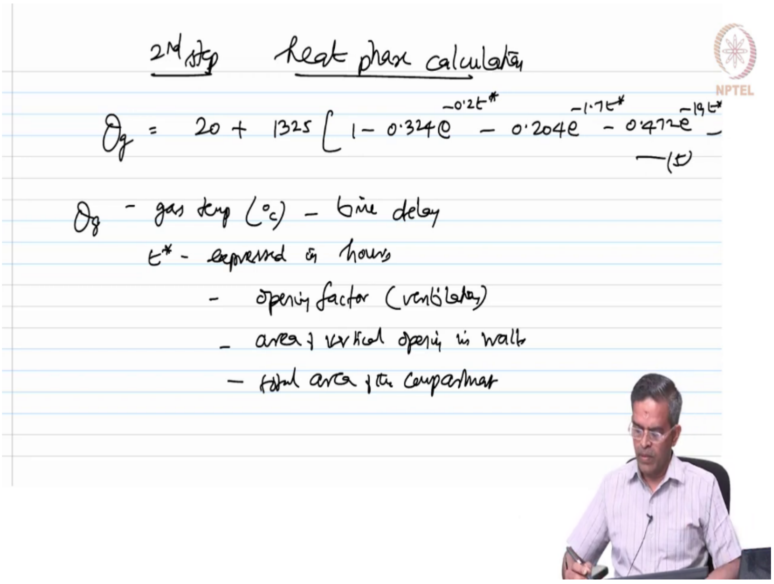

Now, the second step involved in fires resistant design or the fire load estimate is heat phase calculation.

$$\theta_g = 20 + 1325\left[1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right]$$

(Refer Time: 44:17) equation number 5.

Where θ_g is expresses the gas temperature in degree Celsius which is based upon the time delay. t star is expressed in hours. t star depends on opening factors that is the ventilation then area of the vertical opening in walls. Total area of the compartment for which fires resistant design is attempted.

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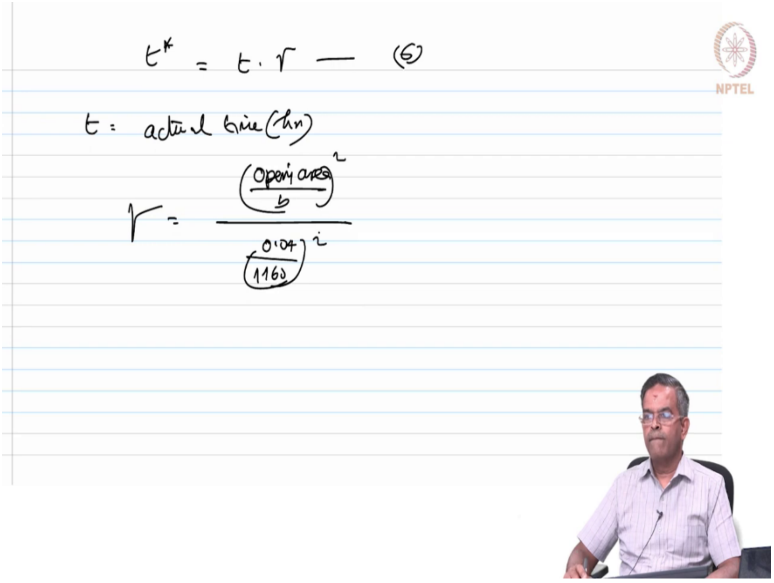

$$t^{*} = t.r$$

where t is the actual time in hours and gamma is opening factor by breadth b square. Let me write down here. Gamma is opening area by breadth square which is 0.04 by 1160 square. Let us not.

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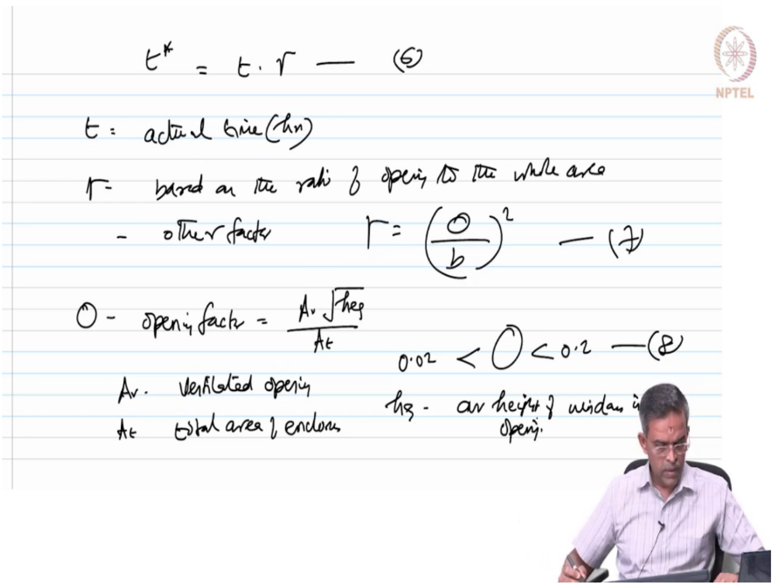

$$\gamma = \left(\frac{O}{b}\right)^{2}$$

So, gamma is based on the ratio of opening to the whole area. This is referred as other factors that influence the design. Now, gamma is O by b square, where O is called as the opening factor which is

$$O = \frac{A_v \sqrt{h_{req}}}{A_t}$$

$$0.02 < O < 0.2$$

where A v is ventilated opening, A t is the total area of enclosure, and O lies between 0.02 to 0.2. h equivalent is the average height of windows in the openings.

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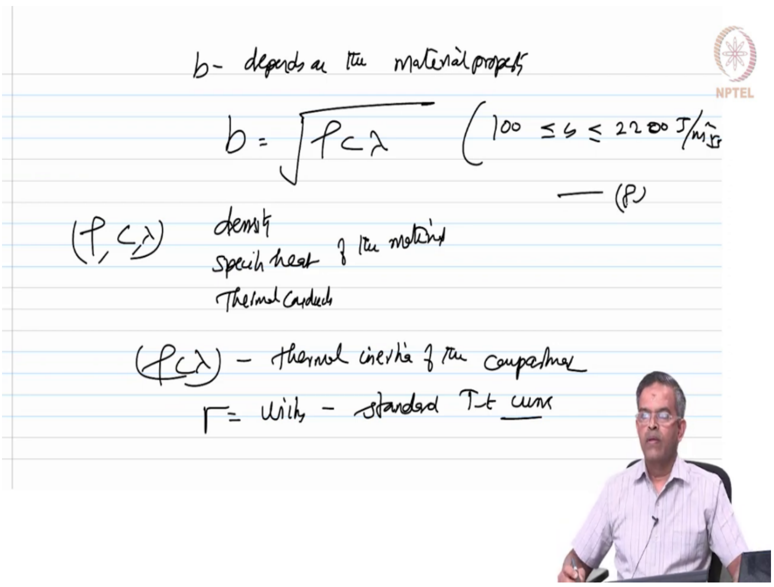

In this expression, b depends on the material property;

$$b = \sqrt{\rho c \lambda}$$

for 100 and 2200 joules as square meter per root s k where ρ, c, λ are density, specific heat, and thermal conductivity of the material. ρ, c, λ product is called thermal inertia of the compartment. Gamma, if it is unity, which is referred to which will refer to the standard time temperature curve. We have got seen two curves, right, standard and actual the equation 8.

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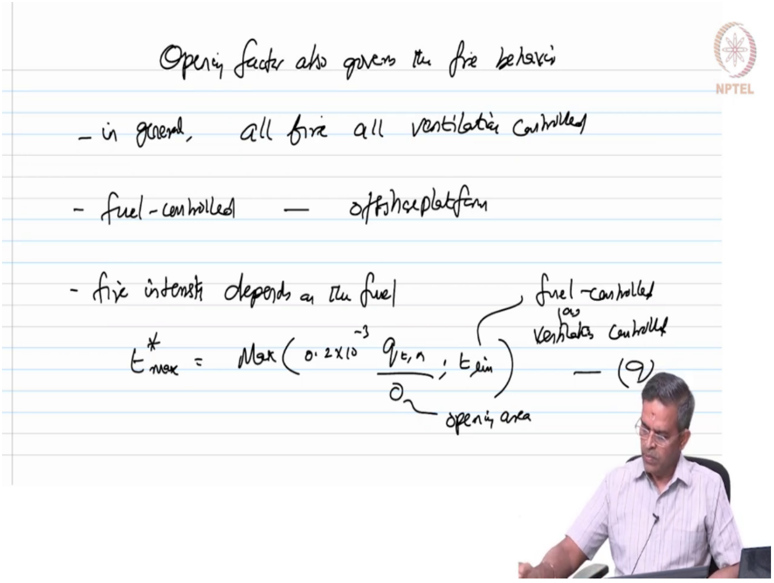

Opening factor also depends on or also governs the fire behavior. In general, all fire are ventilation controlled. Few of them could be fuel controlled. For example, in offshore platforms, you have got lot of ventilation around. So, there is no problem of ventilation, but inventory of fuel will control the fire.

$$t^{*}_{max} = Max(0.2\times10^{-3}\frac{q_{t,\alpha}}{O}; t_{lim}$$

Fire intensity depends on the fuel. where O is the opening area and t limit depends on whether it is fuel controlled or ventilation controlled - equation 9.

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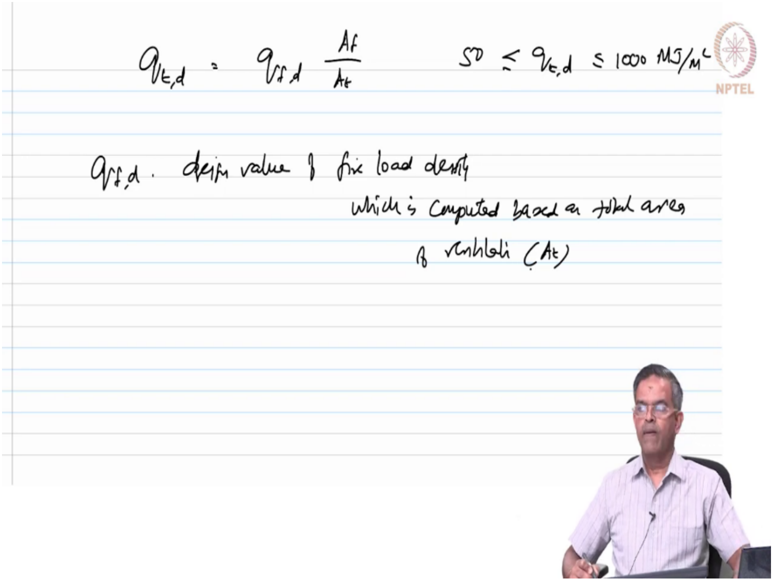

$$q_{t,d} = q_{f,d}\frac{A_f}{A_t}$$

Now, for 50 less than or equal to $q_{t,d}$ less than or equal to 1000 megajoules as square meter, where $q_{f,d}$ is called the design value for fire load density, which is computed based on the total area of ventilation which is A_t.

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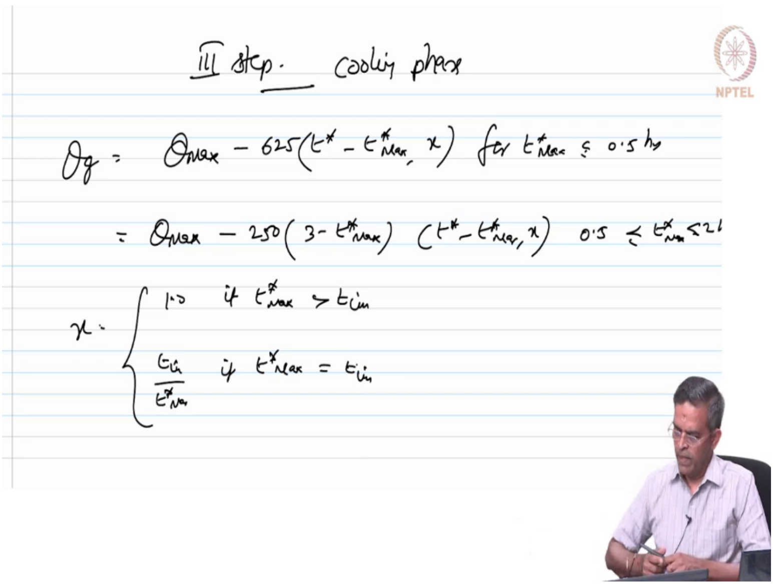

The 3rd step is the cooling phase. Now,

$$\theta_g = \theta_{max} - 625\left(t^* - t^*_{max}, x\right) for\ t^*_{max} \leq 0.5\ hrs$$

$$\theta_g = \theta_{max} - 250\left(3 - t^*_{max}\right)\left(t^* - t^*_{max}, x\right) for\ 0.5\ hrs \leq t^*_{max} \leq 2 hrs$$

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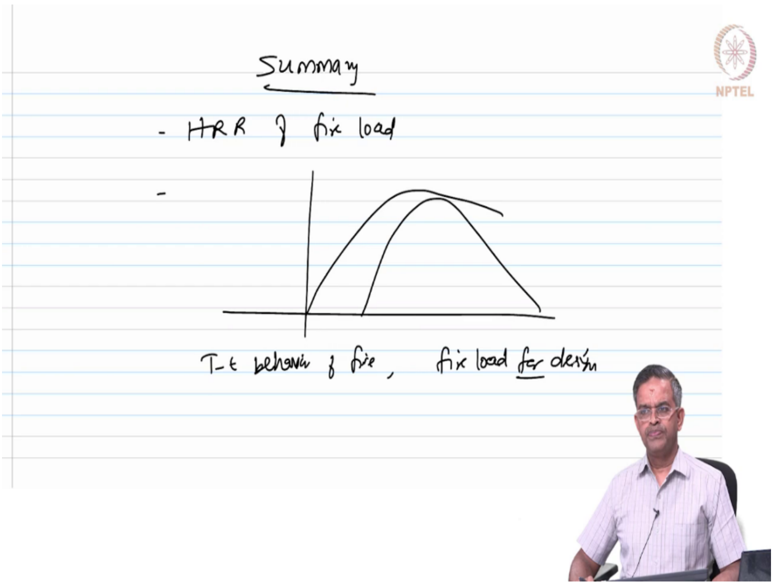

So, friends, in this lecture, we learnt about the heat release rate of fire load. We also learnt about the standard fire curve and the cooling phase of the fire curve. We understood the time, temperature, behavior of fire, and understood how to compute the fire load for design.

So, more details of this fire-resistant design part can be seen in a separate course of NPTEL conducted by IIT, Madras by me on Offshore Structures under Special Loads including Fire Resistant Design. So, design examples are available. And I also authored a book on fire resistant design which can be useful to you for working out more examples on this. Please refer to them. And try to also refer the DNB code and the European code for learning more about the parametric fire curves.

Thank you very much. And have a good day. Bye.