Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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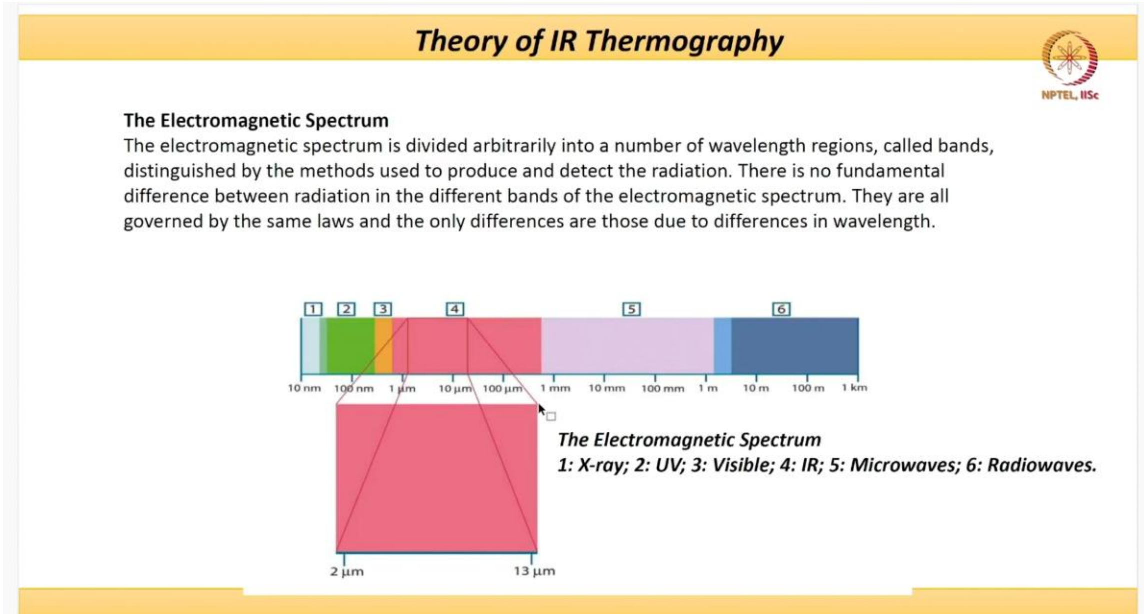
Week – 12
Lecture - 55

Infrared Thermography – 1

All right, so today we are going to talk about the theory of IR thermography. So, IR thermography is particularly important for measuring temperature, primarily temperature signatures, in a non-intrusive fashion. That means it is also a field measurement. That means you don't need point measurements like those a thermocouple provides, for example. So, IR thermography is a little bit different from that. So again, we take a look at the electromagnetic spectrum.

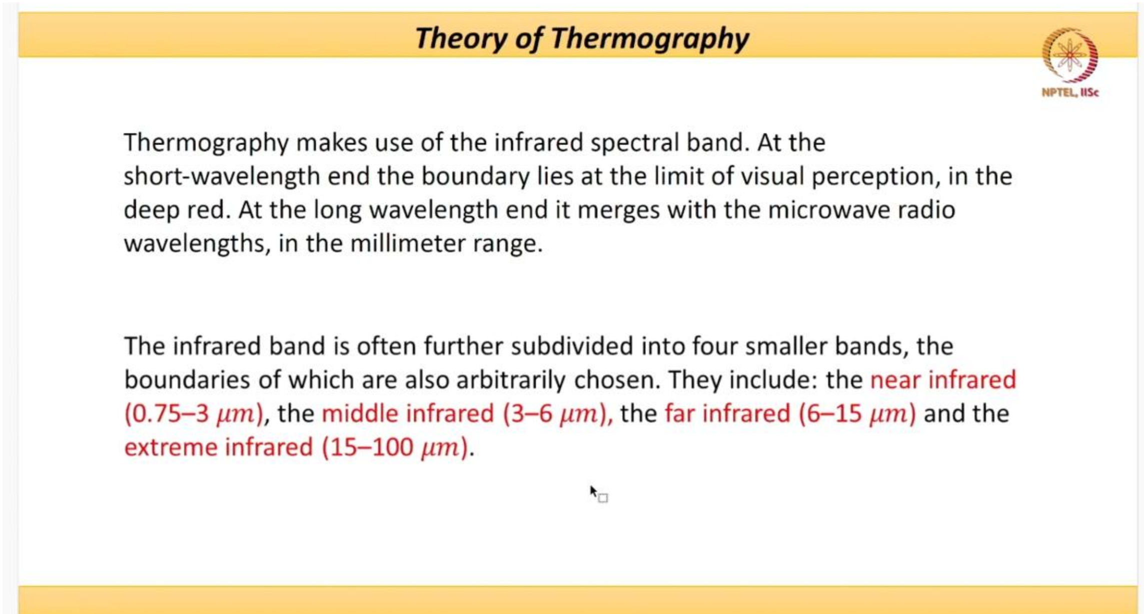
The electromagnetic spectrum is arbitrarily divided into a number of wavelengths and regions called bands. All right. So these bands, if you look at them, are distinguished by their corresponding wavelength signature. Once again, we covered this already in multiple lectures; the first one, for example, which is about the order of 10 nanometers, is where the X-ray lies.

2 is where the UV lies. 3 is the visible range, basically where we actually see; our human eyes can see. 4 is the infrared range. So IR is subsequently divided into several other parts. And this is the part that we are going to talk about.



And then, of course, we go to the microwaves, which are 5, and then the radio waves, which are 6. So, this is the full electromagnetic spectrum. Now, thermography makes use of the infrared spectral bands. So, at the short-wavelength end, the boundary lies at the limit of visual perception. So, when the visual perception ends, this particular thing actually starts.

So at the long wavelength, it merges with the microwave audio. So it has a very huge range that you can talk about. So the infrared band is often subdivided into four smaller bands. So they are the near infrared, which ranges from 0.75 to about 3 microns.

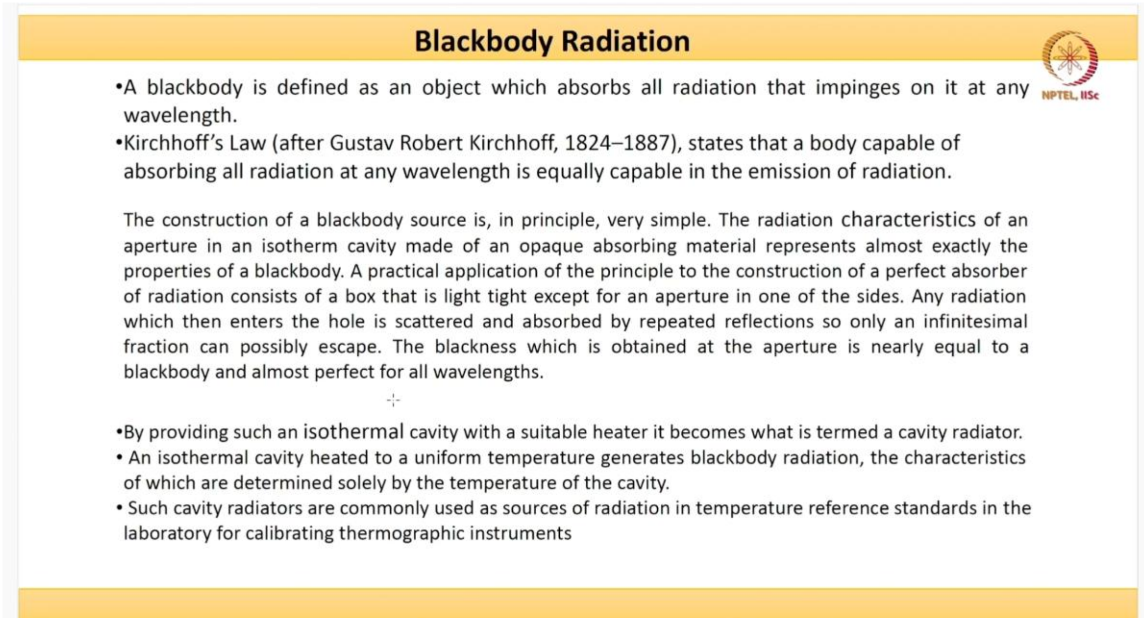


This is right at the edge of the visual limit, about 3 microns. And then the middle infrared ranges from 3 to 6 microns. The far infrared ranges from 6 to 15 microns. And the extreme infrared ranges from 15 to 100 microns. So you can see that it pretty much covers from 0.

75 microns all the way up to 100 microns, which represents a change of about two orders of magnitude in terms of wavelength. So it is a big band. And you can also see that it extends over quite a bit of a region. 100 microns is roughly the size of a human hair or the diameter of a human hair. Next, we define what is known as blackbody radiation.

Now, what is a black body? From high school physics, you know that a blackbody is defined as an object that absorbs all the radiation that impinges on it at any wavelength. So it is an object that absorbs everything. Whatever wavelength you hit it with, it will absorb. Then you also know about Karshov's law, which is named after Gustav Robert Kirchoff in the 19th century, which states that a body capable of absorbing all radiation at any wavelength is equally capable of emitting radiation at any wavelength. So, this was Kirchhoff's law.

So this is what blackbody radiation is all about. So, the construction of a blackbody source is also very simple. So, how do you construct it?



So the radiation characteristics of an aperture in an isothermal cavity, which is made up of opaque absorbing materials, represent almost the perfect properties of a blackbody. So the practical application is the construction of a box that is light-tight, except that you have a small aperture on one of the sides. Any radiation that enters this hole is scattered and absorbed within this box by repeated reflections, and only an infinitesimal fraction can actually escape.

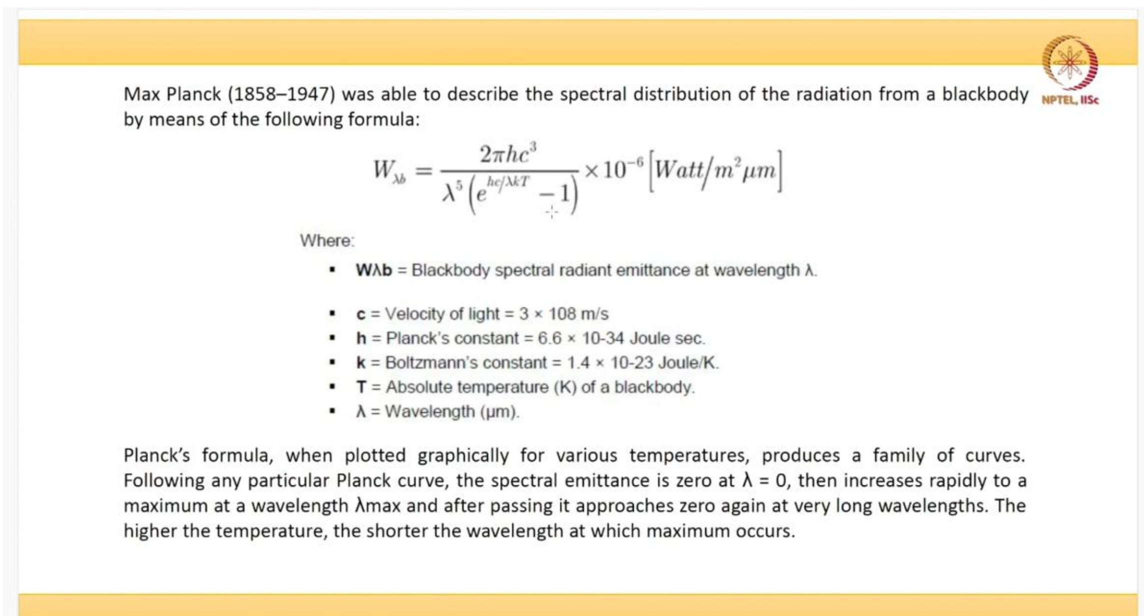
So the blackness obtained at the aperture is nearly equal to that of a black body and almost perfect for all wavelengths. So this is how you normally construct it. You constructed a box with a small aperture. By providing any isothermal cavity with a suitable heater, it also becomes what we call a cavity radiator. So if this isothermal cavity is equipped with a suitable heater and you heat it to a uniform temperature, it generates blackbody radiation.

The characteristics are solely determined by the temperature of the cavity. So whatever the temperature of the cavity is, that determines the temperature characteristics of the radiation, so these cavity radiators are very commonly used in radiation as temperature reference standards for calibrating thermographic equipment. For example, this provides a perfect temperature calibration device. You can understand that this is raised to a particular temperature, and the characteristics of H are determined only by the temperature of the cavity. So this is how these things are constructed.

So, Max Planck, in the early 20th century, was able to describe the spectral distribution of radiation from a black body by means of this formula. So before this, there were many attempts, but nobody could actually model or provide a formula for the entire radiation that is emitted by a black body. Planck was the first to do that. Now, he did it by pure luck to a certain extent because this was more like a very complicated, intuitive guess, I should say. So if you look at it, you will find that there is a wavelength whose spectral distribution actually scales as wavelength to the power of minus five.

And it obviously has the h, which is Planck's constant, k, which is called Boltzmann's constant, and c, which is the velocity of light. So, the Planck formula, we will see on the next page what it does. This now has a temperature. You can see the temperature right there. So, for various temperatures, it will produce families of curves if you look at them carefully.

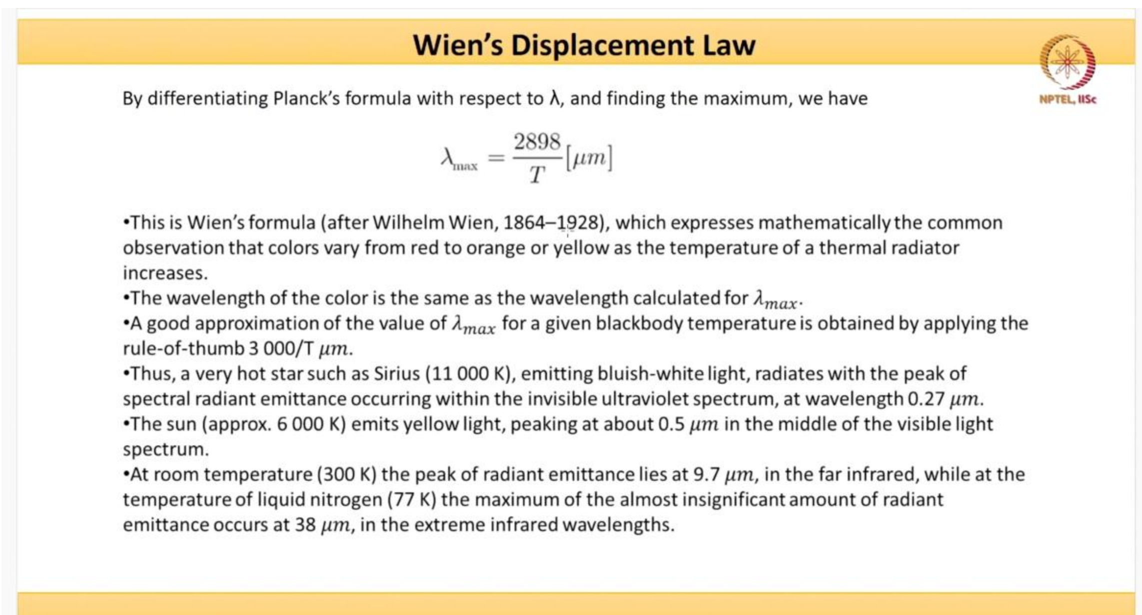
So for any particular curve, particularly the Planck curve, the spectral emittance is zero



at lambda equal to zero and then increases rapidly to a maximum at some wavelength, and then, after passing it again, it goes to zero at very long wavelengths. So this is how it actually functions. So, when λ is equal to 0, the spectral emittance is also equal to 0, but then it peaks and goes to 0 once again at very long wavelengths. You can realize that it comes from the λ to the power of minus five dependence. So this is how the black-body spectral radiant emittance, according to Planck's law, is plotted for various absolute temperatures.

So these are the temperatures: 500, 600, 700, 800, and 900. And these are the corresponding wavelengths. So as you can see, the curves are mostly peaks at a particular wavelength. And this wavelength shifts to higher wavelengths as we decrease the temperature. But it gets pushed to the lower wavelengths when the temperature goes higher and higher.

Right, so if you differentiate Planck's formula with respect to lambda and you want to find out the maximum, you have the $\lambda_{max} = \frac{2898}{T}\ [\mu m]$. So, in other words, as the temperature grows, the λ_{max} becomes smaller and smaller, which is exactly what you see over here. So 900 degrees Kelvin is where the wavelength is very, very short compared to something at, say, 600. And this varies as 1/T, as this particular formula shows. So this is called Wayne's formula, which expresses mathematically the common observations that colors vary from red to orange or yellow as the temperature of the thermal radiator increases.

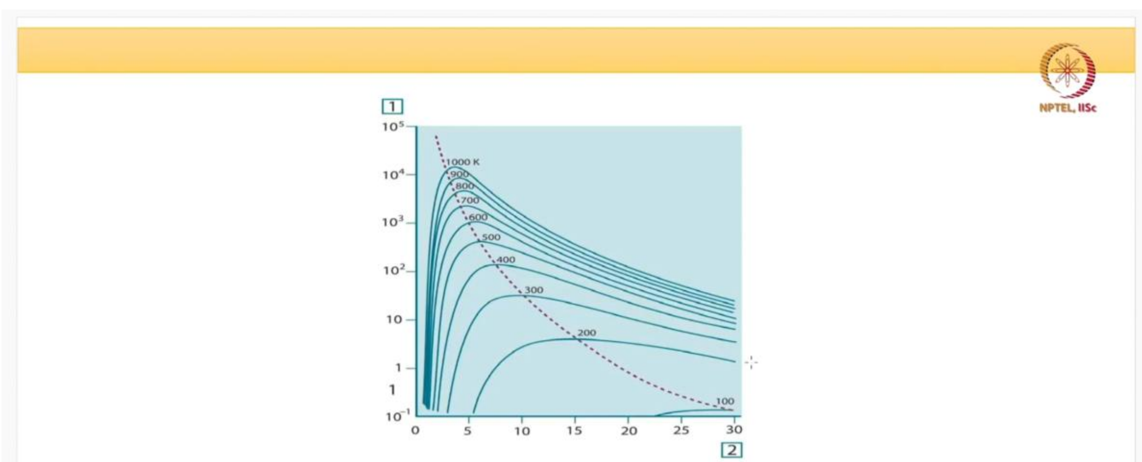


Because that is the wavelength that we observe. This is the wavelength at which the maximum spectral radiance occurs. So the wavelength of the color is the same as the wavelength of λ_{max}. You got this by now. So that's why we see this change in color from red to orange to yellow.

A good approximation of λ_{max} for a given blackbody temperature is obtained by applying the rule of thumb that this is 2898, which is difficult to calculate, about 3000 /T in micrometers. So a very hot star such as Sirius, which is 11,000 Kelvin, emits bluish-white light and radiates with the peak spectral radiance occurring somewhere in the invisible ultraviolet, which is the very low wavelength part, at around 0.27 micrometers, which is 270 nanometers. The sun, which is a much cooler star at 6000 Kelvin, emits light in the yellow and peaks at about 0.5 microns, which is in the middle of the visible light spectrum.

At room temperature, for example, which is 300 Kelvin, the peak radiant emittance lies around 9.7 micrometers, which is in the far infrared. So you can see why measuring temperature in the infrared becomes a useful thing. Because you are trying to measure not objects like stars, but rather objects that are around room temperature or a little bit higher than that. While the temperature of liquid nitrogen is 77 Kelvin and the maximum, almost insignificant amount of radiant emittance occurs at 38 micrometers, which is in the extreme infrared wavelength, also remember that this peak actually comes down drastically, so 300 Kelvin will be somewhere below 500, and you know 77 Kelvin will be minuscule.

So it is not just the maximum wavelength; it is also the intensity that varies quite a bit. So this is just one criterion, but the radiant emittance is quite low. But it lies in the extreme infrared wavelengths. So lower the temperature, the higher the wavelength. Essentially, that is what determines the maximum wavelength.



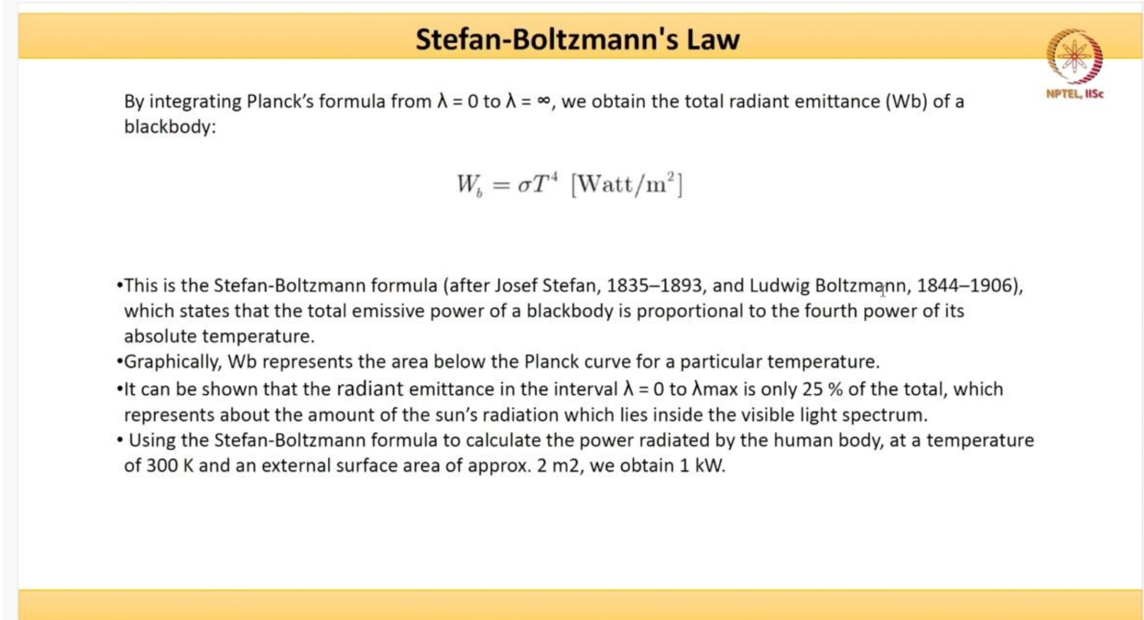
Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. 1: Spectral radiant emittance (W/cm2 (μm)); 2: Wavelength (μm).

So, uh, you know, if you plot this, it goes up to about 100 Kelvin. The liquid nitrogen is even lower than this, so that's why we get around 38. The Planckian curves are plotted on a semi-log plot from 100 to 1,000 Kelvin. So this is 1,000, this is 100, and the dotted line represents kind of the locus of the lambda max, so, uh. It represents the locus of the maximum radiant emittance at each temperature as described by Wien's displacement law.

So this is the spectral radiant emittance, and this is the wavelength. So this is how the curves are plotted. So this is the locus of emittance. Of the peak as it shifts, we are making a case for why infrared is important, so if you integrate Planck's formula all the way from zero to infinity in the wavelength space, we obtain the total radiant emittance of a black body, which is given as sigma t to the power of four. This is the Stefan-Boltzmann formula, named after Joseph Stefan and Ludwig Boltzmann.

Ludwig Boltzmann was a pioneer of statistical mechanics, which states that the total emissive power of a black body is proportional to the fourth power of its absolute temperature. So at very low temperatures, this will be low. As you increase the temperature, this increases drastically because of the fourth power dependence. So generally, this represents the area below a Planck curve for a particular temperature. So if you look at this particular curve, this will be the entire area under it.

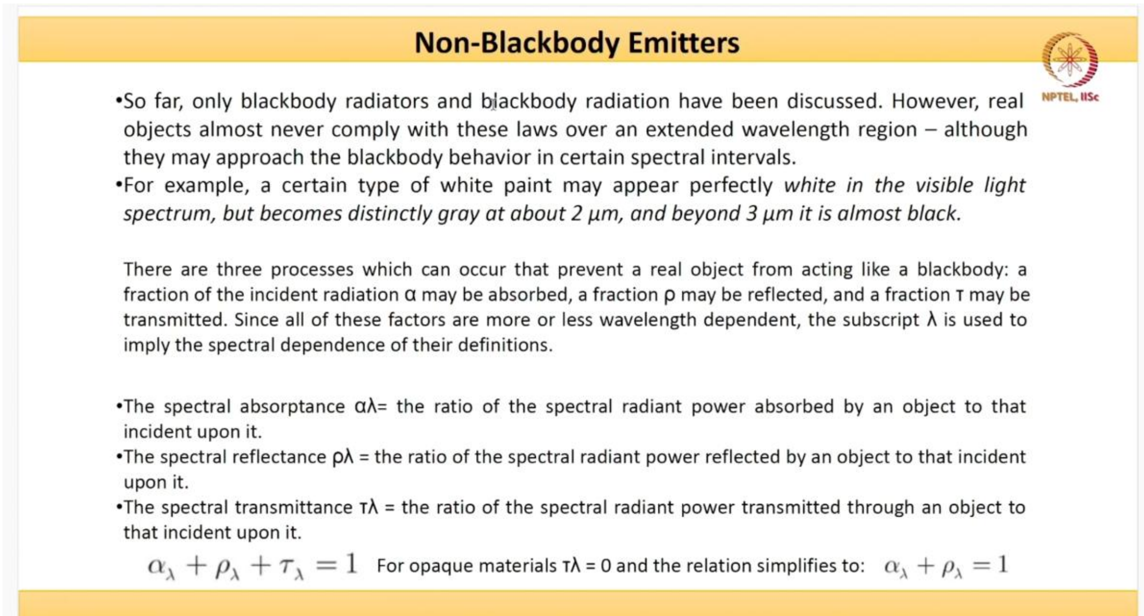
So you choose any curve; the area under the curve basically gives you Wb, which is the total radiant emittance, okay? So it can be shown that the radiant emittance in the interval from zero to lambda max is only 25% of the total, which represents the amount of the sun's radiation that lies within the visible spectrum. So it is only 25% because the curve, if you look at it, has a long tail. So if you look at it, the curve has got a long tail. The tail portion is quite long.



It's not symmetrical at all. So, that is what you get. Using the Stefan-Boltzmann formula to calculate the power radiated by the human body at a temperature of, say, 300 Kelvin, we find that with an external surface area of about two square meters, we obtain about one kilowatt. This is the power that is radiated by the human body. So, that is what it is.

So it comes from the Stefan-Boltzmann law. So non-blackbody emitters, so far we have considered only blackbody radiators and blackbody radiation; however, real objects almost never comply with these laws over an extended wavelength region. Also, they may approach the blackbody behavior in certain spectral intervals. For example, when a certain type of white paint may appear perfectly white in visible light, but becomes distinctly gray at about two microns and about three microns, it is almost black. So there are three processes that occur which prevent a real object from acting like a black body. So a fraction of the radiation alpha may be absorbed by the body, okay? A fraction, uh, you know, rho may be actually reflected, and a fraction, tau, may be actually transmitted.

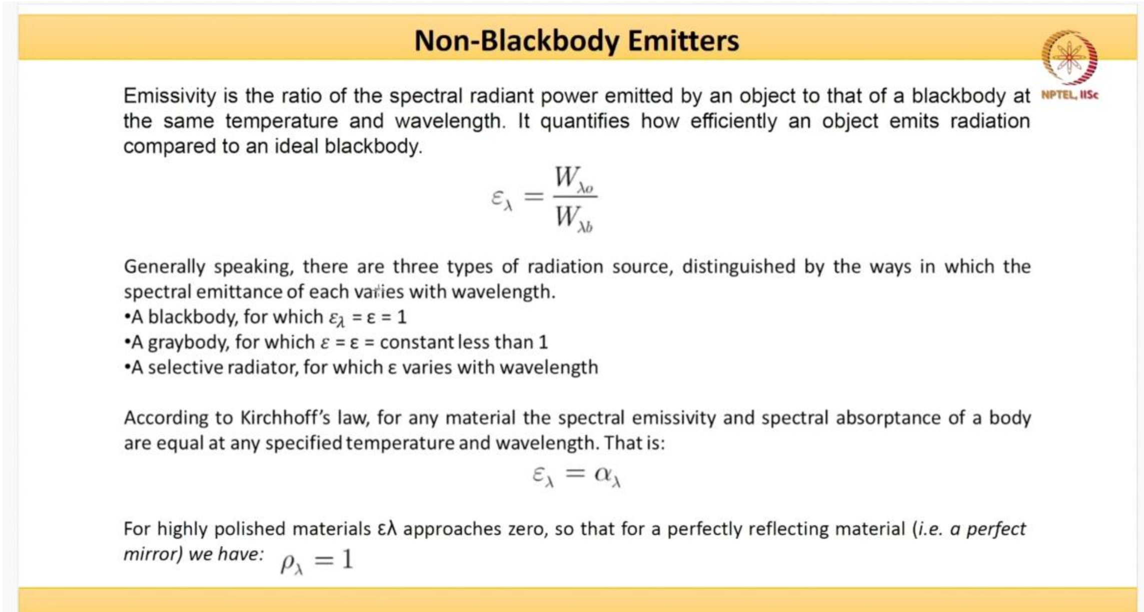
Since all these factors are more or less wavelength dependent, we use a subscript lambda to imply that there is a spectral dependence for their definitions. So, for example, the spectral absorbance, which is $\alpha(\lambda)$, is the ratio of the spectral power absorbed by a body to the total power that is incident on the body. Similarly, spectral reflectance, which is rho lambda, is a ratio of the spectral radiant power reflected by an object to that of the incident power upon it. The spectral transmittance, which is tau lambda, is the ratio of the spectral radiant power transmitted through an object to that incident upon it. So you can see if you sum the total of all these three terms, because they all have the total power in the denominator, this is going to be 1.



Okay, because we have essentially accounted for all the energy. For opaque materials, the transmittance is zero. So the relation simplifies to there being an absorptance and then a reflectance. So the sum total of these two could be equal to one at any particular wavelength, for example.

Okay. So, the emissivity is a ratio of the total spectral radiant power emitted by a body to that of a black body at the same temperature and wavelength. So the black body is like a reference point. The black body, which is at the same temperature and wavelength, when put in the denominator, means that the emissivity is the ratio of the spectral radiant power emitted by an object, any object, compared to that of a black body. Essentially, that's what it is. So lambda B actually designates a black body, and this designates any object.

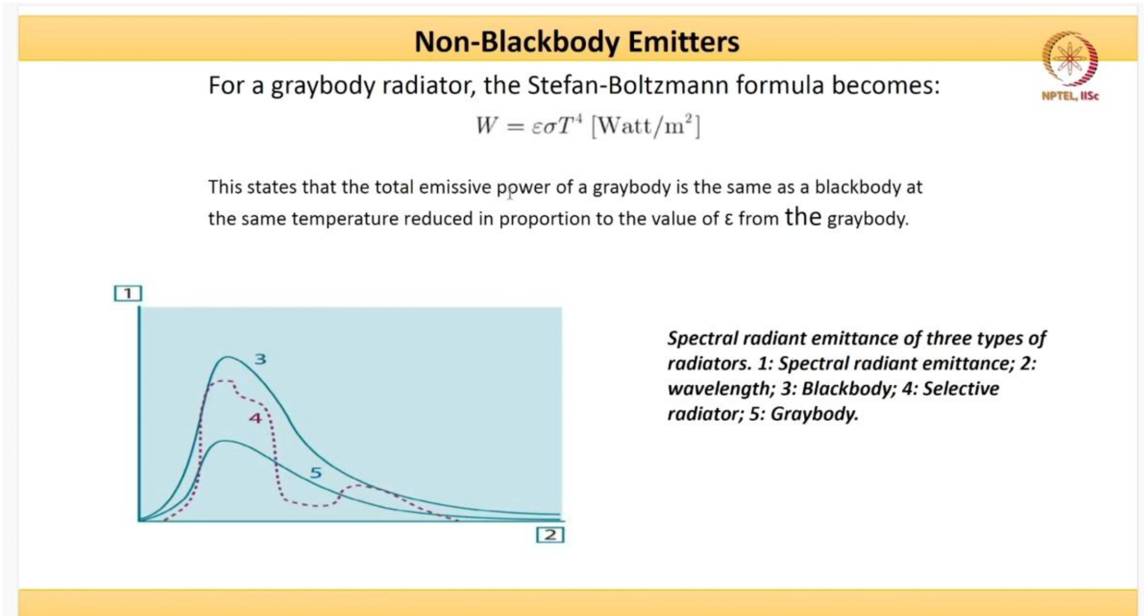
So, generally speaking, there are three types of radiation sources distinguished by the ways in which the spectral emittance of each varies with wavelength. A black body for which this is equal to one is. So the emissivity is equal to one at any given wavelength. A gray body for which this is a constant; the emissivity is a constant, but it is less than one. And a selective radiator, in which this is now a function of the wavelength.



In a gray body, we do not have wavelength dependence. It is constant across all wavelengths, but it is consistently a factor that is below a black body. A selective radiator, on the other hand, is one that emits at certain wavelengths, but that varies, you know, with the wavelength that you are concerned with. So many of the missiles and other things have selective radiators as well. According to Kirchhoff's law, for any material, the spectral emissivity and the spectral absorptance are equal at any specified temperature and wavelength, which means that emissivity E λ is equal to α λ. So, for highly polished material, this approach is ineffective.

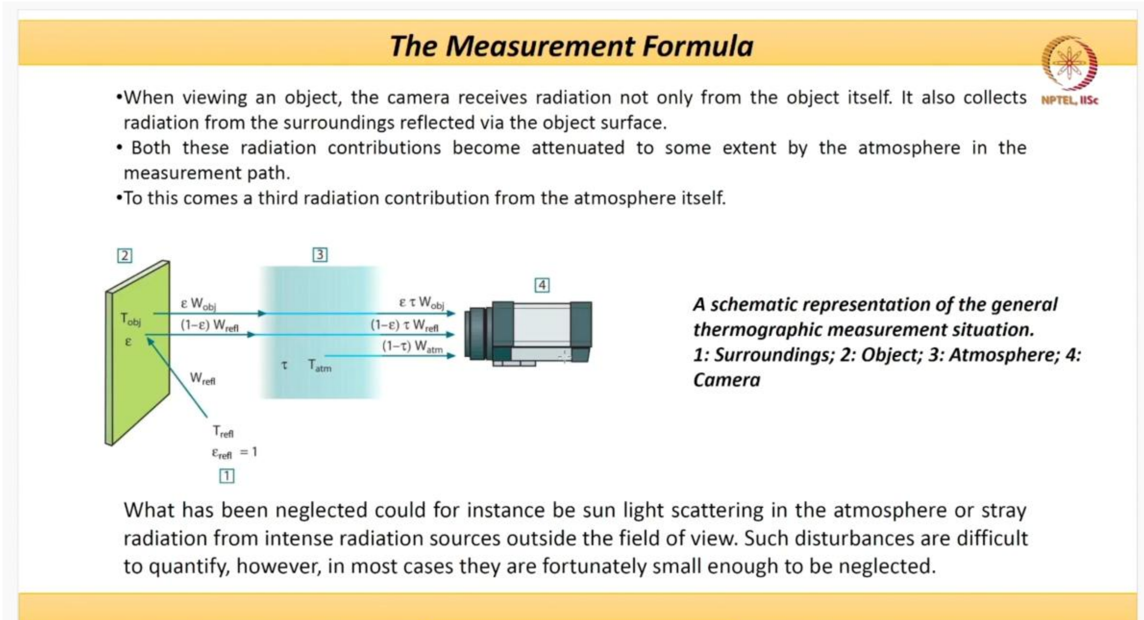
So, that is perfect for a reflecting material; we have rho lambda equal to 1. Like a mirror, a mirror is always reflecting. Okay, so this is almost equal to one. These are the stories of the black body emitters. So far, only black body emitters, and so, okay, in the wrong way.

Let us see for a gray body radiator. The Stefan-Boltzmann formula, therefore, is revised; you have this coefficient, you know, epsilon, which just sits on it and is the emissivity. This states that the total emissive power of a gray body is the same as that of a black body at the same temperature, reduced by a proportionality, scaled by a factor, which is epsilon. So this is, for example, a typical graph. So this is the spectral, again, this axis of the spectral radiant emittance.



And 2 is the wavelength. 3 is actually a perfect black body. 4 is a selective radiator. So you can see it has got a very weird shaped curve that means it has got a selective, you know, at certain wavelengths it emits, and at certain wavelengths its emission is decreased, and five is like a gray body where everywhere there is a scaling factor which upsets it from a true black body, so this is how this is actually working. So how do you measure this? When you view an object, the camera receives radiation not only from the object itself, but it also collects radiation from the surroundings reflected off the object's surface. Right? So when you are actually looking at an object with a camera, this is an object of interest.

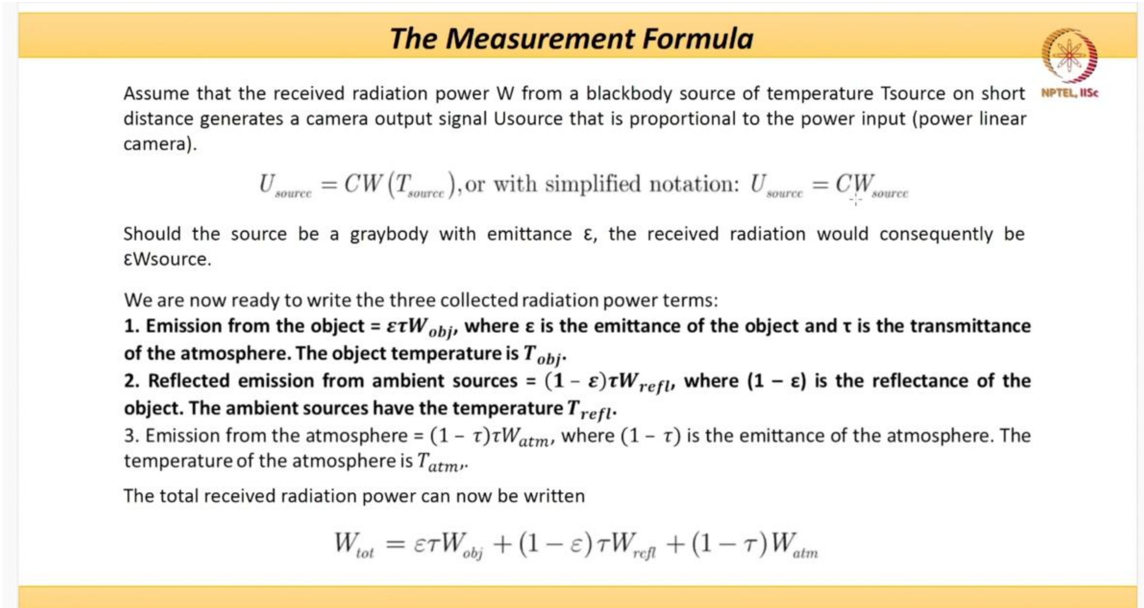
It is two. And this is the surrounding, which is basically three, which is the atmosphere. And four is your camera. And one is the surroundings, three is the atmosphere, four is the camera, so when you view an object, the camera receives not only the radiation from the object itself, but it also collects radiation from the surroundings reflected via the object's surface, so both these radiations become attenuated to some extent by the atmosphere because the atmosphere is in the measurement path, so it should absorb; it should also behave in the same way as a medium. So, to this, there comes a third radiation contribution from the atmosphere itself. Therefore, what has been neglected, for instance, will be sunlight scattering in the atmosphere or stray radiation from outside the field of view.



These disturbances are difficult to quantify, but in most cases, you should do the measurement in a setting where these things are minimal. Okay, so as you can see, this is the temperature of the object in which we are interested because that is what we want to measure. Okay, this temperature can have spatial variation as well. So now you have the atmosphere, and you have this very complicated, you know, budget. Okay, so part of it is actually, part of the radiation that is incident is actually emitted.

A part of it is actually reflected. So here, you can also see that it passes through the atmosphere. So it has a transmittance of the atmosphere, which is multiplied by this emissive. Power, and then you actually have a reflected part in the same way, and then the atmosphere also contributes something to the camera. So the camera receives radiation from three basic sources. One is from the object that is emitted, plus part of it is lost during transmission through the atmosphere, so it receives attenuated radiation.

And then it also receives some reflected radiation because that also passes through this medium, gets attenuated again, and reaches the camera.



Then the atmosphere itself actually contributes to a great extent because it can also radiate and contribute from the atmosphere. So we are neglecting sunlight, stray light, and any other radiation sources that may be present in the vicinity. So it collects radiation from all possible objects. Now, if you assume that the received radiation power W from a blackbody source of temperature T_{source} at a short distance generates a camera output signal U_{source} that is proportional to the power input.

So this is like a powerful linear camera. So the $U_{source} = CW_{source}$. So it generates an input, a camera signal that is proportional to the input power. Now, should the source be a gray body with emissivity epsilon, the received radiation would consequently be an CW_{source}. Because this is for a black body, if you replace it with a gray body, we know that this will be just ϵ. So the camera responds to the incident radiation or the radiation power from a black body in a linear fashion.

So whatever power it receives from the source, it is multiplied by a proportionality constant, and it is reflected in theU_{source}, which is the signal generated by the camera. Now this W_{source}, when it becomes a gray body with emittance ϵ, will consequently have the received radiation equal to epsilon times W_{source}. Right. So this is an important, you know, argument that this is a power linear kind of camera.

The more the source or the signal that is actually generated in the camera. OK, so just to make sure that you understand what we did in this particular class, we kind of knew about the blackbody and we knew about the different non-blackbody emitters. And we talked about the Stefan-Boltzmann law. And then we talked about the Planck curves.

Right. We talked about what the selective radiators are and what they will be. Okay, and we also saw examples of the selected radiators, and then we saw that when you try to measure the temperature of an object using this camera, which is like an IR camera, for example. It basically collects radiation from many sources. And we described what these factors are. And once that is done, we saw that if the camera is linear, our linear camera should respond to that incident radiation power in a linear fashion.

So we will stop at this moment for this class. And then in the next class, we are supposed to complete the IR thermometer.