Module 1 LIGHT SOURCES
Lecture 2. Electrical Incandescent Light Sources

For more than a century, incandescent lamps have been the mainstay of artificial lighting. Today, although discussions are under way related to the banning of this technology due to economic, energy, and environmental reasons, most of these lamps still play an important role. Many European countries have started a gradual banning of the incandescent lamp. This banning will initially include conventional incandescent lamps of high wattage but not reflector lamps and spot lights such as halogen lamps. So, an evaluation of this technology is still very relevant and remains important to the light sources professional. Incandescent light sources have a rich history of developments and discoveries, their own unique path of technological evolution and characteristics that make this type of lamp still desirable. At the end of this chapter, some new developments and ideas are discussed that could not only bring this classic technology back in favor but even lead to a new invention and the birth of a new novel light source technology. Incandescent lamps, as the name implies, are based on the phenomenon of incandescence. The principle does not differ from that of the blackbody, which radiates as it is being heated, starting from the infrared part of the spectrum and covering more and more of the visible spectrum as the temperature increases. Figures 1 and 2 show molten glass, which begins to radiate in the visible spectrum as the temperature increases.

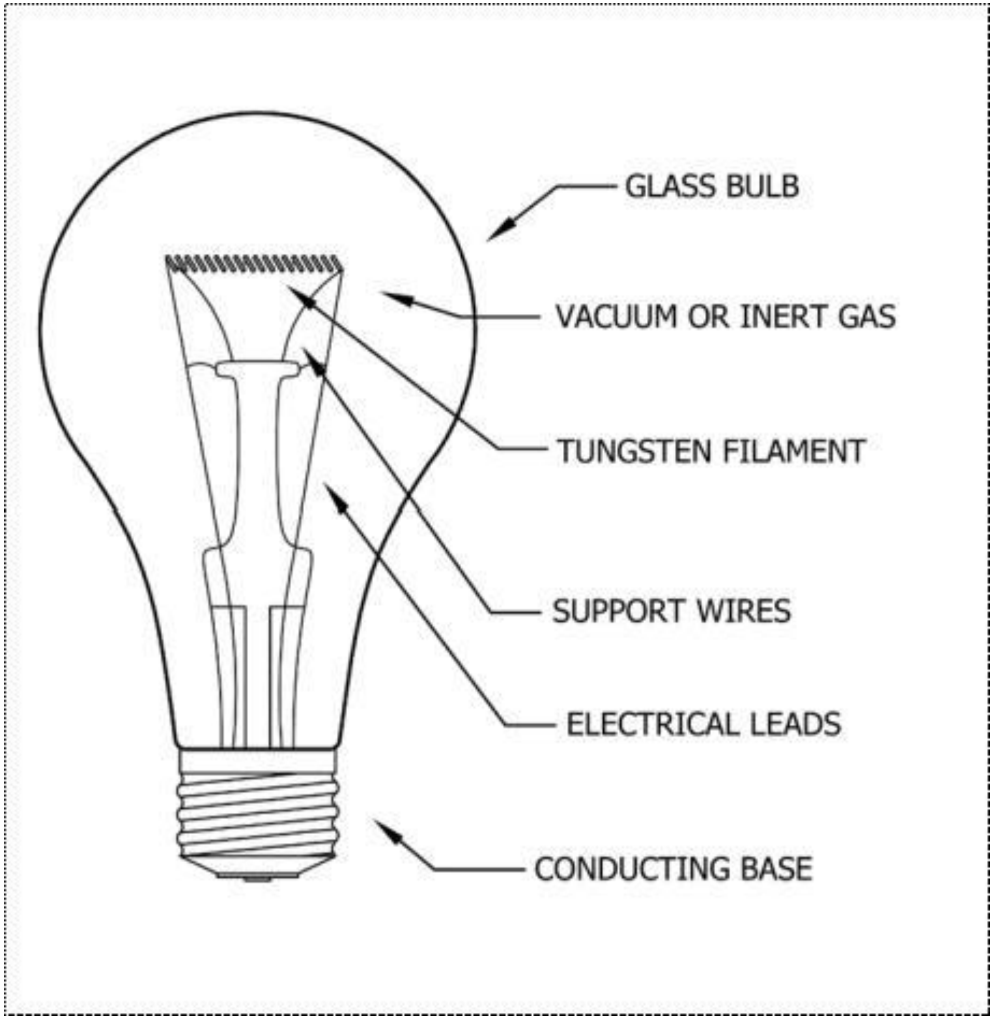
Visible light emissions from an incandescent material.

The heating here is provided by the electric current flowing through a solid material in the same way that the electric oven or kettle operates.
The flow of electricity through a filament increases its temperature as it resists the flow of electrons. The increase in temperature excites the electrons of the filament atoms to higher energy states, and as they return to their original states, they release this energy by emission of photons. Due to continuous blackbody-like emissions, incandescent lamps have excellent color rendering properties and are given an index of 100. The biggest proportion of the emitted radiation is, of course, in the infrared part of the spectrum and almost 90% of the electrical energy is lost as heat. With regard to the remaining 10% of the electrical energy, most of it is converted into red emissions, giving the source a warm white color. Incandescent lamps are therefore ideal for creating warm environments and reproducing the colors of the objects illuminated. They are not, however, an economic solution since their efficacy does not exceed 20 lm/W. A simple multiplication of the total power consumed by the lamp times the efficacy number gives us the maximum luminous flux in lumens. There are also lamps with colored glass bulbs that act as filters, thus giving off light of specific colors or different tones of white. Since the colored glass blocks undesired wavelengths in order to produce the desired color or decreases the amount of red that passes, the lamp becomes even less efficient.

2 Traditional Incandescent Lamps

The name that is linked with the invention of the electric lamp, and more specifically with the electric incandescent lamp, is that of Thomas Alva Edison, and 1879 (the year Edison filed his patent for a practical lamp with a carbon filament) is referred to as the birth year of this lamp. Thomas Edison was a inventor, and his name is connected with the incandescent lamp to such a degree due to some important contributions that led to the development and commercialization of this product. But the history of this lamp began decades before Edison’s time and is still being written today. This history includes many technologists and scientists from various countries who played important roles, while the decisive factor in the evolution and spread of the incandescent lamp was the distribution of electricity to greater parts of the population.

During the first attempts to convert electrical energy into light by means of incandescence in the early 19th century, scientists used platinum and also carbon filaments inside a glass bulb. The bulb was always under vacuum or contained a noble gas at low pressure in order to protect the filament from atmospheric oxygen, which accelerated the process of filament evaporation leading to the end of lamp life. After nearly a hundred years of testing, the incandescent lamp took its current form, which employs tungsten filaments. A photo with a detailed analysis of the anatomy of a modern conventional incandescent lamp can be seen in Figure 3. Figure 4 shows the variety of shapes and forms of incandescent lamps used today, while Figure 5 show incandescent lamps used with decorative luminaires for indoor lighting.

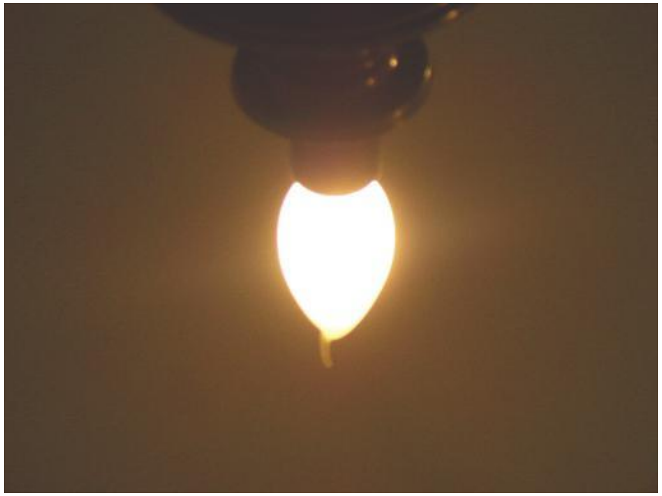


The anatomy of an incandescent lamp.

Various types of incandescent lamps

Filaments

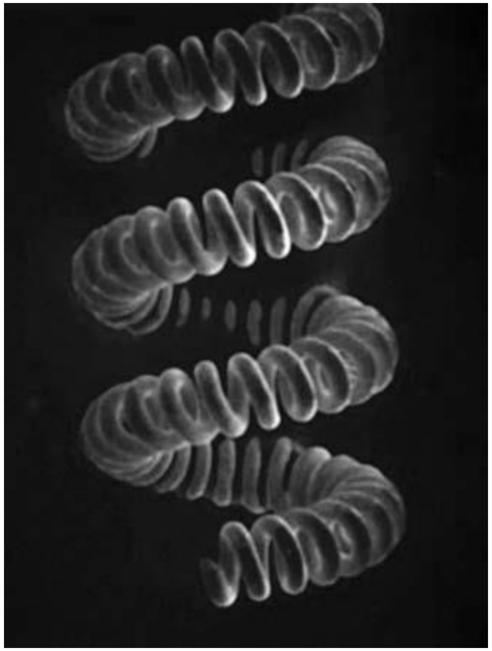
Incandescent lamps play key roles in indoor lighting such as home lighting due to the warm and comfortable white light they emit, the variety of shapes they come in, and their simple operation. The warm light (more red than blue in the emitted continuous spectrum) emitted by incandescent lamps used in a typical home can be seen in Figures. The choice of tungsten was made for the simple reason that it is a metal with a high melting point (3660 K), so it allows for the operation of lamps at relatively high filament temperatures (2800 K for a conventional incandescent lamp). Higher temperatures mean greater efficacy because a larger percentage of radiation will be in the visible, but also a decrease of the average lamp life.



Operating incandescent lamp emitting their characteristic warm white light.

Greater power means greater efficacy. For a 5 W lamp with 25 lm flux, the efficacy is about 5 lm/W, while for a 250 W lamp with a flux of 4000 lm, the efficacy is 20 lm/W. More support wires make the filament mechanically stronger but reduce the temperature to their thermal conductivity, so one has to choose between efficacy and lifetime. Other elements such as thorium, potassium, aluminum, and silicon or combinations of those may be added to improve strength. Some lamps have two filaments with three connections at their bases. The filaments share a common ground and can be used together or separately.

For these lamps, three numbers are given where the first two show the consumed power on each filament, and the third number is their sum. To improve the function of the lamp, the filament is in spiral form, as seen in Figure 9, which provides economy of space and heat. The power of the lamp depends on the operating voltage and the resistance of the filament as it is heated, and the resistance of the filament depends on the length and diameter. The value of the resistance of a cold filament is about 1/15 of that under operation. For a given lamp power, voltage, and temperature, the filament has a specific diameter and length. Small differences in the resistance value along the length of the filament, which are mainly due to differences in the diameter, result in the creation of hot spots. Tungsten is evaporated faster at these hot spots, leading to a dramatic decrease of the lifetime of the lamp. Figures 10 show incandescent filaments emitting the characteristic red glow or warm white light.



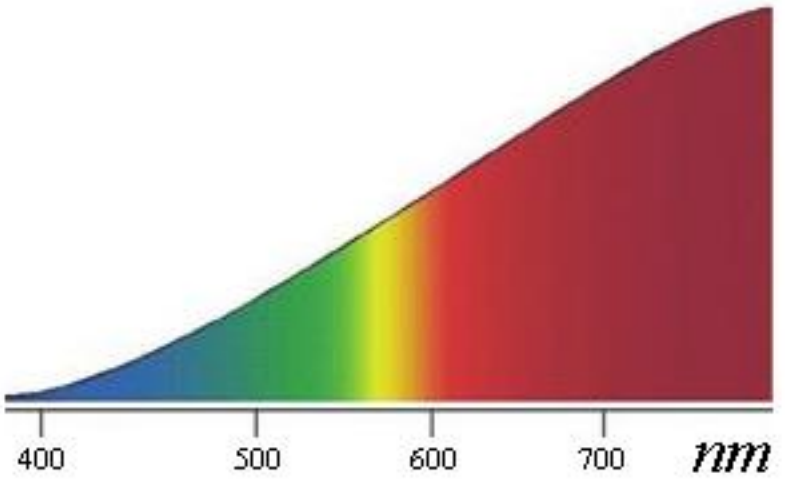
Incandescent tungsten filament.

A tungsten spiral filament.

There are no specifications for the glass of the bulb, but the supports of the filament are made of molybdenum and copper so that they melt in case which can provide the necessary insulation. The bases of the lamps are usually screw bases, known as Edison bases, having the code letter R followed by a number indicating the diameter in millimeters, or Bayonet bases, also having a number indicating the diameter and the code letter B. In case the bulb is not under vacuum, the gases contained are argon and nitrogen at low pressure. The main purpose of the inclusion of the gas is to reduce or control the burning of the filament, and a more specific reason for using nitrogen is to prevent formation of sparks. If there is a leak in the bulb, then the filament comes in contact with atmospheric air, producing tungsten oxides that solidify on the walls. If the bulb is under vacuum, then the blackening of the walls by the dark tungsten oxides is homogenous. In case the bulb contains a gas such as argon, then the oxides are transferred to the top of the bulb due to convection currents. The blackening of the bulb is the second most important factor, after filament vaporization, in reducing the light output. Water is probably the impurity that mostly leads to wall blackening, and the way it contributes toward that has been named the water cycle. Inside the bulb, the water molecules break up, creating molecules of oxygen and hydrogen. The oxygen molecules react with tungsten, and the tungsten oxides that result travel toward the cold spots of the bulb, where they deposit. The hydrogen molecules reach those spots and react with the oxides, resulting in tungsten being left on the wall and new water molecules ready to start a new cycle. Incandescent lamps are available in many shapes and sizes, while the applied voltage can be from 1.5 to 300 V. Some of the important advantages of the incandescent lamps are their low manufacturing cost, and they operate with both DC and AC current.

Advantages

Advantage of this type of lamp is that it functions as a simple resistor, so the connection voltage and current are proportional. This means that no additional gear, such as the ballast found with fluorescent lamps, is needed. The lamp accepts the voltage of any household outlet, except in the case of some special low-power lamps for which the voltage is limited to 12 V by means of an integrated transformer. Not using a transformer certainly has advantages, but the application of high voltage would mean that in order to keep the power constant the current would have to be reduced, so the filament would have to be made thinner and longer. These changes make both the lamp and the halogen cycle less efficient. The emitted spectrum of these lamps is continuous and covers the entire visible range, as shown in Figure.



The emission spectrum of an incandescent lamp is a continuous one.

This means that such light sources have a very good color rendering index, and it has been designated as 100. The largest percentage of radiation is in the infrared, so around 90% of the electric energy is lost in the form of heat. Regarding the 10% of visible radiation emitted, most of it is in red, giving the white color of the source a warm tone. Incandescent lamps are therefore ideal for creating cozy environments and for applications where very good reproduction of colors is needed. However, they are not an economic solution, since the efficacy is small (not exceeding 20 lm/W) and the average lifetime is around 1000 h. A simple multiplication of the total power of the lamp by the efficacy value gives the luminous flux in lumens.

Average rated lifetime is defined as the time duration beyond which, from an initially large number of lamps under the same construction and under controlled conditions, only 50% still function. Measurements of rated average lamp lifetimes are usually made by applying an operating cycle. For example, the lamps can be operated for 18 h a day and remain switched off for the other 6 h or 3 h on and 1 h off. Such measurements offer a good basis for comparisons on technical life and reliability, although the same figures are unlikely to be obtained in practice, because parameters such as supply voltage, operating temperature, absence of vibration, switching cycle, etc., will always be different.

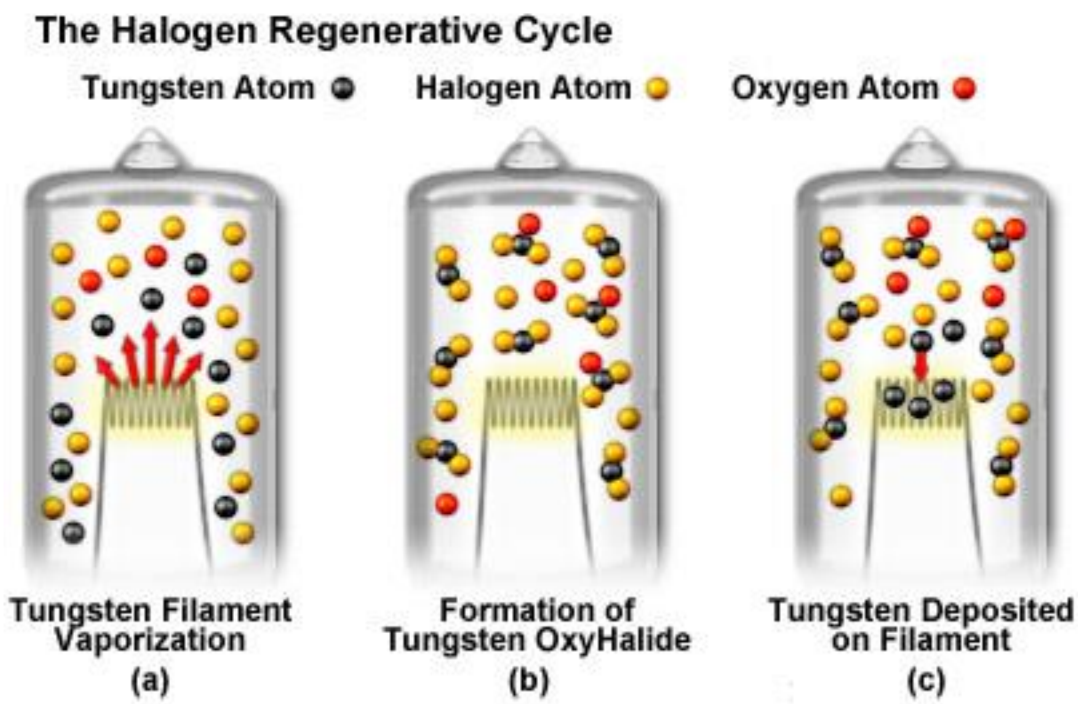
The service lamp life is another term and depends on the lifetime and lumens maintenance. Often, 70% service life or 80% service lifetime is used. This is the number of operating hours after which, by a combination of lamp failure and lumen reduction, the light level of an installation has dropped to 70% or 80% compared to the initial value.

Attention must, however, be paid to changes in the operating voltage because an increase in voltage will increase the brightness but will also reduce the lifetime, and vice versa. Many “long life” lamps are based on exactly this relationship. The temperature of the filament depends on the voltage, while the average life, current intensity, power, luminous flux, and efficiency depend on the filament temperature. Thus, all parameters have a relationship with voltage, which has been calculated as follows:

Current intensity (A) proportional to V
Mean lifetime (t) proportional to V
Power (W) proportional to V
Luminous flux (lm) proportional to V
Efficacy (lm/W) proportional to V

HALOGEN INCANDESCENT LAMPS

The halogen lamp is based on the same principle of incandescence, but the advantage it offers, compared to the ordinary/conventional incandescent lamp, is that its rated average lifetime is twice as long, exceeding 2000 h. The increase in the average lifetime of the halogen lamp compared to a conventional incandescent lamp is the result of a chemical balance that takes place within the lamp between the tungsten filament and halogen gas. The chemical balance is called the halogen cycle, and the gas used is bromine (or compounds of bromine), which replaced iodine, which was used in the first halogen lamps. It is because of the inclusion of iodine in the early lamps that the term iodine lamp is still used today. The halogen cycle works as follows: A tungsten atom that has escaped to the gas phase, due to the high temperature of the filament, interacts and bonds with a halogen atom, forming a compound that is not deposited at the cold point of the lamp, but continues to travel in the gaseous phase until it again reaches the filament, where the high temperature dissociates the compound; the tungsten atom returns to the filament and the halogen atom to the gas phase, ready to start a new cycle.



The halogen cycle

This cycle allows operation of the lamp at higher temperatures (3000–3500 K compared to 2800 K for conventional lamps) with higher luminous efficacy, intensity, and color temperature. Because of the higher temperatures required for the halogen cycle to take place, a harder glass such as quartz is used, and the dimensions of the lamp are smaller while the filament is thicker. By using a stronger glass, an increase of the gas pressure is also allowed, reducing further the vaporization of tungsten. Quartz is transparent to UV radiation below 300 nm (the usual soft glass is not transparent to electromagnetic waves with wavelengths shorter than 300 nm), so an additional filter is required if this radiation is not desirable. The additional filter also provides protection from glass fragments in case the bulb shatters. Another method of blocking ultraviolet radiation is by using specially doped quartz glass. A halogen lamp with no filter or special quartz glass can be used as a source of ultraviolet radiation in special scientific applications.

Atmospheres of tungsten-halogen lamps comprise an inert gas with about 0.1% to 1.0% of a halogen vapor added. The inert gas may be xenon, krypton, argon, or nitrogen, or a mixture of them having the highest atomic weight consistent with cost as well as arc resistance suitable to the lamp design and the operating voltage. The halogen vapor may be pure iodine (I_2) or a compound of iodine (e.g., CH_3I) or of bromine (e.g., HBr, CH_3Br, or CH_2Br_2). The minimum bulb wall temperature for operation of the halogen cycle is about 200°C for bromine, which is significantly lower than 250°C for iodine. Bromine is also colorless, while iodine has a very slight absorption in the yellow-green. Unlike conventional tungsten-filament lamps, which operate with an internal gas pressure of about one atmosphere, most tungsten-halogen lamps operate with an internal gas pressure of several atmospheres to reduce the rate of tungsten evaporation. The amount of halogen that is added is such that it balances the evaporation rate of tungsten at the nominal voltage. An increase in the voltage leads to higher rates of tungsten evaporation, rendering the amount of halogen insufficient and leading to wall blackening. If the applied voltage is lower than the nominal one, then the lamp temperature might be too low for the halogen cycle to work. At least in this second case, the evaporation rate of tungsten is low enough for blackening not to occur.

The halogen lamps compared to ordinary/conventional incandescent lamps have longer lifetimes (2000 h or more compared to 1000 h), higher color temperatures (3000–3500 K compared to 2800 K), and higher luminous efficacies (30 lm/W compared to 20 lm/W). A typical halogen incandescent lamp is shown in Figure.

Attention should be paid to avoid impurities on the surface of the lamp, especially fingerprints, which can cause damage to quartz under the hightemperature conditions. Lamps with reflectors (reflector and parabolic aluminized reflector) can be used as projection lamps for directional lighting.

Besides the known bases, halogen lamps have bases with a double contact carrying the code letter G followed by the size of the base in millimeters. All incandescent lamps produce large amounts of heat, which is emitted together with the visible light toward the desired direction after reflecting from the aluminum reflector of each lamp. If the aluminum reflector is replaced by a dichroic reflector, then we talk about a cool-beam lamp since at least 2/3 of the infrared radiation passes through the reflector and only the visible radiation and the remaining 1/3 of the reflected infrared radiation pass through the glass and are emitted in the desired direction. Therefore, the materials behind a cool-beam lamp, such as the base of the lamp where the largest proportion of the infrared radiation escapes to, should be able to withstand this exposure to thermal radiation.

Halogen lamps offer a compromise between conventional incandescent lamps and more efficient compact fluorescent lamps. Halogen lamps still have all the advantages offered by the incandescent technology such as instant start and peak brightness, complete control of dimming ratios, absence of harmful materials such as mercury, lifetime independent of switching frequency, etc.

On the other hand, they offer additional advantages compared to conventional incandescent lamps such as longer lifetimes for the same or greater efficacy and a higher color temperature. See Table for a complete comparison of various lamp characteristics between different lamp technologies.
Another development that further increases the luminous efficacy of halogen lamps is the Infrared Reflecting Coating (IRC). The inside wall of the lamp is covered with several dichroic coatings that allow the transmission of visible light but reflect part of the infrared radiation back to the filament, raising the temperature to the desired levels with less energy consumption. The efficiency increases by up to 40% compared to conventional halogen lamps and the average lifetime reaches up to 5000 h.

Various Parameter Values for Various Lamp Technologies

	Eå cacy lm/W	Power/W	Color Rendering Index	Average Lifetime/Hours
Incandescence	**20**	**15–1,000**	**100**	**1,000**
Halogen	**30**	**5–2,000**	**100**	**2,000–5,000**
Fluorescent	**55–120**	**5–125**	**55–99**	**10,000–25,000**
Inductive mercury	70–80	55–165	80	60,000–100,000
Sodium low pressure	200	35–180	0	20,000
Xenon DBD	30	20–150	85	100,000
Xenon high pressure	30	1,000–15,000	90	2,000
Sodium high pressure	50–150	35–1,000	25–85	10,000–30,000
High-pressure mercury	60	50–1,000	15–55	10,000–30,000
Very high-pressure mercury	60	100–200	60	10,000
Metal halide	70–100	35–2,000	70–90	10,000–20,000
Sulfur	95	1,500	80	60,000 (20,000 driver)
LEDs	**30**	**0.1–7**	**0–95**	**50,000–100,000**

Halogen lamps behave in a similar way as conventional incandescent lamps when the applied voltage differs from the specified one. Small increases of voltage lead to increases of luminous flux and efficacy but also to decreases of the average lifetime. Each parameter has a different proportionality value, but approximately a 10% increase in the voltage value leads to a similar increase of the flux and efficacy and a 50% decrease of the lifetime. In general, for the optimum operation of the lamp, it is best to avoid changes with regard to the specified values by the manufacturer, especially when it comes to the applied voltage. Attention should be paid to avoiding impurities on the bulb surface, particularly fingerprints, as they damage the quartz glass at high temperatures. To remove the impurities, the bulb must be cleaned with ethanol and dried before use.

All incandescent lamps produce large amounts of heat that is emitted along with the visible light in the chosen direction after reflecting off the aluminum reflector found in each lamp. If the aluminum reflector is replaced by a dichroic one, then we can have what we call a cool beam, since at least 2/3 of the infrared radiation pass through the reflector and only the remaining 1/3 and the visible light is reflected back toward the desired direction. In such cases, the materials behind a cool-beam lamp such as the base, where most of the infrared radiation escapes to, must be able to cope with this exposure to thermal radiation. Of course, the production of heat by incandescent lamps is not desirable in lighting, but in other applications where heat is required, these lamps have a significant advantage over other light source technologies. For example, proponents of the incandescent lamp claim that heat produced balances some of the energy that would otherwise be needed to heat a place in the winter.

The low cost of this kind of lamp is also a major advantage and must be taken into account when considering the phaseout of this technology, as it is the only one affordable for a large percentage of the world population. In poor communities, the introduction of other technologies would only be possible under strong or total financial coverage by governmental or private institutions.

Incandescent lamps have many applications in houses, shops, restaurants, and offices since they offer very good color rendering, and their variety of bulb geometries allows them to be used for decorative lighting.

Evaluation of the technology

Table shows some important lamp characteristics and which of the main three light source technologies offers them to the greatest degree. Although some important characteristics such as efficacy and lifetime are offered to a greater degree by discharge lamps (fluorescent, neon, sodium, etc.) and solid-state lighting (light-emitting diodes), incandescent lamps offer advantages in almost all other cases. Incandescent lamps offer instant start and peak brightness, total control of dimming ratios, absence of any harmful material such as mercury, and the fact that switching frequency does not affect their lifetimes. Other advantages of incandescent lamps are the low manufacturing cost, their ability to operate with both alternating and direct current, and the fact that extra gear is not required. Their color rendering index is exceptional, and this kind of lamp technology has found many applications such as the lighting of homes, restaurants, shops, and offices, while their variety of shapes and forms renders them ideal for decorative lighting. Lamps with reflectors (reflector and parabolic aluminized reflector) can also be used as spot lights. Although this technology of electrical light sources is the oldest one that penetrated the market, some of its characteristics remain unsurpassed by the other two technologies (discharges and SSL) and offers advantages that enable it to resist new developments and still play a prominent role.

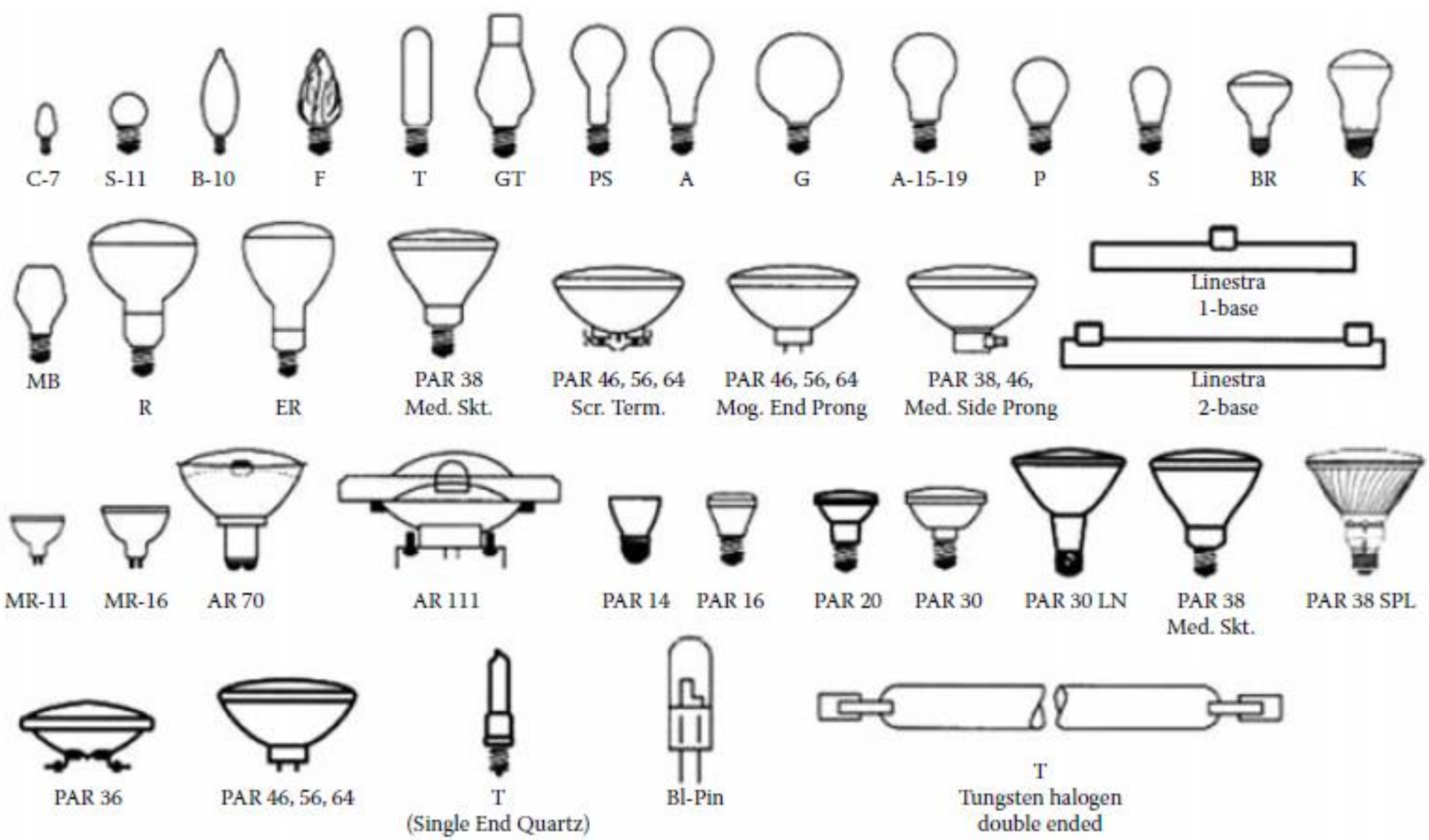
Research on incandescent lamps continues, with most of the work focused on the filament, as it is not only the source of light but also the key element that defines the lifetime of the source. It is expected, therefore, that novel filaments might lead to a new generation of incandescent lamps with significantly longer lifetimes and efficacies. The research is focusing currently on nanomaterials and, specifically, the use of carbon nanotubes, in the hope that the electrical characteristics of these new materials will offer advantages in a light source. Ideally, the material chosen will be one that manages to convert some of the heat produced into visible light and will also offer mechanical strength and durability. Here are some recent published papers on the subject.

Comparison of Incandescent Lamp Technology with the other Two Main Technologies of Plasma- and Diode-Based Lamps

	Incandescent-Halogen	Electrical Discharges	LEDs
Color rendering index	√		
Range of color temperatures		√	
Instant start	√		
Lifetime			√
Switching frequency	√		
Efficacy		√	
Cost	√		
Dimming	√		
Operation (AC–DC)	√		
Absence of extra gear	√		
Toxic/harmful materials	√		
Variety of shapes—forms	√		
Range of power—voltage	√		

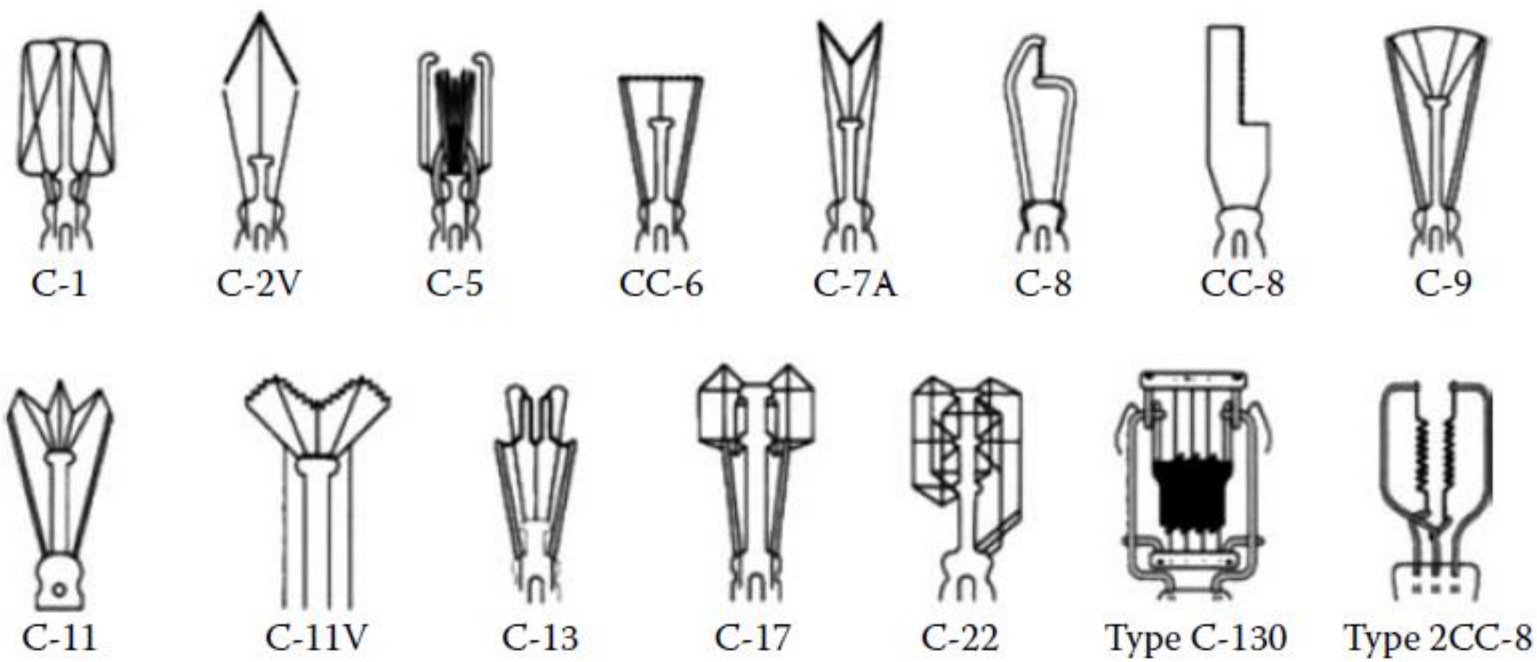
Codes/Product Categorization

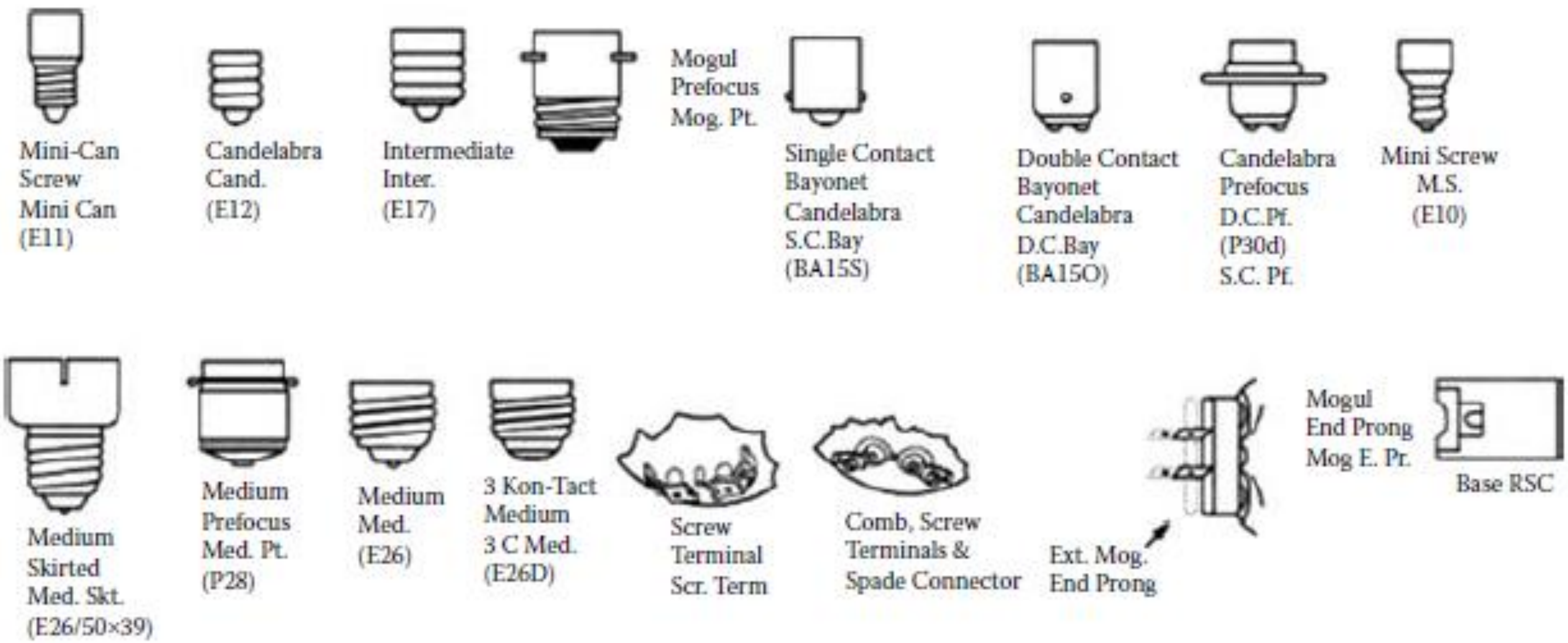
Incandescent lamps are described by various codes that give information regarding their type, base, and filament, as shown in Figure.
Type of lamp: A letter (or more) indicates the shape of the lamp, and a number (or more) shows the maximum diameter of the bulb in eighths of an inch.



Filament type: The letters in front of the code indicate whether the filament is **S**traight, **C**oiled, or a **C**oiled **C**oil, while the number indicates the arrangement of the support wires. Figure 3.21 shows various types of incandescent lamp filaments.

Bases: A letter indicates the kind of base (Edison, Bayonet, G, or GY for Pins), and a number shows the maximum diameter of the base or the distance between the pins in eighths of an inch. Figure shows various types of incandescent lamp bases.





Types of incandescent lamp bases.