FILAMENT LAMPS

Electric filament lamps are light sources containing a solid body that is brought to a high enough temperature that some fraction (typically ~10%) of the emitted radiation is in the visible portion of the spectrum. The emitting body is generally in the form of a coil or coiled-coil and is referred to as a filament. Light sources incorporating such filaments are often referred to as incandescent lamps, although halogen lamps employ the same type of filaments. Many different designs of incandescent lamps exist in the market today, each satisfying a particular market niche. Wattages range from 1 to several thousand, though the most common are the 60 W, 75 W, and 100 W lamps with the screw base, which is often referred to as the Edison base. In the industry, these are also called A-line in North America, or the older term GLS, for General Lamp Service. This paper discusses the science and general design considerations of incandescent and halogen lamp types. Even though the bulk of the discussion is valid for both, a separate section will focus on the issues of specific importance to halogen lamps.

The first commercially successful electric incandescent lamp, made by Thomas Edison in 1879, generated light by passing an electric current through a thin strand of carbon. The initial carbon filament lamp marketed by Edison operated at around 110 V, consumed about 80 W, lasted about 600 h, and provided light at an efficiency approximately 11 times below that for lamps of similar wattage and life today. Lamp efficiencies are referred to as efficacy, and the units (discussed later in more detail) are given in lumens per watt of input power, where the lumen is a measure of the visible light output. To improve on efficacy and life, a higher melting point material capable of being formed easily into a compact filament had to be found.

In 1908, William Coolidge working at the GE Research Laboratory developed the method for converting tungsten, a brittle metal with a melting point of 3650 K, into a ductile material capable of being formed into a practical filament for a lamp. By 1911, the first lamps made with ductile tungsten filaments were introduced into the market, and today tungsten is used almost exclusively as the material of choice for commercial use. The next major advancement was made in 1913. It actually paved the way for the eventual development of the halogen lamp in the late 1950s. This was the discovery by Irving Langmuir (also at the GE labs) that the addition of a nonreactive gas such as nitrogen or argon can retard tungsten evaporation, thus extending life and enabling higher temperature operation. At the same time, coiling the tungsten filament would result in reducing the power that went to heat the gas as well as enabling the easy fit of a long thin wire filament into a small bulb envelope. The net result was a lamp with extended life and/or higher efficacy (i.e., more light per input power). Figure 1 shows the historical trend toward increased efficacy for filament lamps expending 60 W at 120 V with a life of 1000 h (one of the most common lamp types of the A-line series). As we will see, each new development (use of tungsten, gas, and the related requirement for coiling) which enabled higher temperature operation and resulted in higher luminous efficacy, needed to be accomplished without sacrificing the life of the filament as a result of market considerations. For further discussion on the history of the incandescent lamp including the development of ductile tungsten, see Refs. 1–4.

SCIENCE OF INCANDESCENCE

Blackbody Characteristics

When radiation encounters an object three things can occur. The radiation can be transmitted through the body, be reflected from the body, or be absorbed by the body. A material that perfectly transmits all radiation impinging on it is called *colorless,* that which reflects all radiation is called *white,* and that which absorbs all radiation is called *black.* No physical materials are perfect representatives, but air is nearly colorless, chalk is nearly white, and carbon black is nearly black.

Mathematically, the radiant emission properties of incandescent solid materials can be quite well represented by idealizing the material as a blackbody, where deviations from the ideal are dealt with by employing the concept of emissivity. A *blackbody* is defined as an ideal body of uniform temperature

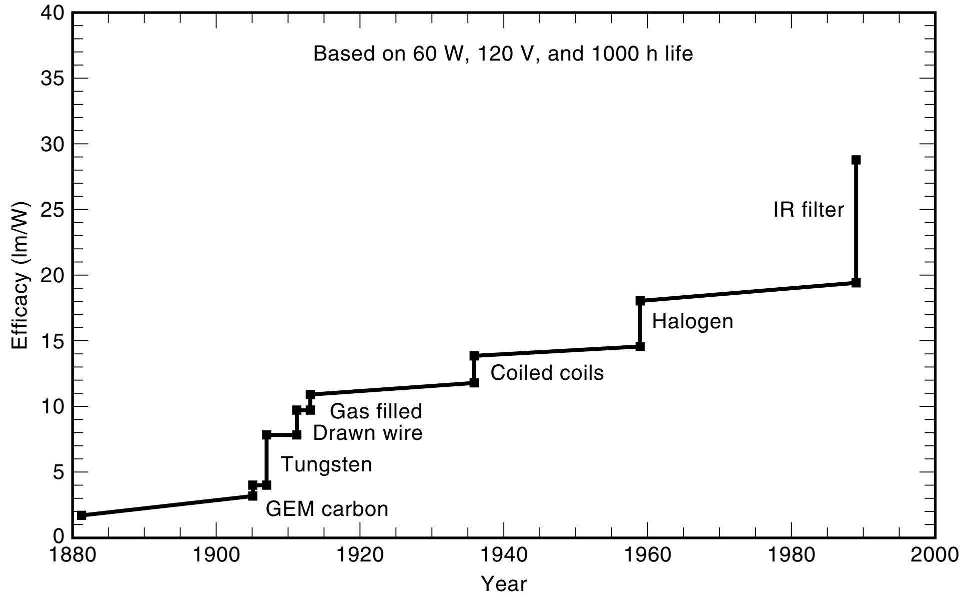

Figure 1. Historical efficacy of incandescent lamps.

that perfectly absorbs all radiation incident upon it. By Kirchhoff's Law, the temperature radiation of a body is at any temperature and any frequency the same percentage of blackbody radiation as the absorbed radiation of the body is of the total impinging radiation. Thus, since a blackbody absorbs perfectly it also, for equal areas, radiates more total power and more power at any given wavelength than any other source operating at the same temperature. The unique feature of the blackbody is that its radiation characteristics may be specified solely by the absolute temperature.

Radiative Emission

Max Planck, in about 1900, derived an equation for the spectral distribution of radiation from a blackbody, by using the second law of thermodynamics and assuming that the energy levels available for the radiation are quantized. This equation fit the known spectral measurements extremely well and was a great improvement over earlier theoretical predictions. Planck's equation, in terms of wavelength, for the spectral radiant emittance $M_{e,\lambda}$ (i.e., the emitted power per unit area per unit wavelength), is

$$M_{e,\lambda}(T) = \frac{c_1}{\lambda^5(\exp[c_2/\lambda T] - 1)}\,\mathrm{W \cdot m^{-3}} \tag{1}$$

where the latest values for the constants are

$$c_1 = 2\pi hc^2 = 3.7415 \times 10^{-16}\,\mathrm{W \cdot m^2} \tag{2a}$$

$$c_2 = hc/k = 1.4388 \times 10^{-2}\,\text{m-K} = 14,388\,\mu\mathrm{m \cdot K} \tag{2b}$$

In these expressions, h is Planck's constant (6.6256×10^{-34} J · s), k is Boltzmann's constant (1.38×10^{-23} J · K^{-1}), and c is the speed of light (3.0×10^{8} m · s^{-1}). Figure 2 shows the spectral emittance distribution for temperatures between 2000 K and 3500 K, every 500 K, plotted in log-log format. This temperature range encloses all known tungsten-based incandescent lamps. It is clear from Fig. 2 that higher temperatures would be desirable to put more of the emitted power in the visible range. As will shortly be shown mathematically, the fraction of radiated power in the middle of the visible region reaches a maximum at around 6500 K. This, of course, is about the temperature of the sun, which is also nearly a blackbody radiator.

Integrating Eq. (1) over all wavelengths, we find that the total emittance of a blackbody is proportional to the fourth power of the temperature (Stefan–Boltzmann Law):

$$M_e^b = \sigma T^4\,\mathrm{W \cdot m^{-2}} \tag{3}$$

where

$$\sigma = 2\pi^5 k^4/(15h^3c^2) = 5.6697 \times 10^{-8}\,\mathrm{W \cdot m^{-2} \cdot K^{-4}}$$

is known as the Stefan–Boltzmann constant. In this expression, the superscript b (sometimes omitted unless specifically needed for clarity) simply denotes a blackbody. Thus from Fig. 2, we note that the area under each curve is proportional to the fourth power of the temperature.

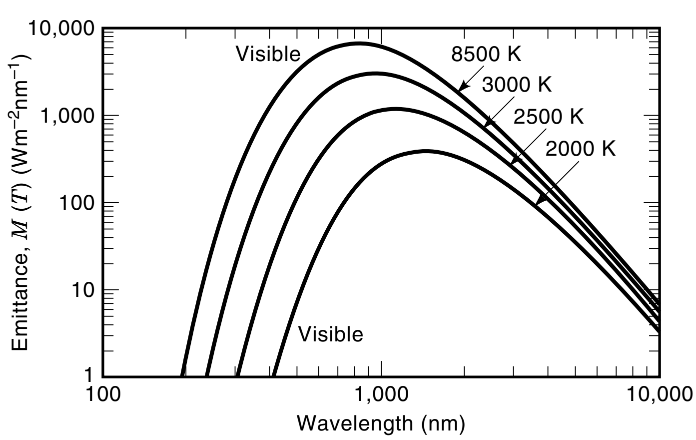

Figure 2. Spectral radiant emittance of a blackbody with temperature as a parameter.

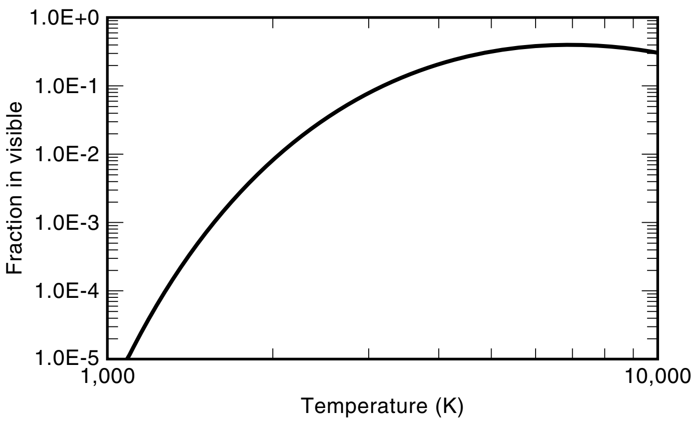

Figure 3. Fraction of blackbody irradiance in visible as a function of temperature.

Blackbodies are, by definition, perfectly diffuse. Thus the radiance (i.e., the emitted power per unit area per unit solid angle) is equal to the emittance divided by π, or

$$L_e^b = M_e^b/\pi \tag{4}$$

By differentiating Eq. (1) with respect to λ and equating the derivative to zero, we find that the maximum spectral emittance occurs at

$$\lambda_m = 2897.8/T\ \mu\text{m} \tag{5}$$

Equation (5) is called Wien's Law. Substituting this expression for λ_m into Eq. (1), we find the peak spectral emittance to be

$$M_e(\lambda_m) = 1.2867 \times 10^{-5} T^5\ \text{W/m}^3 \tag{6}$$

In Fig. 2, this implies that the line, not shown, joining the peaks of the emittance for each temperature in the log-log scale is a straight line, and furthermore that the peak values increase proportionally to the temperature to the fifth power.

It is also clear from Fig. 2 that the emitted power at any given wavelength below the maximum emitted power increases more and more rapidly with temperature as the wavelength decreases. Thus for temperatures between 2500 K and 3000 K, typical of ordinary general lighting lamps, the emitted power in the middle of the visible increases at about the ninth power of the temperature.

By integrating Eq. (1) from 400 nm to 750 nm, the approximate radiant emittance of a blackbody in the visible region of the spectrum can be obtained. Dividing this integral by the total emittance [i.e., Eq. (3)], we obtain the fraction of the emittance (emitted power) in the visible region. Figure 3 shows this fraction as a function of temperature between 1000 K and 10,000 K. Note that between 2500 K and 3500 K the visible emittance fraction increases from about 5% to 20% of the total radiated power. The peak emittance value is slightly over 40% and occurs around 6900 K.

Luminous Efficacy of a Blackbody

The luminous efficacy of a blackbody is equal to the ratio of its total luminous emittance (flux) to its total radiant emittance (flux). This value is obtained in a similar manner to that for the fraction in the visible shown in Fig. 3. The difference is that the luminous flux is obtained by integrating the product of the spectral emittance by the eye sensitivity curve V_λ. The eye sensitivity curve, not shown, is a near bell-shaped curve peaking at a value of one at 555 nm and going to approximately zero at 380 nm and 760 nm, respectively. Further, a scaling factor of 683 is used to define the lumen output per watt at 555 nm. The total radiant flux is given by Eq. (3). Thus the equation for the luminous efficacy is

$$\eta_b = \frac{683 \int_{380}^{760} V_\lambda M_{e,\lambda} d\lambda}{\sigma T^4} \tag{7}$$

The luminous efficacy is plotted as a function of temperature in Fig. 4. Here we show only values above 1 lm/W of input power. Note that the lumen efficacy of a blackbody is around 20 lm/W at 3000 K and peaks at a value of about 98 lm/W at a temperature of around 6500 K. As we will see, the luminous efficacy of tungsten is significantly higher than that of a blackbody.

Radiation from Actual Surfaces

Emissivity. As was mentioned earlier, perfect blackbody materials do not exist in nature, even though some such as carbon come close to exhibiting blackbody characteristics. In general, however, the radiation properties of most material surfaces can be described by using the blackbody radiation laws in conjunction with the material surface's *emissivity*. Emissivity is a measure of how closely the flux radiated from a given material approaches that of a blackbody. The total emissivity is defined as the ratio of the radiant emittance of the real surface to that of a blackbody. In other words,

$$\epsilon = M/M^b \tag{8}$$

where, as earlier, the b superscript denotes blackbody.

The emissivity of a given surface can vary with the wavelength, the angle of observation, and the temperature. Thus the *spectral emissivity* ϵ_λ is defined by

$$\epsilon_\lambda(T) = M_\lambda(T)/M_\lambda^b(T) \tag{9}$$

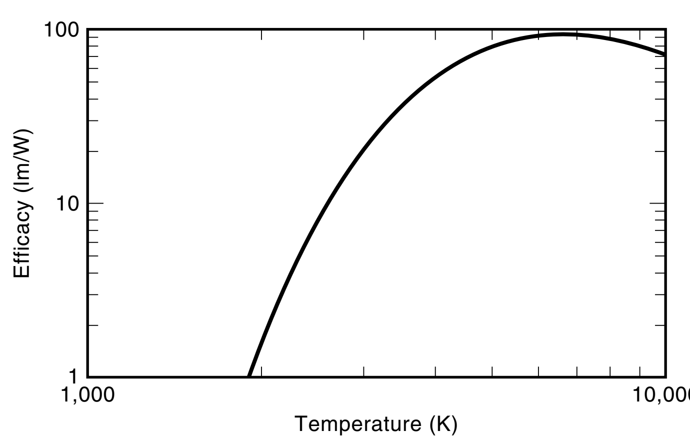

Figure 4. Lumen efficacy of a blackbody as a function of temperature.

Directional spectral emissivity $\epsilon_\lambda(\varphi, \phi)$ is defined by

$$\epsilon_\lambda(\varphi, \phi) = L_\lambda(\varphi, \phi)/L^{\mathrm{b}}_\lambda(\varphi, \phi) \tag{10}$$

where $L_\lambda(\varphi, \phi)$ is the spectral radiance of the surface element in the direction (φ, ϕ), and $L^{\mathrm{b}}_\lambda(\varphi, \phi)$ is the spectral radiance of a blackbody at the same temperature. In this context, ϵ may be referred to as hemispherical total emissivity, ϵ_λ as hemispherical spectral emissivity, and $\epsilon(\varphi, \phi)$ as directional total emissivity. They are all related to the directional spectral emissivity above by appropriate integrations over wavelength and/or angles.

If the material is uniformly diffuse, the directional emissivity follows that of a blackbody (i.e., $\epsilon \propto \cos\varphi$ at all angles and wavelengths). If the material surface is gray, the spectral emissivity is independent of wavelength.

The normal spectral emissivity of tungsten, based on data from Ref. 5, is shown in Fig. 5. Note that the emissivity changes quite dramatically with wavelength and also with temperature. Note, interestingly, that the emissivity is independent of temperature at around 1300 nm. The directional emissivity of tungsten also deviates from a blackbody such that the total emissivity is a few percent higher than is calculated based on a diffuse or Lambertian radiator. Specifically, note from Fig. 5 that the emissivity of tungsten is higher in the visible portion of the spectrum than in the infrared at all temperatures (i.e., tungsten is a selective radiator enhanced for visible radiation). This implies that the efficacy of radiation from tungsten is higher than that of a blackbody.

The hemispherical or total emissivity of tungsten at a given temperature is theoretically obtained by the ratio of the integral of the product of the spectral emissivity and the Planck function over all wavelengths at that temperature divided by the total radiant emittance, σT^4. Because spectral emissivity values are not well known in the infrared nor are directional emissivities known in general, the total emissivity as a function of temperature is empirically determined. One way to do this is to measure the total power used to resistively heat a long tungsten wire of known surface area up to a known (measured) temperature. Such a measurement would be done in vacuum to ensure no cooling and power loss to the gas, and with long enough wire so that the end losses are minimal. The result is shown in Fig. 6. Also shown is the average visible emissivity obtained similarly to the total emissivity, except that the integration is only over the wavelengths in the visible region.

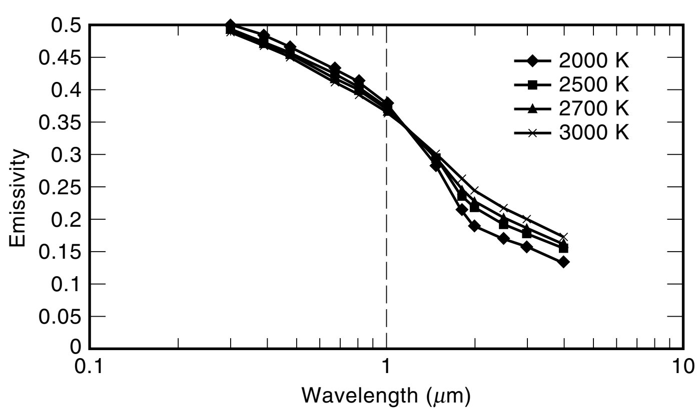

Figure 5. Normal spectral emissivity of tungsten for several temperature values.

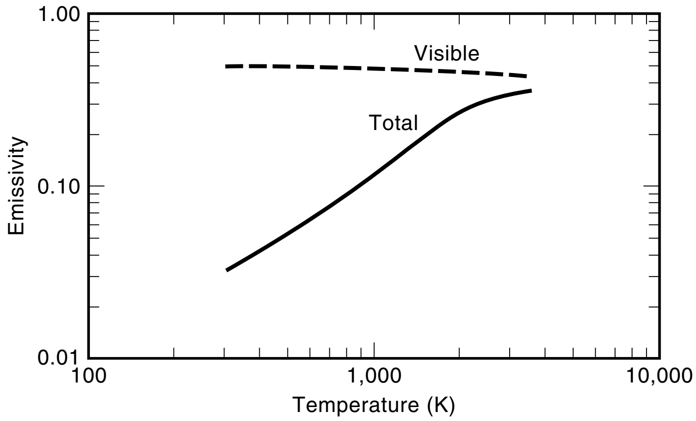

Figure 6. Total and average visible emissivity of tungsten versus temperature.

A measure of the tungsten selectivity is the ratio of the average spectral emissivity in the visible region to the total hemispherical emissivity. This ratio at any given temperature can be deduced from the plots of the average visible and total hemispherical emissivities plotted in Fig. 6. The spectral selectivity is very high at low temperatures; unfortunately this is not of much significance because the total lumen output is also very low.

One more comment needs to be made on the shape of the spectral emissivity curve in Fig. 5. Note that for every temperature shown, the emissivity is higher in the blue region of the spectrum (around 450 nm) than in the red (around 650 nm). This implies that the *color* or *distribution* temperature of tungsten will be higher than the actual surface temperature. One way to think of color temperature for an emissive body is as follows. It is the virtual temperature of a blackbody that matches the shape of the emissive body's emittance curve in the visible region. Thus at a material or true temperature of 2800 K, the color temperature of tungsten wire will be about 60 K higher, even though the absolute emission is higher overall for the blackbody. Coiling the wire tends to make the radiation emitted more like a blackbody as a result of internal reflections on the coil, so the difference between the color and material temperature decreases. For double-coiled filaments, which are typical in common household (A-line) lamps, the average color temperature exceeds the true temperature by about 40 K at 2800 K.

Another related concept is that of *brightness* temperature at a particular wavelength (generally 665 nm, the value used by most optical pyrometers). This is the temperature of a blackbody that gives the same absolute emittance at 665 nm as the material in question, in our case tungsten. The brightness or luminance temperature of tungsten is significantly lower (about 275 K at 2800 K at 665 nm) than the true temperature. This, of course, is a direct consequence of tungsten's spectral emissivity being below unity ($\epsilon = 0.419$ at 2800 K at 665 nm).

Tungsten Efficacy. The spectral selectivity of tungsten (i.e., the fact that the emissivity in the visible is higher than that in the infrared) is an important contributor to the efficacy that can be obtained at a given temperature. Adding the spectral emissivity term to the numerator of Eq. (7) and the total emissivity to the denominator, the luminous efficacy is given by

$$\eta_\epsilon = \frac{683 \int_{380}^{760} \epsilon_\lambda V_\lambda M^{\mathrm{b}}_{\mathrm{e},\lambda} d\lambda}{\epsilon \sigma T^4} \ \mathrm{lm/W} \qquad (11)$$

A plot of the radiant efficacy of tungsten compared to that of a blackbody is shown in Fig. 7. Note that at a temperature of 3000 K the radiant efficacy of tungsten wire is about 27 lm/W, whereas that of a blackbody is about 21 lm/W, an increase of about 30% resulting from the spectral selectivity of tungsten. Coiling the tungsten, as is the practice in all lamps, reduces the selectivity somewhat because the coil tends to behave more like a blackbody.

Mass and Heat Loss in a Gas

Operating a tungsten wire at high temperature in a vacuum leads to evaporation of tungsten atoms from the surface. The evaporation rate is a very strong function of temperature, being proportional to about the 36th power at a temperature of 2800 K. Measurements show (6) that the vapor pressure or evaporation rate of tungsten is well described by the Arrhenius-type equation, where

$$m = 3.8 \times 10^8 \exp^{-\Delta H^\circ/RT} \ \mathrm{g \cdot cm^{-2} \cdot s^{-1}} \qquad (12)$$

where $\Delta H/R = 102{,}300$ K.

The evaporation rate changes by about a factor of 3 every 100°C when the temperature is between 2700 K and 2900 K. At a temperature of 2800 K, the evaporation rate, using Eq. (12) is about $13 \times 10^{-9}\ \mathrm{g \cdot cm^{-2} \cdot s^{-1}}$.

When gas is added to surround the filament in the lamp, the tungsten evaporating from the surface encounters these gas atoms. The resulting collisions of tungsten with the gas cause the majority of evaporated tungsten atoms to return to the wire. A small fraction escapes (i.e., diffuses away to the wall). Thus adding a gas slows the amount of tungsten leaving the filament. The higher the gas pressure and the larger the gas atoms, the less likely it is that an evaporated tungsten atom will escape the wire. In argon at about 1 atm, the number of tungsten atoms that escape is about 1 in every 500 that evaporate from the surface. Obviously, the less likely escape is, the longer it will take to erode the wire, significantly increasing life expectancy. Thus adding a gas to surround the filament increases life at a given temperature. Furthermore, the mass loss process with an inert gas surrounding the wire is better described as a diffusional flux of atoms from the cylindrical wire filament in a tungsten mass density gradient. The diffusion coefficient is dependent on the properties of the inert gas (i.e., gas density, atomic mass, and the cross sections for interaction between the inert gas and tungsten atoms). Because a gas atmosphere near a hot wire sets up a convective flow, a major difficulty is encountered in determining whether, and to what extent, a stable density gradient, which assumes a quiescent gas, can be assumed.

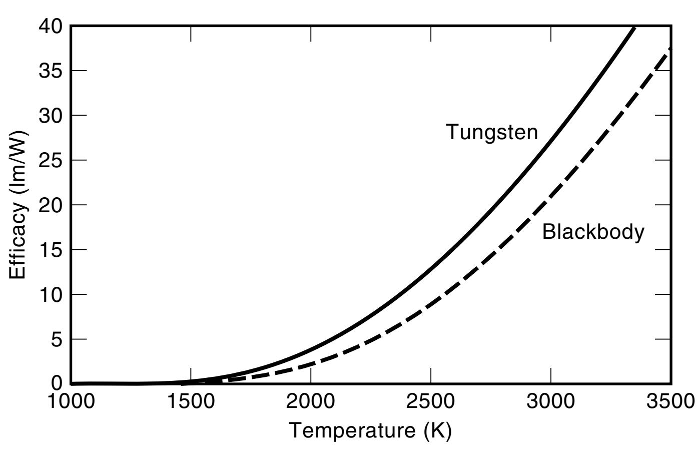

Figure 7. Total and average visible efficacy of tungsten versus temperature.

In addition to reducing the mass loss of tungsten, the added gas interacts with the filament to remove heat from it. Thus a sizable fraction of the power input is expended on non-light-generating processes. For a straight wire, the addition of an inert gas like argon is more costly in lumen efficacy than it is helpful in extending life (i.e., if long life were required, it would be better to lower the wire temperature in vacuum to get longer life than adding argon). However, in 1912 Langmuir (7) found that for thin wires, the heat dissipation by free convection increased very slowly with increasing wire diameter. Moreover, a coil dissipates heat as if it were a wire with a diameter equal to that of the cylindrical coil. Thus he reasoned that by coiling the wire, the heat loss to the gas from a given length of wire could be greatly reduced because the total length of the cylinder is many times shorter than that of the straight wire. In this way, it was possible to increase the efficacy by operating the coiled wire at a higher temperature in a gas filled lamp. In 1913 gas filled lamps with coiled filaments were introduced. Later, two coilings (i.e., a coiled-coil filament) improved the situation further. Hence today's household incandescent lamps in the United States use coiled-coil filaments to take as much advantage of the life increase resulting from the fill gas. This is generally not true in Europe or other parts of the globe where the mains is 220 V to 240 V, where singled coiled filaments are still preferred in GLS products. Of course coiling tungsten wire requires a ductile wire. The development of a ductile wire process by Coolidge in 1909 made possible the coiled tungsten filament used in current incandescent lamps.

Langmuir explained the reason for the slow increase in convective heat loss with wire diameter as follows: the velocity distribution around the hot wire of diameter d is such that the velocity at the surface of the wire is zero. Furthermore, at the surface, the temperature of the gas is equal to the wire surface temperature and decreases with distance from the wire surface. Also, because the viscosity of the gas increases with temperature, it could be expected that there exists a gas layer around the wire where the gas is quiescent. Thus the heat loss to the gas near the filament surface could be assumed to be the result of conduction, not convection. On the other hand, at some distance from the filament, the gas is in convective motion. In the convective region, Langmuir made the simplifying assumption that the gas temperature was equal to the wall or lamp envelope temperature. Thus he could calculate the heat loss by conduction over a sheath of gas surrounding the filament. This quiescent gas layer is called the Langmuir sheath. The difficulty comes in calculating the thickness of the sheath. See Chapter 2 and Annex A of Ref. 8 for how this can be done.

PRACTICAL FILAMENT LAMPS

Why Tungsten?

Tungsten has been the material of choice in incandescent lamps for about 80 years. What specifically are the advantages of tungsten over other incandescent materials? Three major advantages of tungsten over other materials are of primary importance. Tungsten has:

1. The lowest evaporation rate (vapor pressure) of any metal (discussed previously),
2. The spectral selectivity which enhances visible light output (also discussed previously), and
3. Thermo-mechanical stiffness (non-sag characteristic) at high temperature.

The primary reason tungsten is the preferred material for incandescence is that it can be operated at a *higher temperature* than any other metal. The melting temperature is about 3650 K. Furthermore, the evaporation rate (vapor pressure) of tungsten as a function of temperature is lower than any conductive solid; about a factor of ten lower than tantalum, the next best material in terms of vapor pressure. Everything else being equal, the higher the operating temperature the higher the lumen efficacy as demonstrated in Fig. 4 for a blackbody.

As discussed previously, the *spectral selectivity* of tungsten is also an important contributor to the efficacy that can be obtained at a given temperature. Some ceramic compounds such as hafnium nitride or tantalum carbide display an emissivity curve that is even more selective than that of tungsten. That is, at a given temperature, they give off more radiant energy in the visible region and less in the infrared compared to tungsten. These have so far proved unsuitable for incandescent lamps because of their extreme brittleness, which causes an inability to form into suitable filaments and the tendency to disproportionate at high temperatures. Furthermore, despite higher melting point temperatures, these materials generally display higher vaporization rates for typical lamp gas fills than does tungsten (see Ref. 9).

Finally, the fact that tungsten wire is ductile enough that it can be drawn from solid tungsten ingots at low temperatures and then transformed into a stiff, rigid body through doping and recrystallization at high temperatures is a unique and important feature of doped tungsten. Without this property coiled filaments would not be practical. The capability of extended operation without sag or distortion at temperatures greater than 90% of melting is noteworthy; it is a characteristic not found in most metals.

Coiling

As mentioned earlier, the primary reason for coiling a tungsten filament is to reduce the amount of heat lost to the gas. Instead of having a long thin wire with a large surface area in conductive contact with the gas, the wire is coiled into what is effectively a much shorter cylinder with a dramatically reduced effective surface area. Even though the effect of coiling is beneficial to reducing gas losses, there is a small penalty paid in efficacy. This is because light exiting a filament from the inside of a coil has the opportunity to first undergo one or more internal reflections. This has the effect of making that portion of the light more blackbody-like with a lower selectivity, albeit higher overall emissivity, than that of a straight tungsten wire. The effect of coiling on lamp efficacy will be seen later when the basics of filament coils are introduced.

Often, to minimize the thermal gas-loss, it is beneficial to double-coil the tungsten wire. That is, the wire is first coiled into what is called a primary coil. This coil is itself then coiled into what is referred to as the secondary coil. Some coils are even triple coiled, although in most cases the benefits are small to nonexistent.

Coiling is accomplished in practice using wire mandrels about which the wire or primary coil is wound. The primary coil is usually made by winding the tungsten wire around a molybdenum wire mandrel. This primary mandrel stays inside the primary coil while the whole thing is then wound around a larger retractable mandrel to make the secondary coil. In the end, filaments are washed in acid to dissolve out the primary molybdenum coil.

Coils are referenced with regard to two main parameters, the pitch ratio K_p and the mandrel ratio K_m. Referring to Fig. 8, these coiling parameters are defined as follows:

$$\text{pitch ratio:} \quad K_p = \frac{h}{D} \tag{12a}$$

$$\text{mandrel ratio:} \quad K_m = \frac{m}{D} \tag{12b}$$

Here, h is the turn separation of the coil (measured from the center of the wire on one turn to the center of the wire on an adjacent turn), D is the wire diameter, and m is the inside diameter of the coil. This is equivalent to the outer diameter of the mandrel wire about which the tungsten wire is wound.

The pitch ratio given in Eq. (12a) is actually slightly different than that used by most engineers and coil manufacturers. The latter, "engineer's" pitch ratio is given by

$$K'_p = \frac{h'}{D} \tag{13}$$

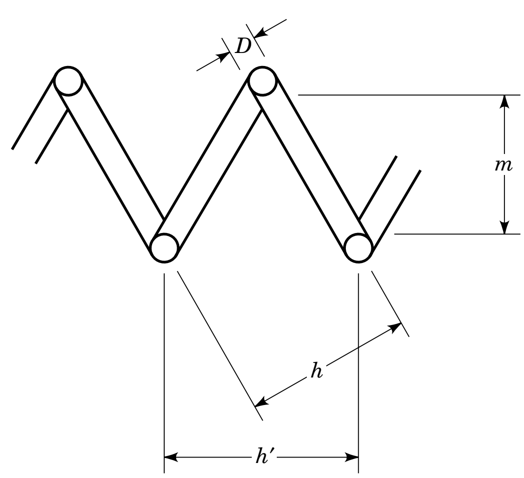

Figure 8. Schematic of single coil with definitions of h, h', D, and m.

This latter definition is the one generally known because h' is easy to measure. It is simply the inverse of the number of turns per unit length (usually written as TPI, for turns per inch). The relation between K'_p and K_p is

$$K_p = \frac{2K'_p(K_m + 1)}{\sqrt{K'^2_p + 4(K_m + 1)^2}} \tag{14}$$

(Note that the expression for this found on page 146 of Ref. 2 is incorrect.) These coiling parameters are used to relate the wire length and diameter to the coil length and diameter, which show up in the gas loss equation and a multiplying factor δ for the efficacy, as will be shown later.

Rudiments of Lamp Design

An incandescent lamp is rated by how much power it consumes, how much light it generates, and how long it is expected to burn before failure. In addition, the voltage or current of the power source needs to be specified. These lamp ratings or operating characteristics are met by choosing a tungsten wire of a given length and diameter such that, when placed across a given power source, it reaches a temperature that gives the specified power, lumens, and life values. Thus incandescent lamp design is principally concerned with simultaneously matching the conditions of *voltage* (or current or resistance), *power* consumption, *lumen* output, and *life* by manipulating the wire *length,* wire *diameter,* and filament *temperature.* Note that because there are only three intrinsic parameters that relate to the filament (i.e., wire length and diameter and filament temperature), only three of the four lamp characteristics listed here can be specified independently.

Even though only three filament-related parameters are considered to be intrinsic (i.e., affect all parameters), other lamp-related parameters such as coiling, gas type and pressure, and wall temperature have a significant impact on some of the lamp characteristics. These other parameters, however, are considered to be supplemental rather than intrinsic parameters as are the wire dimensions and temperature. A brief review of the underlying principle physical relationships between the lamp characteristics and filament parameters follows. These relationships constitute the fundamentals of design. Because of the interrelating relationships of the various parameters, the approach is by necessity iterative.

Design Procedure

One approach is to start with the lamp voltage V and the desired power P as being fixed. From Ohm's Law, this fixes the filament resistance $R = V^2/P$. As will be shown momentarily, the filament wire length and wire diameter may then be derived from simultaneous solutions of the resistance and power equation, where an initial value of the temperature has been specified. Given these initial values for wire length, diameter, and temperature, the luminous flux and life may also be derived. From the ratio of calculated to specified values for either lamp life or the lumen output, the temperature can now calculated. With this new temperature, the wire length and wire diameter are recalculated. This process is iterated until the solution no longer changes within a specified error. This process is shown in detail later.

Consider the two equations for resistance and power. First, the resistance of a wire is a given by the ratio of the wire length l to the cross sectional area, $A = \pi d^2/4$, times a temperature-dependent material property, the resistivity $\rho(T)$. Here, d is the wire diameter. Thus an initial value for the wire length is given by

$$l = \frac{RA}{\rho(T)} = \frac{V^2\pi d^2}{4P\rho(T)} \tag{15}$$

Similarly, we can obtain an expression for the wire length l from the equation for power. The power input P to a lamp filament is dissipated by radiative losses P_r, which dominate, as well as heat loss to the gas P_g and conduction to the leads P_l. Thus

$$P = P_r + P_g + P_l = P_r + \Delta P \tag{16}$$

where the two nonradiative loss terms have been collected together in ΔP.

The radiated power from a tungsten wire can be obtained by multiplying the blackbody emittance in Eq. (3) by the total tungsten emissivity and the wire surface area. The effect of reabsorption of radiated power by a coiled wire, called the coiling factor δ, will be described later. The coiling is weakly dependent on both the wavelength and temperature. For the power, which represents integration over all wavelengths, the expression δ_t will be used. Thus

$$P = \pi \cdot d \cdot l \cdot \delta_t(T) \cdot \epsilon(T) \cdot \sigma \cdot T^4 + \Delta P \tag{17}$$

Solving Eq. (17) for the wire length l gives

$$l = \frac{P - \Delta P}{\pi \cdot d \cdot \delta_t(T) \cdot \epsilon(T) \cdot \sigma \cdot T^4} \tag{18}$$

Equations (15) and (18), both of which give expressions for the wire length, can now be solved simultaneously for the wire diameter d. This gives

$$d = \left[\frac{4P\rho(T)(P - \Delta P)}{V^2\pi^2\delta_t(T)\epsilon(T)\sigma T^4}\right]^{1/3} \tag{19}$$

Note that an initial value for ΔP must be specified. For GLS lamps, the lead conduction is small (about 1%) and the gas loss varies from about 8% to 20%, depending on lamp voltage, wattage, and coiling. For automotive lamps or other low-voltage lamps, the lead conduction losses and gas convection losses are about equal, usually around 5% each. A value for ΔP of about $0.1 \times P$ is a good place to start the iteration. As values for d, l, and T become better defined in the calculation, ΔP can be better estimated as well.

After an initial estimate for the wire length and diameter are derived using Eqs. (15) and (19), an initial value for the total luminous flux from the filament may be derived by multiplying the wire surface area, $S = \pi dl$, times the Planck blackbody distribution function weighted by the eye sensitivity curve and the spectral emissivity curve for tungsten in a manner similar to that shown previously. The luminous flux $\phi(T)$ is given by

$$\Phi(T) = S\int_{380}^{760} V_\lambda \epsilon_\lambda(T)\delta_\lambda(T)M^{\rm b}_{{\rm e},\lambda}(T)\,d\lambda \tag{20}$$

This equation is solved for the flux value $\Phi(T_0)$, in terms of the initial estimate of temperature T_0 and given the values for l and d calculated earlier. However, since the lumen value is assumed specified, the ratio of Φ_{given} to $\Phi(T_0)$ can be used to calculate a new value for the temperature, T_1, from the exponential part of the $M^{b}_{e,\lambda}$ term, which is then inserted into Eqs. (15) and (19).

The coiling factor δ can be thought of as modifying the emissivity of the coil. For straight wire, $\delta = 1$. For a coil, the light generated on the inside of the coil has a chance of being reabsorbed, thereby increasing the filament temperature. For a tungsten coiled coil, a typical value at 2700 K is $\delta \sim 0.79$. The coiling factor δ is a function of temperature and coiling parameters, and is given, for a single coil, by the following expression (see Ref. 2):

$$\delta_1(T_1) = \frac{1}{2}\left[1 + \frac{1}{\pi(K_\text{m}+1)} + \left(1 - \frac{1}{\pi(K_\text{m}+1)}\right)\frac{K_\text{p}-1}{K_\text{p}-r(T_1)}\right] \tag{21}$$

The coiling parameters K_m and K_p are given by Eqs. (12)–(14). The temperature dependence of δ is carried through the reflectivity $r(T)$, which is given by

$$r(T) = 1 - \epsilon(T) \tag{22}$$

where $\epsilon(T)$ is the total emissivity of tungsten.

For a double coil (coiled coil) the coiling factor is given by:

$$\delta = \delta_1\delta_2 \tag{23}$$

where δ_2 is the coiling factor for the secondary coil and is given by

$$\delta_2 = \frac{1}{2}\left[\left(1 + \frac{1}{\pi(K_{\text{m}2}+1)}\right)\delta_1 + \left(1 - \frac{1}{\pi(K_{\text{m}2}+1)}\right)\frac{K_{\text{p}2}-f_1}{K_{\text{p}2}-r_1}\right] \tag{24}$$

and where $r_1 = 1 - \delta_1\epsilon$ is the reflectivity of the primary coil, and ϵ is the temperature-dependent total emissivity. The opacity f_1 is given by

$$f_1 = 1 - \left(\frac{K_{\text{p}1}-1}{K_{\text{p}1}}\right)^2 \tag{25}$$

Here, all subscripts 1 and 2 refer to the primary and secondary coils, respectively.

The temperatures and wavelength-dependent parameters that are needed in this iterative procedure are the tungsten resistivity, total emissivity, and spectral emissivity along with the gas-loss term needed for Eqs. (16)–(19). A second-order polynomial fit to the resistivity data from 2000 K to 3600 K taken from Ref. 10 provides the following functional form for $\rho(T)$, with T measured in Kelvin:

$$\begin{aligned}\rho(T) = &-3.19353\times10^{-6} + (2.63402\times10^{-8})T\\ &+ (1.8011\times10^{-12})T^2\ \Omega\,\text{cm}\end{aligned} \tag{26}$$

The total tungsten emissivity is also taken from the same source. A second-order fit to the data from 2400 K to 3600 K gives the following functional form:

$$\begin{aligned}\epsilon(T) = &-2.03926\times10^{-2} + (1.88601\times10^{-4})T\\ &- (2.35764\times10^{-8})T^2\end{aligned} \tag{27}$$

The spectral emissivity for tungsten at 2600 K is taken from Ref. 5. A second-order fit gives the following functional form:

$$\epsilon(\lambda, T = 2600) = 0.55788 - (233904)\lambda + (4.91792\times10^{10})\lambda^2 \tag{28}$$

Here the wavelength λ is measured in meters.

For nitrogen, argon, and krypton gas, typical values for $P_\text{g}(T)$, the gas-loss term, may be taken from the following expressions, which were derived for a typical 40 W, 120 V filament lamp with 80 kPa (~600 torr) cold pressure fill:

$$\begin{aligned}\text{for N}_2: P_\text{g}(T) = &-1.2522 + (1.6968\times10^{-3})T\\ &+ (6.4245\times10^{-7})T^2\ \text{W}\end{aligned} \tag{29}$$

$$\begin{aligned}\text{for Ar}: P_\text{g}(T) = &-0.8535 + (1.3868\times10^{-3})T\\ &+ (3.1375\times10^{-7})T^2\ \text{W}\end{aligned} \tag{30}$$

$$\begin{aligned}\text{for Kr}: P_\text{g}(T) = &-0.6236 + (9.9857\times10^{-4})T\\ &+ (1.5576\times10^{-7})T^2\ \text{W}\end{aligned} \tag{31}$$

Figure 9 shows these gas-loss terms as a function of temperature.

Filament Life. Predicting the life expectancy of a lamp filament is by far the most difficult and least understood of the lamp design problems. Several mechanisms are involved in causing filament burn-out, which is the normal predictable end-of-life mechanism. The most important phenomenon, and the easiest to understand theoretically, is tungsten evaporation from the surface of the wire. This was discussed earlier. Obviously, as tungsten evaporates, the wire diameter decreases. When the wire is reduced to some critical size, the wire either breaks or melts as a result of overheating. Thus one would expect filament life L to be inversely proportional to the evaporation rate. Furthermore, at the same temperature, the thicker the wire, the longer it would take to reduce it, leading to a linear increase with life with wire diameter.

Even though it has been found empirically that filament life does vary inversely with the evaporation rate, the problem is not as simple as it appears. Consider what is expected to happen to an evaporating filament on a constant voltage source. As the wire diameter decreases as a result of evaporation, the resistance increases causing the current, and hence the power, to decrease. But a power decrease must imply a reduction in filament temperature, which greatly reduces the evaporation rate. In the long run, the evaporation rate would become so small as to be inconsequential. Thus when we assume that evaporation is uniform from the whole filament, we find the predicted behavior is one of infinite life.

This obviously is not what happens. Instead it is known that the filament develops hot spots (i.e., regions that are slightly higher in temperature than those nearby). The hotter regions evaporate more rapidly, causing more rapid thinning of the wire than on average. These thin areas will run even

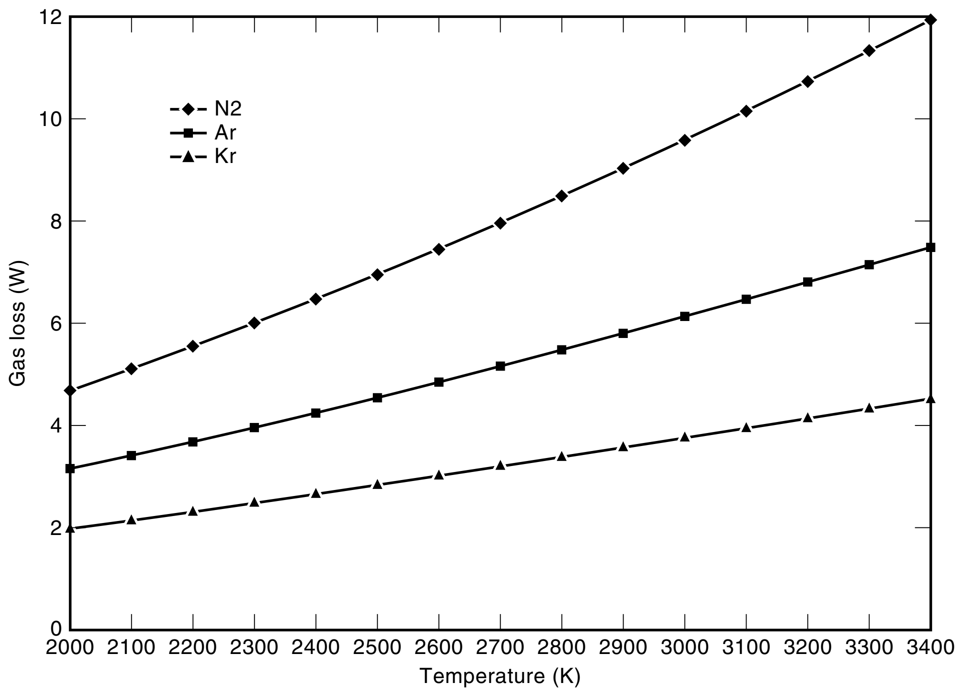

Figure 9. Gas loss (watts) calculated for different gas fills for 40 W, 120 V lamp.

hotter because the resistance is higher there, and because the current must be continuous throughout the wire, the thin areas dissipate more power. Thus a positive feedback cycle develops, causing the hot spot to increase in temperature more and more rapidly until it reaches the melting point of tungsten and the filament fails (see Ref. 11). It is known that hot-spot development is the cause of filament failure, but all the causes of hot-spot development are not known nor is their relationship to each other understood well at all. It is probably because the life-ending mechanism involves hot spots in which the distribution of life is found to follow a normal curve extremely well. Furthermore, the standard distribution of the normal life curve is usually quite large being about 20% to 25% of the expected life.

From the diffusional flow of tungsten atoms through the Langmuir sheath, as already discussed, a relationship between expected filament life Λ and the filament parameters can be put into the following form:

$$\Lambda = \frac{C_\Lambda d^x}{\Gamma(T, \text{gas}, p, \text{coil}, T_\text{w})} \tag{32}$$

Here C_Λ is a normalizing constant empirically determined. It is also found empirically that the dependence of life on wire diameter d is about linear for very large wire diameter [i.e., over 10 mils (2.54×10^{-4} m)], but this dependence increases in magnitude as the wire diameter gets smaller, becoming larger than d^3 for wire diameters less than 2 mils (5.08×10^{-5} m). Because this dependence is difficult to determine, x is used for the diameter dependence. The tungsten atom diffusion term Γ depends strongly on the temperature T but also depends on the gas type and pressure, the coiling parameters, and the wall temperature. Predictive models for the diffusion term are most easily done by extensions of the Langmuir sheath simplification, but for greater accuracy convective-based FEM models have been developed.

The temperature dependencies of the radiated power, lumens, radiant efficacy, and life for tungsten wire are shown in Fig. 10. Here the data for each parameter is normalized to one at a temperature of 2800 K to show more clearly the strength of the temperature dependence. Note that because lumens increase about the square of the radiated power, the efficacy increases at about the same rate as the radiated power. Note further that life, based on the temperature dependence of the evaporation rate, decreases most rapidly with increasing temperature. Hence, for a given design situation, luminous efficacy increases can be traded against shorter life. However, the efficacy increase is only on the order of 10% of the decrease in life. This situation always holds for incandescent and halogen lamps. The life at a given temperature can be increased by increasing the fill gas pressure, going to a denser rare gas, increasing the wall temperature (all of which are done in halogen lamps), and decreasing the voltage that results in larger diameter wire, but the temperature dependence remains as shown in Fig. 10. For further discussion on the filament lamp design approach used here, see Ref. 12.

TUNGSTEN-HALOGEN LAMPS

What should emerge from the preceding discussion on incandescent lamps is an expectation that if some gas (when combined with a coiled filament) is good for increasing life and efficacy, more gas should be better. Furthermore, the denser the gas, the better. Both would reduce tungsten loss through evaporation and would enable higher- temperature filament operation, which results in a more efficacious lamp. Typical incandescent lamps are filled with a mix of argon and nitrogen to a pressure of ~0.8 bar. When lit, these lamps are roughly at atmospheric pressure. To hold higher pressures would require a stronger and smaller lamp body. However, with a smaller lamp body, the surface area is greatly reduced,

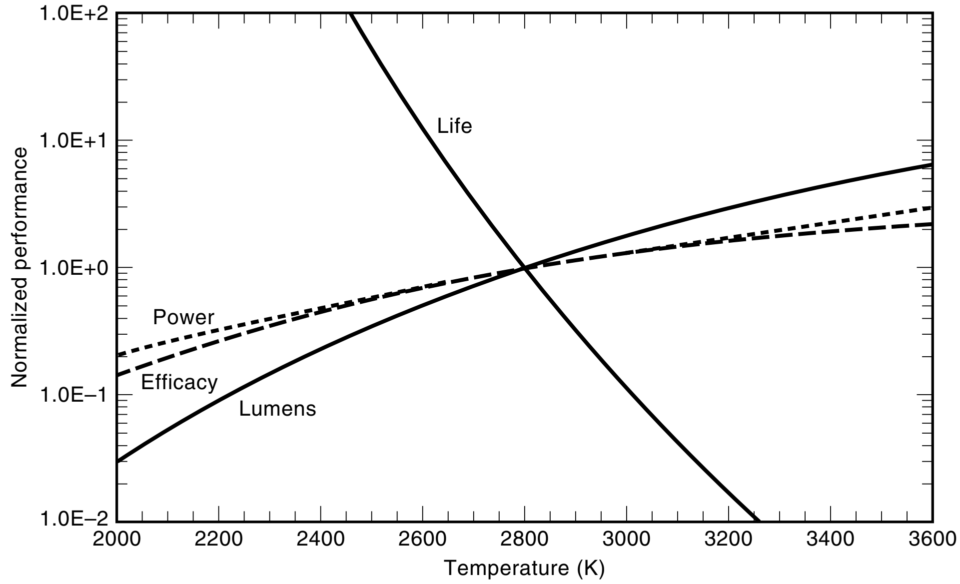

Figure 10. Temperature dependence of various parameters for tungsten wire.

and the flux of evaporating tungsten atoms, although reduced because of the higher pressure, would nonetheless cause eventual wall blackening. What is needed is a way to keep the wall clean despite the close proximity of the wall to the filament.

Halogen lamps are incandescent lamps containing compounds of one or more of the elements I, Br, Cl, and F. These compounds act to prevent the tungsten evaporating from the incandescent coil from depositing on and darkening the lamp wall. The tungsten evaporating from the coil reacts with the halogen in the cooler regions of the lamp and is converted into gaseous halogen-containing compounds. These compounds decompose en route to the hotter regions of the lamp, depositing tungsten metal on the leads or cooler parts of the coil and releasing the active halogen to continue the cycle. For halogen cycles used today, the tungsten is not deposited in exactly the same places on the coil from which it evaporated (13), so the coil in a halogen lamp does not last forever and eventually fails, generally in the same manner as an ordinary incandescent coil.

With such a wall-cleaning agent, the incandescent lamp can be made with a much smaller, and consequently much stronger, bulb. This permits the use of higher pressure fill gases and the economical use of rarer denser inert gases such as krypton and xenon. With higher pressures and denser gases, the rate of tungsten mass loss from the coil is decreased, and so life is increased. Denser inert gases also have lower thermal conductivity, which results in less energy lost by gas conduction. With these changes, the coil may be redesigned for increased light output, increased life, or some combination thereof. A typical halogen lamp may be 10% brighter and last twice as long as an ordinary incandescent lamp. On the negative side, halogen lamps can operate with the lamp walls as hot as 900 K and with internal pressures of 1.5 MPa (15 atm) or more. For safe operation, such lamps must be prevented from contacting combustible materials and a means of containing any fragments from potential wall rupturing must be provided.

Mechanism of the Halogen Cycle

For the iodine halogen cycle, there is general acceptance that oxygen is a requirement and that the volatile tungsten-iodine-containing compound, which returns the tungsten to the coil, is WO_2I_2 (14,15). There is also some agreement that the crude mechanism presented in Reactions 1 through 3 is correct (15,16).

At filament:

$$\mathrm{W(solid)} \rightarrow \mathrm{W(gas)} \quad \text{(R1)}$$

At/near filament:

$$\mathrm{W(solid, gas)} + 2\mathrm{O(gas)} \rightarrow \mathrm{WO_2(gas)} \quad \text{(R2)}$$

At/near wall:

$$\mathrm{WO_2(gas, solid)} + 2\mathrm{I(gas)} \rightarrow \mathrm{WO_2I_2(gas)} \quad \text{(R3)}$$

These reactions are not meant to represent a mechanism in the chemical sense. Not enough is known for that level of detail. In addition to these general reactions, there is a corrosion reaction between the tungsten filament and the iodine, which slightly increases the mass loss rate of the filament. This is represented by Reaction 4.

At filament:

$$\mathrm{W(solid)} + n\ \mathrm{I(gas)} \rightarrow \mathrm{WI}_n\mathrm{(gas)},\ n = 1,\ 2 \quad \text{(R4)}$$

It is likely that an analogous mechanism operates for the bromine cycle where the transport species is WO_2Br_2. There is also the possibility of an oxygen-free transport cycle for bromine where the transport species are WBr_4 and WBr_5. These species are less stable than WO_2Br_2 and are formed at lower rates. Wall cleaning and lead corrosion rates are so sensitive to trace amounts of oxygen that it is difficult to say that, in practical bromine cycle lamps, oxygen is not involved. Oxygen usually enters the lamp in the form of water or metal oxides.

Halogen Lamp Engineering

Halogen Types Used. In an operating lamp, the halogen dose must react quickly enough to convert all evaporating tungsten to the volatile compound but react slowly enough so that the current-carrying leads and coil supports are not corroded. Ordinarily, to avoid excessive failures from lead corrosion and to decrease the extent of coil attack (Reactions 2 and 4), halogen lamps are designed to blacken very slowly, a typical maintenance being 85% to 95% of initial lumen output at 70% of life. The life here is the coil life, which is governed by the hot-spot mechanism described before. This requires not only control of the amount of halogen but also control of the amount of hydrogen and contaminants that can affect the amount of oxygen available to the lamp atmosphere.

Control of reaction rates limits use of the elemental forms to I_2, while Br_2, Cl_2, and F_2 are too reactive. The addition of hydrogen inhibits the rate of lead corrosion and wall cleaning and permits the use of lamps dosed with HBr, CH_2Br_2, and CH_3Br. The addition of oxygen accelerates the rate of lead corrosion and wall cleaning, permits the use of lamps dosed with CH_3I, and mandates very precise control of the oxygen level in all types of bromine lamps. With the improved manufacturing processes of today, most halogen lamps use bromine doses.

Common bromine doses are HBr, CH_2Br_2, and CH_3Br. Doses used in special cases include CH_3I, $PNBr_2$, and mixtures of halogen compounds. HBr, CH_2Br_2, CH_3Br, and CH_3I are gases and are added to the lamp along with the inert fill gas. $PNBr_2$ is a solid and is added to the lamp as a solution in petroleum ether, with the petroleum ether solvent allowed to evaporate prior to evacuation and inert gas fill. CH_3Br and CH_2Br_2 doses are less corrosive than HBr and have a much lower tendency to adsorb on the inner surface of the lamp exhaust and fill equipment, which increases dose reproducibility.

Within seconds of first lighting the coil, CH_3Br and CH_2Br_2 are converted to HBr as shown in Reactions 5 and 6 (17).

$$CH_3Br(gas) \rightarrow HBr(gas) + H_2(gas) + C(solid) \qquad (R5)$$

$$CH_2Br_2(gas) \rightarrow 2\ HBr(gas) + C(solid) \qquad (R6)$$

If used in excess, the carbon released from Reactions 5 or 6 can deposit on the bulb wall causing darkening or can be transported to localized areas of the coil causing embrittlement. The additional hydrogen released from Reaction 5 has an inhibiting effect both on the kinetics of wall cleaning and on the kinetics of lead corrosion.

The amount of the halogen added typically ranges from 0.03% to about 5% (mole or volume percent). The amount of halogen added increases with increasing tungsten evaporation rate, increasing hydrogen to bromine ratio, and decreasing amounts of oxygen. The hydrogen to bromine ratio is a function of the type of halogen dose, because little additional hydrogen arises from the manufacturing process.

Oxygen is not usually added to bromine lamps because sufficient amounts remain in the lamp as contaminants during normal manufacture. The most common sources of this oxygen include water adsorbed on lamp parts and in the exhaust/fill system, water and other oxygen-containing species dissolved in the lamp walls, oxygen dissolved in the metal parts, and metal surface oxides. In some cases, there is too much oxygen contamination, and oxygen getters are required. Many getters have been proposed for use with halogen cycle lamps (18–32). In general, oxygen getters cannot be used in excess, as in the case of ordinary incandescent lamps, because this results in poor lumen maintenance. The sensitivity of the reaction rates to oxygen, the ubiquitous nature of oxygen, and the reactivity of oxygen with many common metallic contaminants present the main challenge to consistent manufacture of high-quality halogen lamps. The fact that there is, in general, no easy technique to measure oxygen in all its important forms inside a lamp makes the chemical design of halogen lamps very difficult. In practice, the halogen dose is determined using a design of experiments approach.

Materials Requirements. To prevent reaction and loss of Cl-, Br-, or I-based halogen doses with the lamp walls, the glass used must not contain alkali or alkaline earth elements. This limits the choice of wall materials to alumino-silicate glasses of negligible alkali content, 96% silica glass (such as Vycor, made by Corning Glass, Inc.) and quartz. At the operating temperatures of halogen lamps, Vycor and quartz are both permeable to H_2 whereas the alumino-silicate glasses are not. Currently, there is no economical lamp wall material that resists attack by fluorine-based halogen doses. Nor has any economical coating been developed. Consequently, there are no commercially available fluorine cycle lamps. The internal metal parts of halogen lamps are tungsten or molybdenum lead wires and supports and the tungsten coil.

Temperature Requirements. Vycor and quartz require the use of molybdenum foil hermetic seals for the current-carrying leads. This restricts the temperature of the seal area to less than 620 K if the seal life is to exceed 1000 h, unless these seals are not exposed to air. The lamp walls must be hot enough to prevent the volatile tungsten-halogen-containing compounds from condensing and removing the halogen from the cycle. For iodine cycle lamps, the coldest permissible wall temperature is about 520 K (33). For bromine cycle lamps, the coldest permissible wall temperature is about 440 K (33). In general, the upper limit to the lamp wall temperature is determined by either its rupture strength or the stability of the tungsten transport species. The latter consideration limits the wall temperature to about 1300 K. In practice, however, the maximum wall temperature is often lower because of unacceptable water release or impurity element migration to the lamp interior.

Lamp Orientation Requirements. Ordinarily, halogen lamps can be operated in any orientation. A special case arises for the linear halogen lamps [i.e., those with lengths over 5 cm (~2 inches) having outer lamp wall diameters of about 1.2 cm (0.5 inch)]. To ensure uniform distribution of halogen, these lamps must be burnt within about 4° of horizontal. When burnt off-horizontal, the linear lamps act like thermal separator columns, and wall blackening will occur in the regions where the halogen is depleted (p. 71 in Ref. 15, p. 143 in Ref. 34) Occasionally, corrosion problems will result for lamps operated in certain orientations when the hot gas flow from the coil is directed onto metal parts (35,36), but these problems are usually resolved in the design phase before production.

Scientific Understanding

A complete understanding of the halogen cycle would require being able to describe mathematically all the interrelated processes shown in Fig. 11. This has not been possible because of the complexity of the problem, and nobody yet has determined the set of rate-determining processes. Without simplification, the number of physical constants needed to describe the problem is overwhelming, as would be obtaining convincing proof of the validity of the model after it is developed.

One simplifying approach, which has seen the most development, is the assumption of thermodynamic equilibrium within the entire lamp. Even this approach assumes that accurate thermodynamic data exists for *all compounds* having significant stability within the 300 K to 3300 K temperature range encountered inside a halogen lamp. In its simplest form, this approach has yielded elemental solubility maps that have been used to indicate the direction and sometimes magnitude of tungsten transport for various doses (14,37–54). In its most advanced form, it has been merged with the numerical solution to the fluid dynamics inside a lamp to yield a complete 3-D transport model (55,56). Although thermodynamic equilibrium is likely to be attained near the incandescing coil, it is not likely to be attained in cooler regions of the lamp (57). In fact, there are many instances where the gas flow away from the coil has concentrations of highly reactive species in excess of the equilibrium amount (35,36). Perhaps the biggest objection to the assumption of thermodynamic equilibrium everywhere inside a halogen lamp is its failure to predict a transport cycle for CH_3Br doses that are known to be effective in practice.

Nevertheless, the thermodynamically derived elemental solubility approach provides a simple framework for understanding the chemical transport in halogen lamps, so a brief discussion is merited. The tungsten elemental solubility is the maximum amount of tungsten that can exist in the gas phase under equilibrium conditions. It is the sum of all molecules that contain tungsten weighted by the number of tungsten atoms in that molecule normalized by total moles or total weight. The molecular composition is calculated by minimizing the free energy with the given temperature, pressure, atom mass balance, and a complete set of thermodynamic data. Many computer codes are available for these calculations: CEC-72 and CEC-80 from NASA, United States; SOLGASMIX and SAGE from THERDAS-Lehrstukl für Theoretishe Hüttenkunde der RWTH, Germany; STANJAN from Stanford University, United States; MULTIPHASE, MTDATA from NPL and AKAEA, United Kingdom; MELANGE, THERMODATA from Domaine U. de Grenoble, France; POLY-3, THERMO-CALC, Royal Institute of Technology, Sweden; IVTANTHERMO from Russian Academy of Sciences, Russia; and GIBBS, HSC from Outokumpu Research Center, Finland.

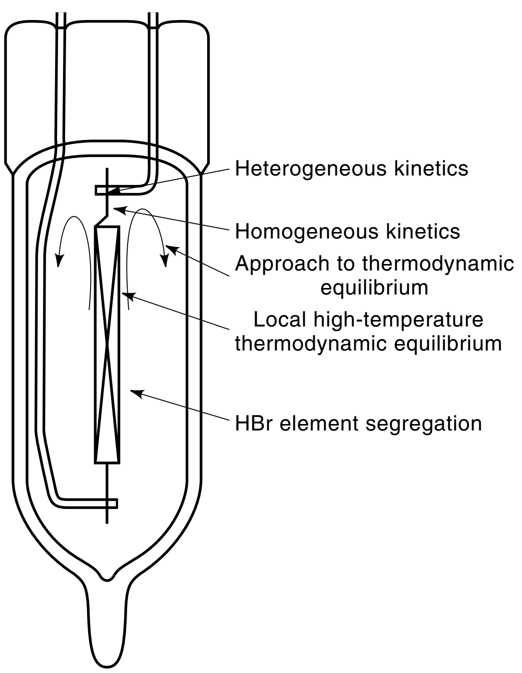

Figure 11. Many phenomena must be considered for a complete understanding of tungsten–halogen lamps.

An area having a high-tungsten elemental solubility can lose tungsten to an area with a lower tungsten elemental solubility. Elemental tungsten solubility curves are plotted as a function of temperature in Fig. 12 for three different levels of oxygen contamination for a lamp filled with 0.05% HBr in 2 MPa (20 atm) of an inert gas, a dose typical of a 1000 h halogen lamp. Figure 12 shows the sensitivity of the tungsten elemental solubility to traces of oxygen, which increase both the high-temperature and low-temperature tungsten elemental solubility. In Fig. 12, the elemental tungsten solubility is represented as the molar ratio with the inert gas. In general, as the temperature increases, the solubility decreases, reaches a minimum at about 2000 K, and then increases again. At the lower temperatures, the species comprising the gas phase tungsten are mostly the more complex tungsten bromides and oxybromides, which lose stability as the temperature exceeds about 1300 K. In the intermediate temperature region, only the simpler bromides and oxides contribute to the tungsten elemental solubility. Eventually, as the temperature reaches the normal operating range, the tungsten elemental solubility becomes dominated by tungsten gas from the physical evaporation of the coil. The tungsten elemental solubility for an incandescent lamp in a pure atmosphere is shown as curve W, gas in Fig. 12.

Focusing on the curve for 0.1 ppm oxygen contamination in Fig. 12, at a temperature typical for a 1000 h life lamp, 2850 K, denoted by arrow A, the gas in the region of the filament will contain 4×10^{-9} moles tungsten per mole of inert gas, arrow B. If this gas is suddenly moved to the wall, no solid tungsten compounds will form as long as the wall temperature is lower than about 1500 K, arrow C. Which tungsten compounds are formed is answered by looking at the details of the thermodynamic calculation to see which, if any, condensed phases are formed.

Maps can be made to show which condensed phases are formed for various lamp operating conditions using thermodynamic calculations. One such map is shown in Fig. 13 where the condensed phases are shown for various lamp wall temperatures and oxygen contamination levels for a 2850 K tungsten coil operating in 2 MPa (20 atm) Ar containing 0.05% HBr. In this map, the tungsten elemental solubility at the coil was used to set the tungsten atom balance in the rest of the lamp. Calculations were per-

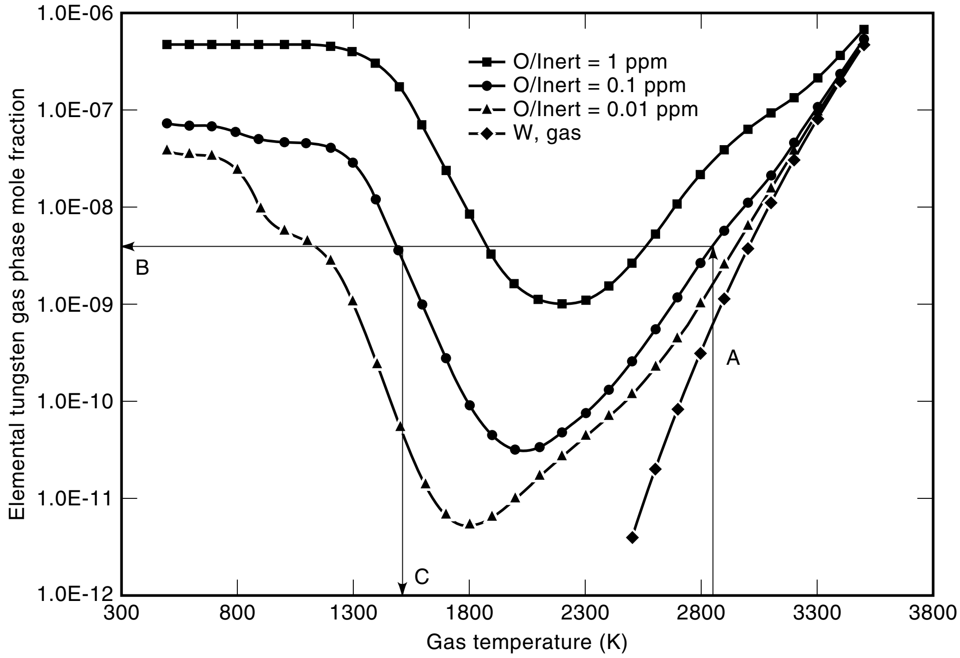

Figure 12. Tungsten elemental solubility calculated for a tungsten–halogen lamp filled with 2 MPa (20 atm) inert gas containing 0.05% HBr is very sensitive to trace levels of oxygen contamination. Transport of tungsten can occur from high elemental solubility regions to low elemental solubility regions.

formed every 100 K and 0.5 log units in oxygen level, which causes the jagged boundaries between phases. Figure 13 depicts the purity and wall temperature required to prevent wall deposits in this halogen lamp. Figure 13 shows that as the oxygen contamination is reduced below 0.1 ppm, the wall temperature range for deposit-free operation is reduced, the minimum wall temperature is increased, and maximum wall temperature is decreased.

The Future

The performance of halogen lamps will continue to improve as designs become more optimized. This will be an incremental

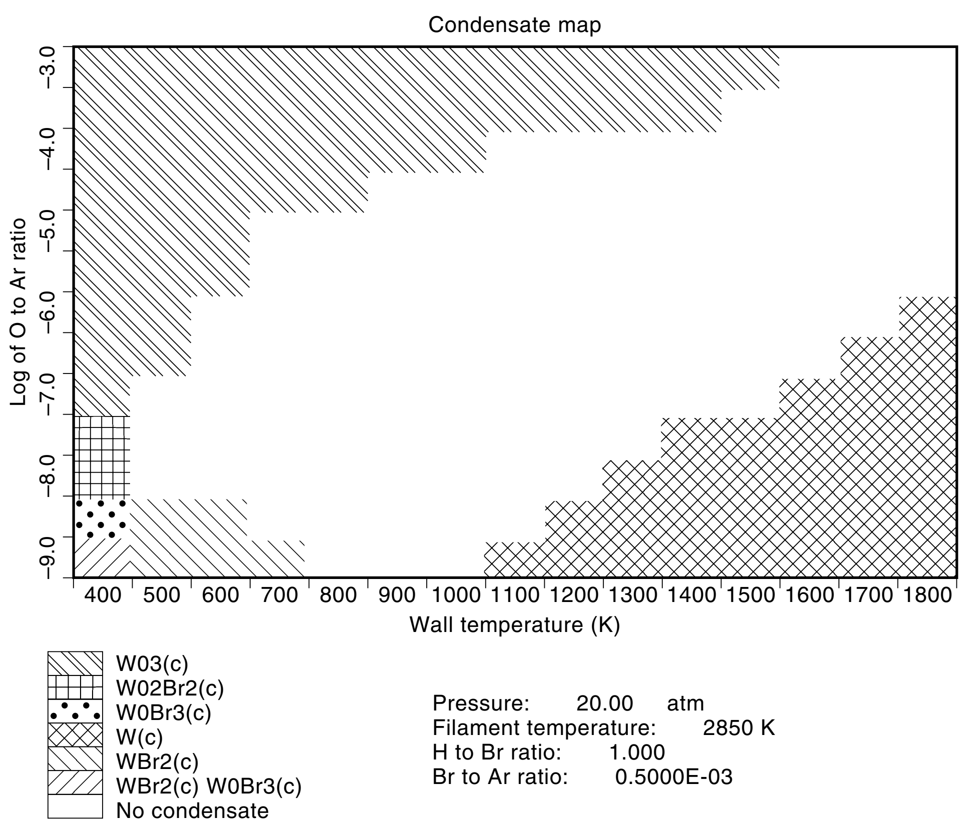

Figure 13. Thermodynamic calculations can be used to map operating conditions leading to clean deposit-free walls. This figure indicates such a region for a tungsten-halogen lamp filled with 0.05% HBr operating at 2 MPa (20 atm) with a coil temperature of 2850 K. Rough boundaries are the result of the discrete nature of the calculations. These maps are useful for showing trends but may not be accurate.

Table 1. Power Balance and Performance of 100 W Incandescent and 90 W Halogen Lamps

Type	Power (W)	% Visible	% Non-Vis.	% Non-Rad.	Efficacy (lm/W)	Life (h)
Incandescent	100	10	75	15	17.1	750
Halogen	90	11	74	15	17.5	2000

process at best, with the optimum performance limited to that of the basic incandescent lamp. The future of halogen lamps will be brighter when the materials problems associated with using a fluorine-based cycle are solved. This cycle might have the promise of increasing life by returning the evaporated tungsten to the hot spot (14,15,34). Another, more speculative, area where halogen or other chemical transport cycles may find use is to stabilize the phases of other materials that could be used as incandescent bodies at temperatures exceeding the melting point of tungsten.

POWER BALANCE AND PERFORMANCE FOR TYPICAL LAMPS

Table 1 shows the power balance and performance comparison for a typical 100 W incandescent lamp and a 90 W halogen lamp. The percent visible and nonvisible radiation refers to that which actually exits the lamp. The nonradiative losses include loss resulting from absorption of the radiation by the bulb wall and the base (which is ~5% for both the 100 W incandescent and 90 W halogen lamps).

The performance advantage of the halogen lamp is clear. In general, life and efficacy performance advantages can be traded off for each other. In this example, the main performance advantage of the halogen lamp is taken in life. As always, though, there is a price to be paid for the performance advantage, and this is the extra cost to manufacture halogen lamps, which results in higher market prices compared to standard incandescent lamps. The higher material costs stem mainly from the cost of denser gas types such as krypton and xenon, which are used in the halogen lamps. The major cost addition, though, comes from the fact that an extra filament tube must be made to replace the simple filament in an incandescent lamp. In addition, the requirements for filling lamps at pressures above 1 bar lead to additional costs, as does that of ensuring that the halogen lamp will contain any particles safely in the unlikely event of rupture of the filament tube. For this reason, little market penetration of the halogen lamp in a general lighting household lamp such as the A-line has yet occurred. Thus, the two lamp types can coexist in the market, each filling a particular market niche.

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FILM DEPOSITION BY PLASMA. See PLASMA DEPOSITION.

FILM GROWTH, HTS. See HTS FILM GROWTH.

FILM THICKNESS MEASUREMENT. See THIN FILM ANALYZERS.

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