Tungsten Filament Lamps
A Case Study

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4TH YEAR M. ENG

RERVM COGNOSCERE CAVSAS

Contents

Introduction

Traditional forms of lighting such as lamps burning animal fat, or lamps burning paraffin to electric light bulb glow because they are hot. A hot body radiates energy, or heat, according to the law of radiation derived by Max Plank in 1900. However the problem is that only a fraction of the energy emitted by any hot body is in the spectrum of visible light.

The choice of metals for the manufacture filament light bulbs is obviously limited to those with a very high melting point, when methods of processing tungsten into filaments emerged it quickly became the major filament material. The service conditions are severe with temperature during operation above the recrystallisation temperature of tungsten. Heating is by direct resistance so accurate dimensional control of the filament is necessary.

Thermal vibration of atoms

A hot body radiates energy, or heat, according to the law of radiation derived by Max Plank in 1900. The distribution of energy with wavelength from an ideal black body is given by the equation;

$$\frac{dEb}{d\lambda} = \frac{2\pi hc\wedge 2}{\lambda\wedge 5[\exp(hc/k\lambda T)-1]}$$

The consequence of this distribution can clearly be seen graphically, as shown below in figure 1 and please alos see the graphs appended which show the energy distribution at temperatures of 1500°K, 1750°K and 2000°K.

At higher temperatures a greater proportion of the energy is at shorter wavelengths, and more is therefore in the visible range. Filament light bulbs therefore need to operate at the highest possible temperature.

Temperature reached by resistance wire in a vacuum

Heat constant $\phi = \sigma\varepsilon A\,(T_1^4 - T_2^4)$

$\phi = 5.67\text{x}10^{-8} \text{ x } 2\pi \text{ x } 40\text{x}10^{-6} / 2 \text{ x } (T_1^4 - T_2^4)$

for $T_2 = 0$ $T_1 = (100 / 5.67\text{x } 10^{-8} \text{ x } 2\pi \text{ x } 20 \text{ x } 10^{-6})^{1/4}$

$T_1 = 2100$ °K

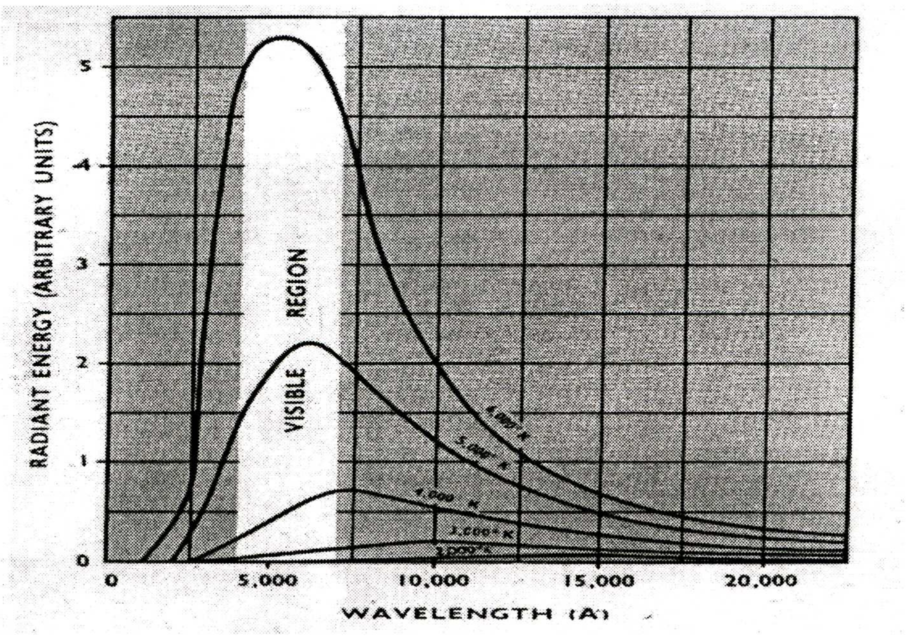


Figure 1; Visible light generated by a black-body at various temperatures.

The energy is due to the vibration of the atoms in the solid, consider an atom vibrating in a solid, X_m = maximum amplitude, V = velocity, V maximum at midpoint, b = atom spacing, E = Young's modulus, T = temperature in degrees Kelvin, k= Boltzman's Constant

Kinetic energy = $\frac{1}{2} mV^2 \sim kT$

mV^2 is equivalent to force x

$\frac{1}{2} EbX_m^2 \sim kT$

The vibration amplitude of a solid atom is proportional to $T^{-1/2}$, just below Tm the amplitude of the vibration is 1/10 of an atomic spacing.

Energy of a photon

E= hf h= planks constant = 6.6×10^{-34} Js

C = fλ, C= speed of light =3×10^8 m/s,

So E = hc / λ

For $\lambda = 5 \times 10^{-7}$ $E = (6.6 \times 10^{-34}) \times (3 \times 10^8) / 5 \times 10^{-7}$ $= 4 \times 10^{-19}$ J

=2.5 eV

Alternatives to the incandescent light bulb

As we have seen much of the electrical energy used by a modern incandescent light bulb is produced as heat and not visible light. Another way of producing visible light is using fluorescence, electrons emit energy as photons when moving from a high energy level to a lower one, if the difference between the two levels is in the right range, the excess energy can be emitted as a photon of visible light.

Discharge lamps and LED produce photons by electron excitation, unlike tungsten filaments which produce light over the whole spectrum, discharge lamps lamp produce light of specific wavelength.

How closely an artificial light source matches sunlight can be represented by a value between 0 and 100 using the colour rendering index (CRI). A value of 100 giving a perfect match to sunlight. Incandescent light bulbs are currently the best widely available having a CRI of 95, whereas most florescent light bulbs have CRIs of only 55 to 75. Some of the best LEDs sit somewhere between with a CRI of 85.

But if light bulbs have a better CRI they lose out badly when it comes to efficiency with which they turn electrical energy to light. Florescent lamps have efficiencies ranging from 50-90 lumens per watt of electrical power, compared between 10 to 20 for light bulbs. LEDs can do even better, with efficiencies more than 100 lumens per watt.

Alternatives to tungsten filament bulbs may also have some advantages from longer life, apart from economic factors. Accidents caused by light bulbs put more than 3500 people in hospital in Britain in 1997, according to the royal society for the prevention of accidents. People risking a painful fall or electrocution when changing a light bulb without the due care.

Economic factors

Although the efficiency of the alternative lighting is higher there are many factors in selecting a lighting source. The current cost of a tungsten filament light bulb is around 30p, and it may use £10 worth of electrical energy over its life-time. Low energy bulbs are much more expensive, more than £5, their lifetimes are considerably longer so they may recoup the higher initial cost over their lifetime.

Service Conditions

Filament lamps can operate at temperatures of upto 2500°C that is a temperature of around 80% of the melting temperature. This is a higher homologous temperature for operation than almost all other metal applications. Instability can appear because of recrystallisation, grain growth, and the resultant type of grain boundary.(B)

Two approaches have been used to stabilise the structure, the production of a fine grained structure in which growth is inhibited and the production of a large grained structure which remains stable. Fine grained structures are produced using small amounts of thoria, this is only partially successful and slow growth will take place. Large grained structures are now the common approach, a mixture of alkali oxide, silica and alumina, which are added to metal oxide in the form of solutions.

High temperature is most easily reached by coiling. Inside of coil is similar to an enclosure the special case where emmisivity is unity as for a black body. A more important effect is the reduced gas flow around the coil compared to a single wire, this critically alters the convective heat transfer and leads to more even heating along the length of the filament.

This makes actual area of coil emitting much smaller, gives a higher temperature for same length and thickness of coil. Higher temperature gives more light emitted in useful visual range. Coils can be double coiled, even though tungsten is usually thought of as being brittle.

Considering a cylinder around the coil, the gas is quite viscous and relatively static. Thus there is little convection and conduction, most heat transfer inside the bulb being by radiation. If the filament is wound into a tight spiral, the stationary layers round adjacent coils interlock, denying free passage of gas through the coil. The effect of this is to reduce the apparent area available for convective heat transfer from the filament, thereby increasing the temperature reached for a fixed wattage, i.e. an improvement in efficiency.

Although having the filament in a vacuum is an effective method of reducing convection in the bulb, this increased the rate of evaporation of tungsten, this could be seen to re-condense on the glass causing a blackening.

Production of Tungsten Filaments

Tungsten makes up 1% of the earth's crust, however must be produced from its ores using a chemical route due to its high melting temperature. Tungsten is almost entirely used as a powder due to the chemical processing route, the first stage of producing filaments is to compact the powder into an ingot.

Two ores are of commercial importance are Wolframite $(FeMn)WO_4)$ and Scheelite $(CaWO_4)$ and the chemical treatments for concentration is different for each. Concentrates are available containing more than 75% WO_3 apart from iron, manganese and calcium tungsten concentrates contain only small amounts of other elements. For production of filaments the content some elements which are difficult to remove must be controlled, such as molybdenum.

Before sintering the powder is compacted by pressing in low alloy steel and heated to around 1150°C for ½ hour in a hydrogen atmosphere. Electrical heating for sintering is produced using a high current, which is necessary because of the low resistance of the thick bar. The current applied is usually equivalent to 90% of the current to melt the bar.

Reduction in surface area is driving forces is to remove pores. Pores on grain boundaries can close more quickly. Binding energy of pore is $\pi r^2 \gamma_g$, where γ_g = grain boundary energy/ unit area.

The final removal of pores in Tungsten sintering is by vacancies flowing outward from the pore, this means atoms flow into the pore and it shrinks. This is governed by diffusion.

Ficks first law $j = -D_v \, dc/dx$ D_v = diffusion coefficient for vacancies

Sintered tungsten bar is then rolled and / or swaged, which is reduction under purely compressive forces. The final reduction is by wire drawing using dies of tungsten carbide and then smaller dies made of diamond. Several stages of drawing are used the first at 1000°C and the final reduction at 500°C. Temperatures are reduced for each subsequent reduction to avoid recrystallisation during processing. The drawn wires acquire a texture with the [110] axis in the drawing direction.

In wire drawing the wire flows through the die the forces perpendicular to the drawing direction are all compressive. Most of the plastic flow is caused by the compressive force which arises from the reaction of the metal with the die.

Since σ_2 and σ_3 are both less than 0 this means that σ_1 is below the uniaxial yield stress. Drawing tungsten results in a highly elongated grain structure. This should lower diffusion by increasing diffusion distances inside the grains along the principle stress direction.

In compacting use K Al Si O, Al, Si and O_2 are vaporised by high temperature of Tungsten, however K is pushed out of solid solution, because of the high lattice strain it would produce, forming agglomerates, these then precipitate and form sinks for vacancies. Bubbles then form at the site of the Potassium these can have a hugely positive effect on the stability of the tungsten in the pinning of grain boundaries.

Filament is next coiled into a helix by wrapping around an iron core, most filaments are then coiled again to form a 'coiled coil'. Once the coil is produced the iron core can be dissolved in acid.

Filament supports are made of molybdenum wires, these must be used in along the length of the coil. There is some loss in efficiency by lowering temperature and by shorting out adjacent coils, because of the loss in efficiency there is a tendency to reduce the number of supports whenever this is possible by improvements in filament chemistry.

Figure 1 shows the construction of a simple fairy light, two molybdenum holders grip the tungsten wire coil. Figure 2 is a higher magnification picture of the tungsten filament from the area outside the holders, this are has not had current passed through it and the surface features from drawing the filament can be seen. These drawing lines where not visible on any of the other filaments since all these had been heated and the surface features had changed, some where seen to be very smooth.

The size of filament is around 40 microns, this is just on the limit of what the eye is able to resolve, therefore it is not easy to see either level of coiling without using a microscope or magnifying glass. Examination using optical methods is also difficult because of the depth of field, SEM is a good technique because the depth of field can be much larger, and higher magnifications can be reached. A series of SEM images are attached at the back of the report (micrographs 1-15).

Failure Modes

Common reasons for failures are; poor assembly, faceting and mechanical damage through impact or vibration. Mechanical damage is influenced by grain size and shape effect probability of this tungsten has a bcc structure therefore toughness is improved smaller grain size. If grains were small and equiaxed the creep strength would be low because diffusion creep would be too fast, therefor and elongated structure is preferred to minimise diffusion.

Faceting

The biggest problem is the filaments is faceting, By vaporisation and condensation or by movement along the surface, one problem this causes is the interruption to the uniformity of cross section leading to non-uniform resistive heating. Hot spot formation can lead to failure as it is also a weak spot, the weight of the filament will create a small tension which will pull out the wire making it thinner and hotter. Evaporation from the hot spot will also take place at an increased rate.

Atoms diffuse or vaporise and condense onto the lowest energy site on the surface. In most crystals crystallographic planes will exist with lower energy than others. The Wulff theorem gives the equilibrium shape from the energies of different crystal structures. Minimising high surface energies is a driving force for faceting Micrographs 3,4,5,6 show good examples of faceting in various filaments, micrograph 2 shows zig-zag surface feature due to faceting, the other micrographs show growth of crystals around the coils, with repeated crystallographic orientation repeated on adjacent coils. micrograph 6 shows a grain boundary between two of these large crystals.

Micrographs 7, 8, 9 show where the filament has fractured during service, the filament has melted at a point possibly due to faceting or some other flaw that has created localised heating, on fracture the hot liquid tungsten has rapidly cooled to form a spherical globule. There is also evidence of porosity escaping to the surface, any gas would have been rapidly expanded at the higher temperature. Micrographs 10, 11 and 12 also show examples of faceted growth of smaller crystals on the surface of the tungsten filament. These are likely to have grown by condensation after the deposition of nano-crystals on the surface.

Failure by grain growth

Grains grow causes the lamp filament to become more brittle, according to the Hall-Petch equation.

$$\sigma_y = \sigma_o + k_y d^{1/2}$$

Grain growth is at first restrained by the minute potassium- gas bubbles that pin the longitudinal grain boundaries. Potassium bubbles are dragged by a moving grain boundary causing bubbles to coalesce, two bubbles form a new bubble of larger volume than the total of the two bubbles.

Fcc / hcp – closed pack but the bcc structure of bcc is not close packed. Also no phase changes occur in tungsten – remains bcc. Figure 10 is another example of growth of a single crystal around the coils. If single crystals are formed entirely across the wire then grain boundary sliding is unimpeded, this will increase the porosity by sweeping up the bubbles as the grain boundary moves.

Consider two bubbles 1 and 2 coalescing into new bubble 3,

$$P_1V_1 + P_2V_2 = P_3V_3$$

Total number of atoms is same so $n_1 + n_2 = n_3$

Pressure of gas in a bubble is, $P = 2\gamma / r$

$$(2\gamma / r_1).4/3.\pi\, r_1^3 + (2\gamma / r_2).4/3.\pi\, r_2^3 = (2\gamma / r_3).4/3.\pi\, r_3^3$$

Hence $r_1^2 + r_2^2 = r_3^2$

It follows that $r_1^3 + r_2^3 < r_3^3$

Micrographs 14 and 15 show good examples of porosity escaping to surface, possibly due to the Otswald ripening type mechanism above. These micrographs are from the Quartz halogen filament, it is possible that there was a higher initial volume of porosity at the g.b. in an attempt to pin the boundaries at the higher operating temperature used.

References

(A) Sidney Perkowitz, "The end of light as we know it", New Scientist, 8th January 2000, p30-33.

(B) D. J. Jones, The application of Tungsten Wire as the light source in incandescent electric lamps, The Metallurgist and Materials Technologist, vol 5, No, 10, October 1973.

(C) Henderson and Marsdon, Lamps and lighting, 2nd Edition, Published 1972, Edward Arnold Publishers.

(D) ELMA, Electric Lamps, Published by ELMA 1949.

TUNGSTEN W

First isolated in Sweden in 1783. It forms about 1% of earth's crust.

Chief ore isWolframite (FeMn)WO_4. Converted to trioxide and Hydrogen reduced.

Atomic mass 183.85 amu (It has isotopes from180 to186) Atomic No. 74.

bcc structure Density 19.3×10^3 kg/m^3

Atomic radius 0.141 nm Burgers vector a/2 ⟨111⟩ 0.274 nm Mol. vol. 9.5×10^{-6} m^3

Electronic structure $Xe\,4f^{14}5d^4 6s^2$

Electrical Properties

Electrical resistivity at 20 °C 5.4×10^{-8} Ωm

Temperature coefficient of resistance 4.8×10^{-3} K^{-1}

Thermal Properties

Melting point T_m 3410 C (3683 K) Boiling point 5933 K

Latent heat of fusion 192 kJ/kg of evaporation 4000 kJ/kg

Specific heat capacity 133 J/kg K

Thermal conductivity 173 W/mK

Thermal expansion coefficient 4.5×10^{-6} K^{-1}

Physical Properties

Self diffusion D_o 5.4×10^{-4} m^2/s Q 585 kJ/mol

Grain boundary diffusion D_{go} 3.3×10^{-3} m^2/s Q_g 385 kJ/mol

Note that $Q \approx 19\,R\,T_m$ and $Q_g \approx 12.5\,R\,T_m$ where R is the gas constant

TUNGSTEN W (Continued)

Mechanical Properties

Young's Modulus E 380 GPa

Shear Modulus G 160 GPa

Bulk Modulus K 320 GPa

Poissons Ratio υ 0.27

Temperature coefficient of Shear Modulus $(T_m/G_0)(dG/dT) \approx 0.5$

Note also the correlations $G \approx 50\ RT_m/V_m$ and $E \approx 120\ RT_m/V_m$ in units of Pa, where V_m is the Molar Volume.

Vicker's Hardness in the range 360 to 500

Elastic limit, typically, in the range 500 to 560 MPa

Tensile ductility between 0.02 and 0.3 (True strain)

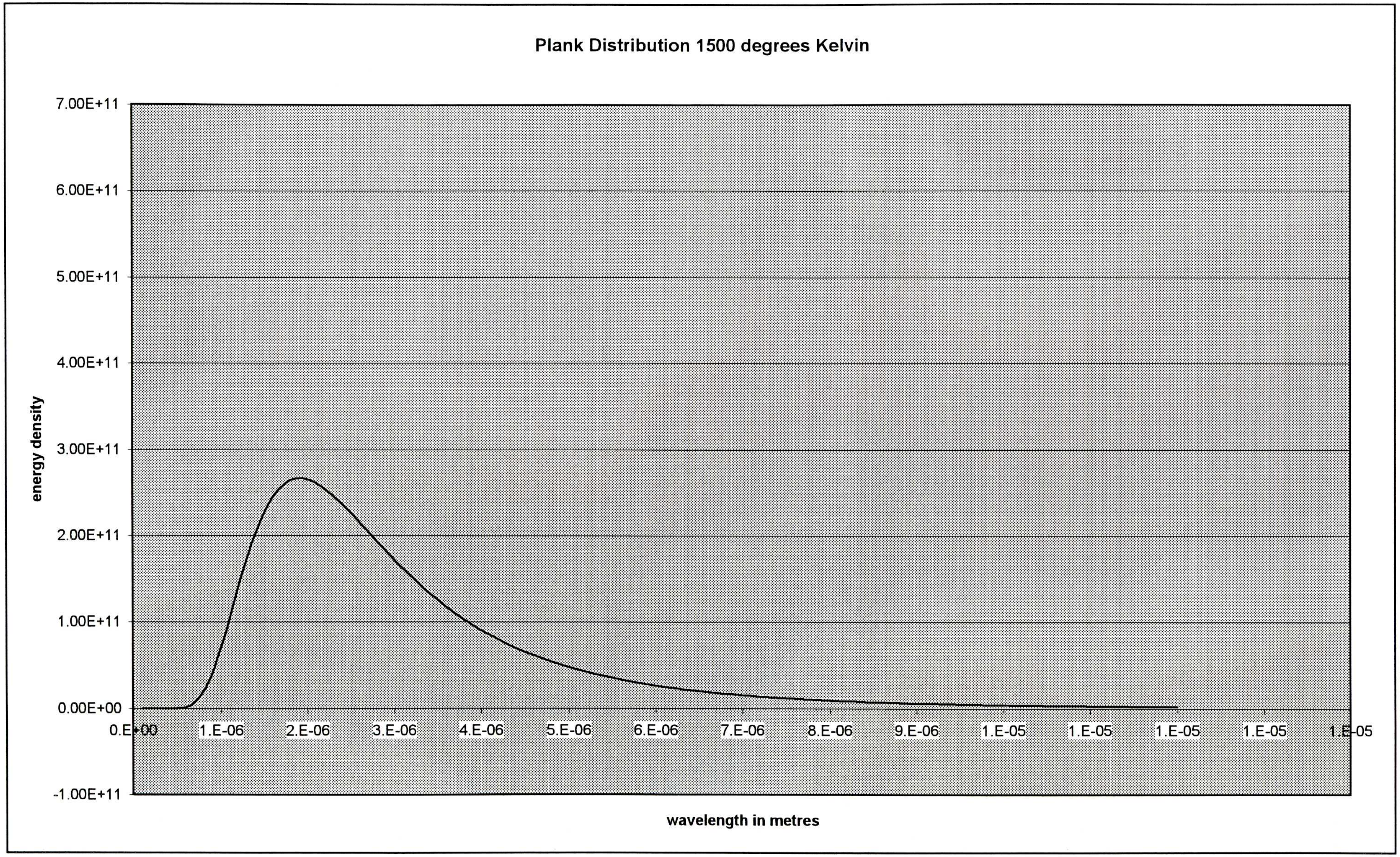
Fracture toughness K_{1c} typically in the range 20 to 40 MPa.m$^{1/2}$

Other Factors

Cost probably about £20 per kg

About 1/3 of the tungsten used eventually becomes recycled

TUNGSPR2
GWG Nov 99


Plank Distribution 1500 degrees Kelvin
energy density
7.00E+11
6.00E+11
5.00E+11
4.00E+11
3.00E+11
2.00E+11
1.00E+11
0.00E+00
-1.00E+11
0.E+00
1.E-06
2.E-06
3.E-06
4.E-06
5.E-06
6.E-06
7.E-06
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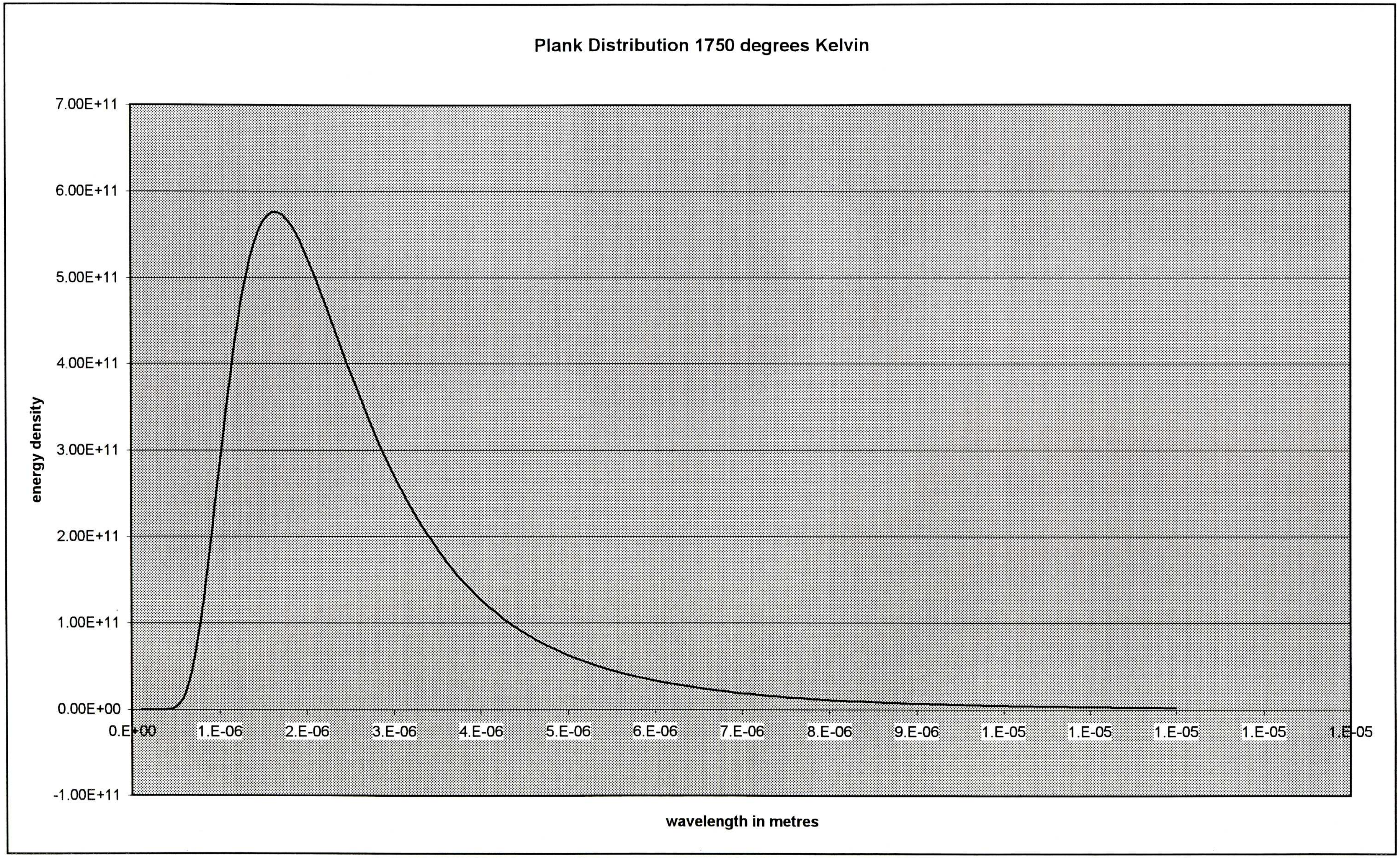
1.E-05
wavelength in metres



Plank Distribution 1750 degrees Kelvin
7.00E+11
6.00E+11
5.00E+11
4.00E+11
3.00E+11
2.00E+11
1.00E+11
0.00E+00
-1.00E+11
energy density
0.E+00
1.E-06
2.E-06
3.E-06
4.E-06
5.E-06
6.E-06
7.E-06
8.E-06
9.E-06
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1.E-05
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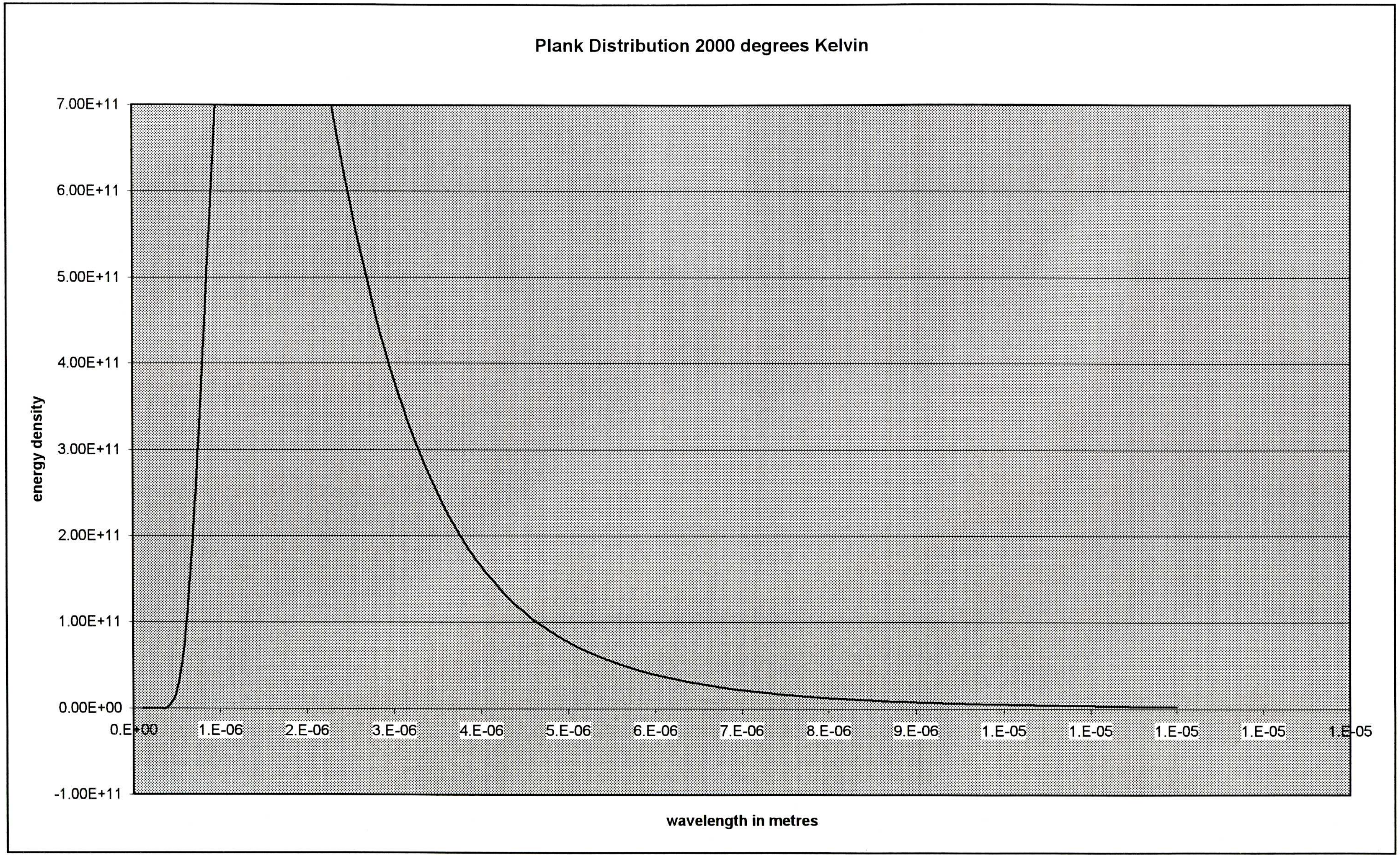
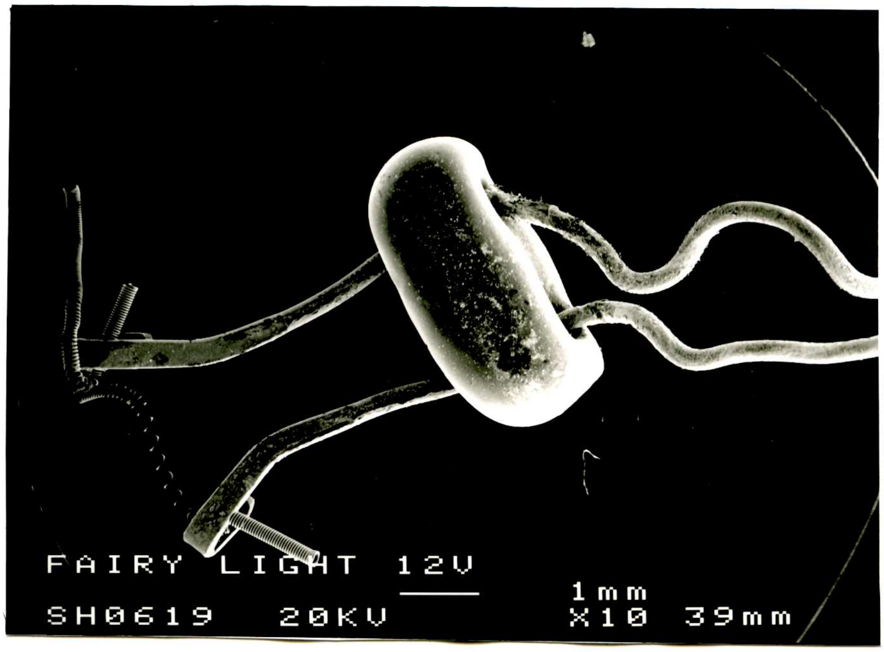
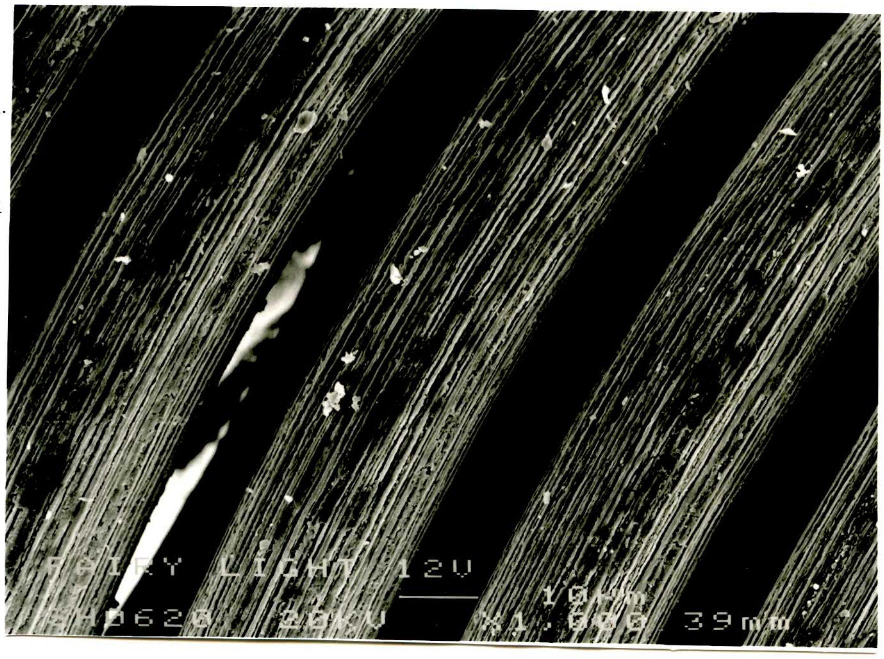
1.E-05
1.E-05
wavelength in metres


Plank Distribution 2000 degrees Kelvin
energy density
7.00E+11
6.00E+11
5.00E+11
4.00E+11
3.00E+11
2.00E+11
1.00E+11
0.00E+00
-1.00E+11
0.E+00
1.E-06
2.E-06
3.E-06
4.E-06
5.E-06
6.E-06
7.E-06
8.E-06
9.E-06
1.E-05
1.E-05
1.E-05
1.E-05
1.E-05
wavelength in metres

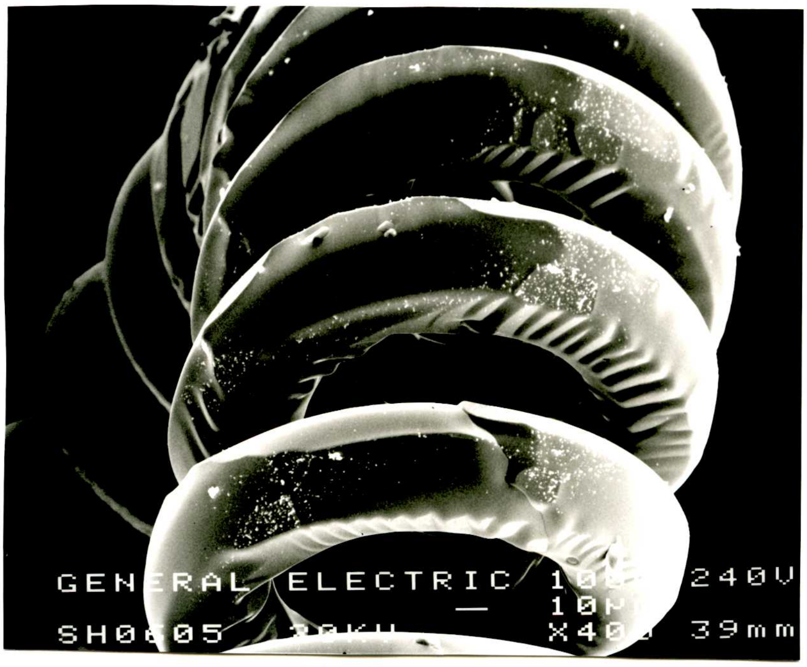
Micrograph 1
Fairy light, Complete holder and filament x 10 magnification.
Fairy light is single coiled,
12V from 20 light chain.



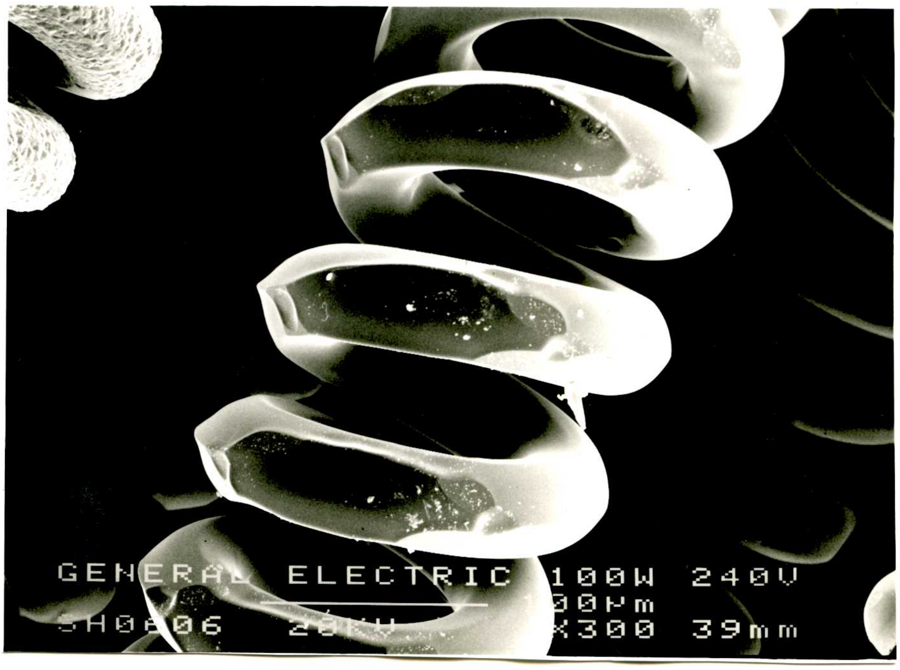
Micrograph 2
Fairy light, filament in unused condition at x1,000 magnification.
The longitudunal lines are marks from passing the filament through a die.



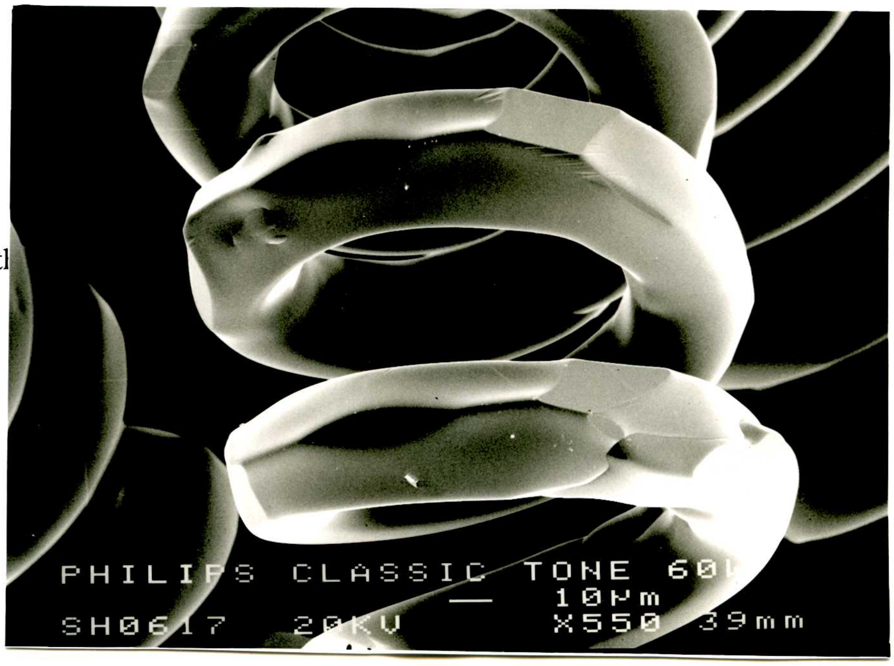
Micrograph 3
General Electric filament 100W,
Note the thickness is about half the thickness of Fairy light
Grain growth has occurred, with some Facets and zig-zag facets, the pattern is repeated on adjacent coils



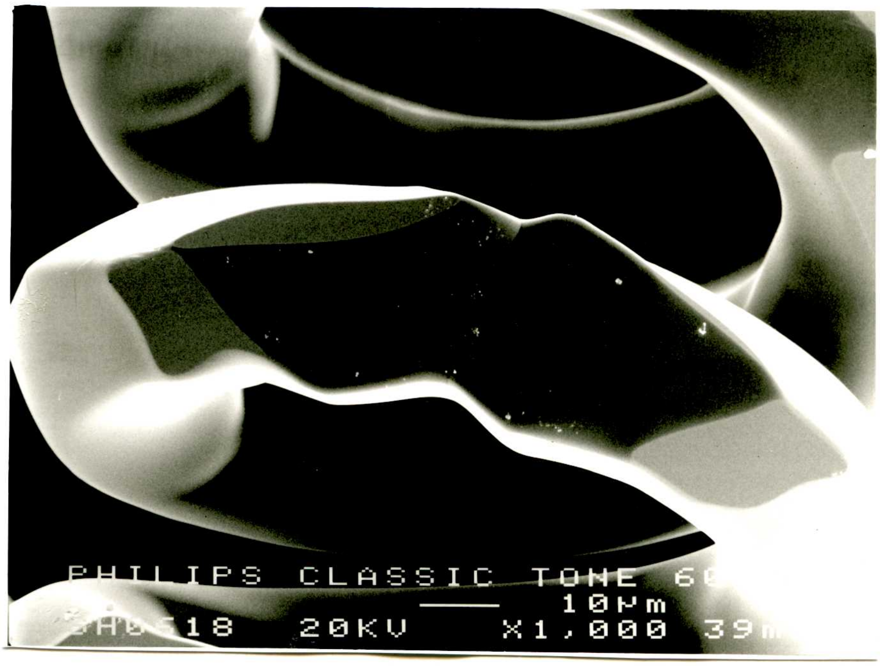
Micrograph 4
General Electric filament 100W,
Crystal orientaion repeated on
adjacent coils.



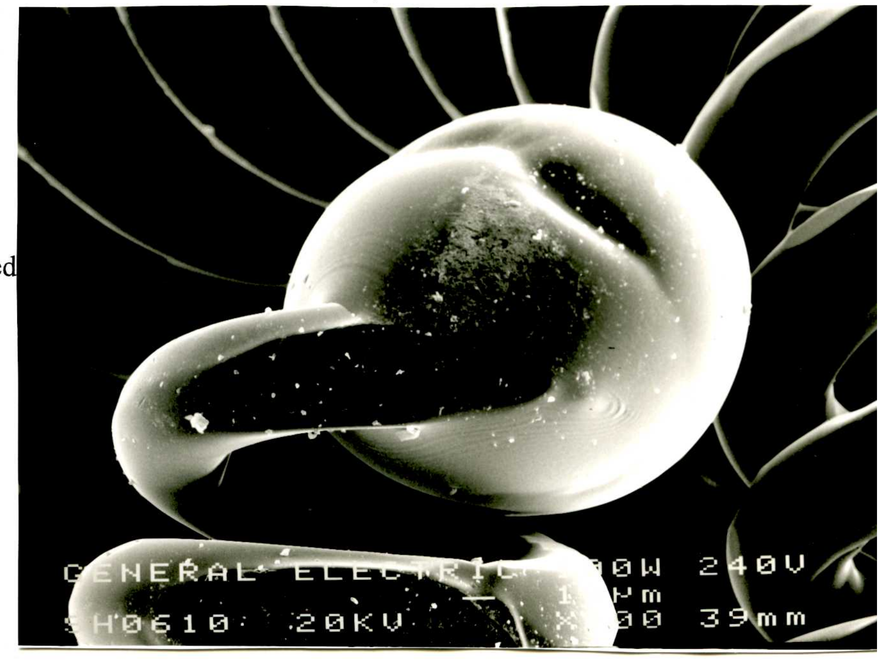
Micrograph 5
Philips Classic tone 60W,
Crystal orientaion repeated on
adjacent coils – this is due to growth
of a single crystal.



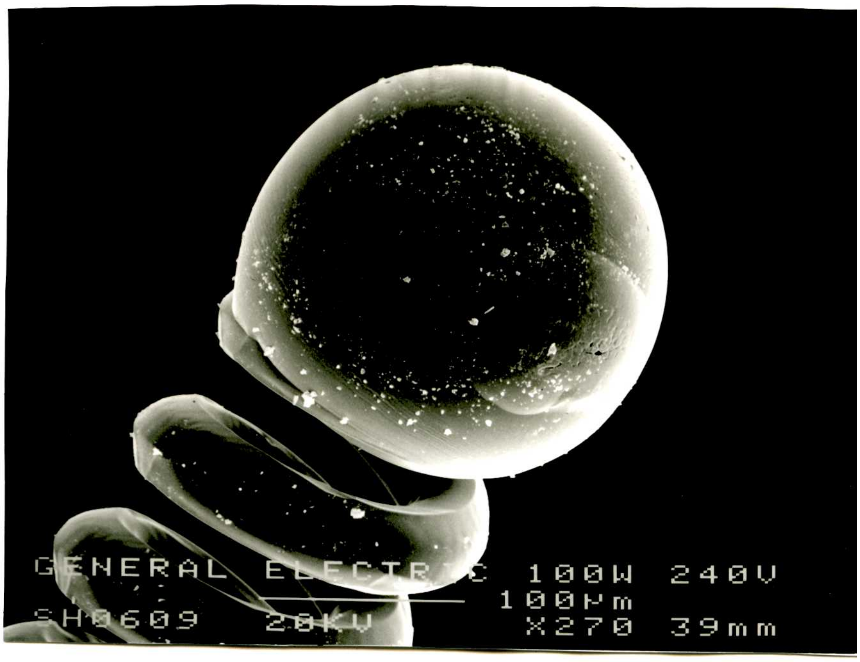
Micrograph 6
Philips Classic tone 60W,
Matched facets, mirrored in grain
boundary. Increased evaporation
from grain boundary.



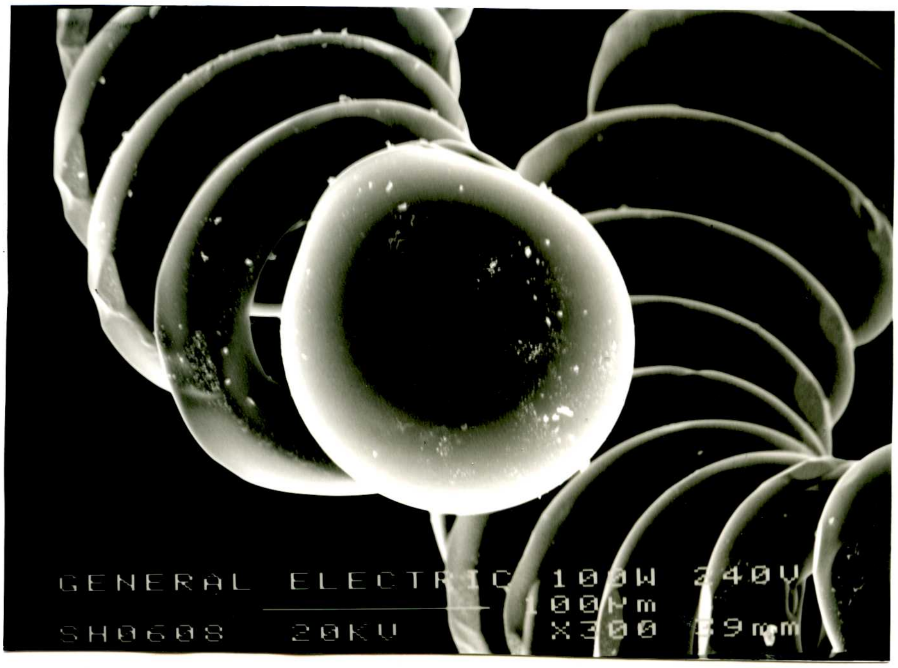
Micrograph 7
General Electric filament 100W,
Formation of globule of material
After the failure of the filament, melted tungsten has rapidly cooled on end of coil.



Micrograph 8
General Electric filament 100W,
As 7 above with some evidence of gas porosity escaping rupturing surface.

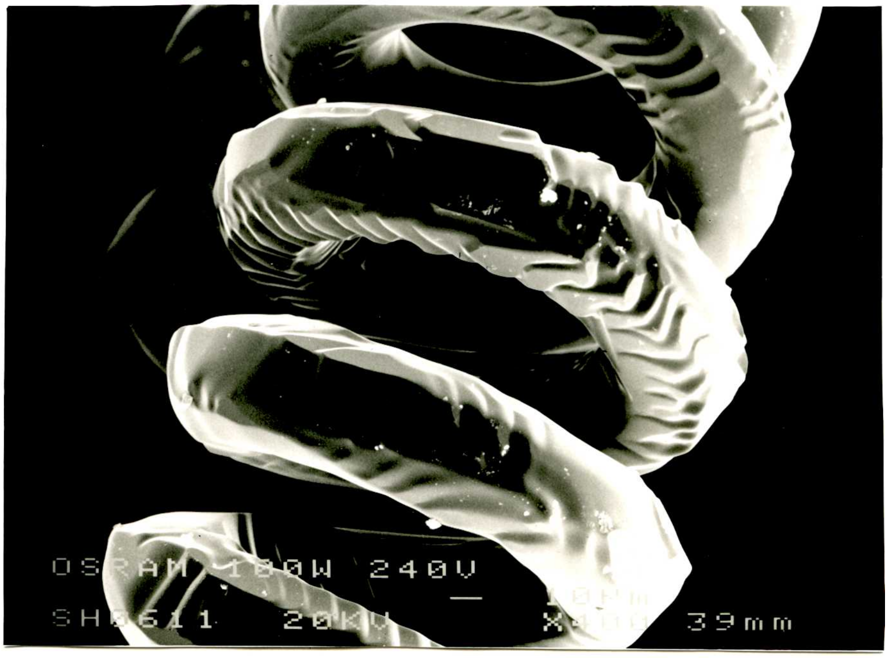


Micrograph 9
General Electric filament 100W,
As 7 & 8



Micrograph 10

100 W Osram, Serated facets



Micrograph 11

Quartz Halogen filament, 300W 120V

Growth of large facets on surface,

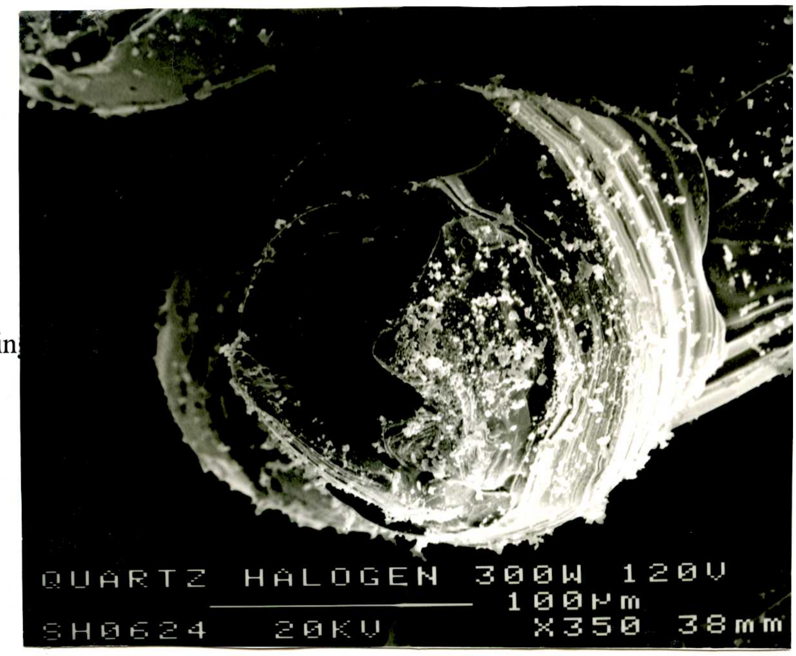
These may have formed by deposition of small crysals on surface followed by growth to form this very blocky structure.

Micrograph 12

Similar to 11, but here growth has occurred between coils.

Micrograph 13
Quartz Halogen filament, 300W 120V
Fracture surface, with subsequent
Cooloing causing tungsten to solidify as
globules.

Micrograph 14
Quartz Halogen filament, 300W 120V
Large escape of trapped gases, the amount
of pottasium added may have been higher
than other filaments because of higher operatin
temperatures.



Micrograph 15
Quartz Halogen filament, 300W 120V
Another example of the escape of the
gas porosity.

Mathew Peet 70%

This is an extensive and interesting report that will be appreciated both by general and scientifically trained readers. It incorporates much useful information and the consideration of alternative light sources and the captions to the Figs. are of particular interest. It is pleasing to see some equations included but all symbols should have been defined. (Note the correct spelling of Planck.) One or two misleading statements have crept in: for example, on p3, mV^2 is not equivalent to a force, though it is an energy related to a force. x is a displacement, not a force.