

Advanced Topic:
Oxidation Resistant Materials

Why can't tungsten wires be used for the light bulb fabrication experiment? If the filaments are still intact from the light bulb dissection experiment, turn on the light bulb after screwing it into a socket. The filament will not last for long. You will see a puff of smoke given off by the filament - this is the tungsten oxide forming and vaporizing. Be sure to stay away from the smoke - do not breathe it. The reason is that the tungsten rapidly oxidizes when it is heated - in general, the oxidation rate of a material increases as the temperature is increased. These oxides of tungsten vaporize at temperatures below about 1500 C. (See the CRC Handbook of Chemistry and Physics.) They are therefore quite unstable in the presence of oxygen at the temperatures required for significant light output (>1000 C) from a filament.

This is quite different behavior from that exhibited by the Kanthal AF wires used in the light bulb fabrication experiment above. These wires are used in kilns in which ceramics are fired.

Oxidation resistant behavior is also exhibited by nichrome heater wires typically used for heater elements in electric stoves, ovens, toaster ovens, toasters, hair dryers and space heaters. These nichrome wires are heated to red hot temperatures of about 600-800 C, where the air passing by them is heated either by conduction or convection.

The Kanthal AF wires are extremely oxidation resistant even at temperatures near their melting point of 1500 C. These wires are composed of mostly iron (72%), with some chromium (22%) and aluminum (6%). As this wire is heated up, it becomes covered with the thermodynamically most stable oxide. Since aluminum oxide is more thermodynamically stable than either chromium oxide or iron oxide, a layer of aluminum oxide forms on the surface of this wire.

How does this layer of aluminum oxide prevent oxidation of the remainder of the wire? The answer is that the diffusion rate of oxygen through aluminum oxide is very slow and it takes a long time for oxygen atoms from the outside to diffuse through the already formed aluminum oxide layer to the unoxidized Kanthal AF material underneath. An example of the microstructure of a section of Kanthal wire that has had 30 micrometers of its surface oxidized to form aluminum oxide is shown in Fig. 5.

Let's calculate how long it will take for oxygen atoms to diffuse through a layer of alumina that is $L=30$ micrometers thick. The diffusion rate D is temperature dependent and at 1200 C is about $D=10^{-16}$

cm²/sec. The time t for an atom to travel through a thickness L if its diffusion rate is D is given by:

$$t = \frac{L^2}{D}. \quad (10)$$

Therefore, it will take $(3 \times 10^{-3} \text{ cm})^2 / (10^{-16} \text{ cm}^2/\text{sec}) = 9 \times 10^{10} \text{ sec} = 10^6$ days. This very long time indicates that the material under the oxide layer will take a long time to oxidize and hence will be very stable.

The Nichrome wires are also quite oxidation resistant. They consist of about 80% nickel and 20% chromium, with a melting point of about 1400 C. Since chromium oxide is more stable than nickel oxide, a layer of chromium oxide will form on the surface of the nichrome wire when it is heated up. The wire is stable at high temperatures because the diffusion rate D of oxygen through chromium oxide is also very low at high temperatures: at 1200 C, $D = 10^{-14} \text{ cm}^2/\text{sec}$. Oxygen diffusion rates through nickel oxide and iron oxide are much higher than those of chromium oxide and aluminum oxide.